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Joint optimization of the selective maintenance and repairperson assignment problem when using new and remanufactured spare parts

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Abstract: This paper deals with the problem of the selective maintenance (SM) optimization for a series-parallel system. The system performs several missions with breaks between consecutive missions. To improve the system reliability during the next mission, its components are maintained during the breaks. Current models in the SM literature usually assume that when a component is subjected to a replacement, it is done by a new one. This paper introduces a novel variant of the selective maintenance problem (SMP) where a mixture of new and reconditioned/remanufactured parts are used to carry out replacements. It has indeed been proved that remanufacturing processes can extend the life of a product returned from the field. This provides not only economic opportunities but also favours sustainable practices. Accordingly, a novel mixed integer nonlinear programming model of the SMP is developed and optimally solved. Numerical experiments show how using reconditioned spare parts impacts the SM decisions.

Keywords: Selective maintenance; Reliability; Preventive maintenance; Remanufacturing, Optimization.

1. INTRODUCTION

Selective maintenance (SM) is applied to multicomponent systems that operate a sequence of alternating missions and scheduled breaks. For the system to successfully complete subsequent missions, maintenance of its components are usually planned during the scheduled breaks. However, due their limited durations, in addition to the possible budget and other kind of maintenance resources constraints, not all components may be selected to undergo maintenance actions. Hence, in order to satisfy the predetermined performance level required during the next mission, it is mandatory to select an optimal set of components to maintain.

Selective maintenance problem (SMP) was first introduced by Rice et al. (1998) and applied to a series-parallel system with subsystems composed of independent and identically distributed ($i.i.d$) components. The lifetime of each system's component is exponentially distributed and the only available maintenance option is the replacement of failed components. Since then, a wide variety of selective models appeared in the literature. Reviews of recent SMP models can be found in (Diallo et al., 2018a,b; Khatab et al., 2018b,a; Liu et al., 2018; Dao Duc Cuong and Zuo, 2017; Pandey et al., 2016; Dao and Zuo, 2016; Zhu et al., 2011). A recent literature review of the SMP is provided in (Cao et al., 2018).

The SMP addressed in the above mentioned papers assumed that replacements of failed components are performed by new ones or repaired with new spare parts. In the present paper, the proposed SM approach allows the manufacturers to engage in sustainable practices. Indeed, repair/replacement of components during the break period are carried out with spare parts chosen from a mixture of new and remanufactured/reconditioned components. Remanufacturing processes such as refurbishing and reconditioning are recognized as sustainable solutions that can offer a second life for components returned from the field. Such solutions allow manufacturers to engage in sustainable practices and provide economic and environmental benefits.

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The concept of a statistical mixture is used to calculate the reliability function of components selected from a mixed population of new and reconditioned spare parts. We also deal with the case where multiple repairperson are available to carry out the replacements/repairs. A novel integrated mixed integer nonlinear programming (MINLP) formulation of the SMP to jointly select the failed components to be replaced with components randomly selected from a mixture of new and reconditioned parts and the assignment of the replacements tasks to multiple repairperson. Its main components and characteristics are computed and discussed in the following sections.

The remainder of the article is organized as follows. Section 2 describes the system under consideration, describes the major working assumptions, and formulates the SMP. Also in this section, the concept of a statistical mixture is used to calculate the system reliability. Furthermore, all components of the integrated SM model are also computed. In Section 3, the mathematical formulation of the joint SM and repairperson assignment optimization problem (SM-RAOP) is presented and solution procedure is proposed. Section 4 investigates numerical experiments and the discussion of their results. Conclusions and future extensions are drawn and discussed in Section 5.

2. SYSTEM DESCRIPTION, SMP FORMULATION AND MODELLING

The SMP addressed in the present work concerns, without loss of generality, a series-parallel system composed of n subsystems ($i = 1, \ldots, n$) in series, each of which is composed of N_i ($i = 1, \ldots, n$) $s-$independent components E_{ij} ($j = 1, \ldots, N_i$). It is assumed that the system has just completed the current mission and is made available for possible maintenance activities during the scheduled break of finite length $\mathcal{D}_0$. After this break, the system operates the next mission of duration u. Two state variables x_{ij} and y_{ij} are used to describe the status of the component E_{ij}, respectively, at the beginning and at the end of a break:

$$x_{ij} = \begin{cases} 1, & \text{if } E_{ij} \text{ is functioning at the start of the break} \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

$$y_{ij} = \begin{cases} 1, & \text{if } E_{ij} \text{ is functioning at the end of the break} \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

During the scheduled break, maintenance activities are performed on failed components to improve the system's reliability during the next mission. Under the proposed SM strategy, if a component fails during the current mission, the system owner replaces it with another component randomly chosen from a pool of new and reconditioned components. For each component E_{ij}, the corresponding spare parts pool contains reconditioned components at proportion p_{ij} ($0 \leq p_{ij} \leq 1$) and new components at proportion $q_{ij} = 1 - p_{ij}$. The proportion p_{ij} can also be interpreted as the fraction of time that reconditioned components are available to be used for replacement. Reconditioned spare parts of equal and constant age τ_{ij} are available for the replacement of component E_{ij}.

There are K repairpersons available to whom component replacement duties are assigned. Since the duration allotted to the break and the maintenance budget are limited, the goal of the equipment operator is to jointly determine the optimal set of components to be replaced and the repairperson assignments to maximize the system reliability for the next mission.

In this paper, the following working assumptions, as defined in (Khatab et al., 2018a), are considered:

(1) The system consists of multiple, repairable binary components (i.e., components and system are either functioning or failed).
(2) During the break, system components do not age, i.e. the age of a component is operation dependent.
(3) No maintenance activity is allowed during the mission. Maintenance activities are allowed only during the break.
(4) Multiple components can be worked on simultaneously without repairpersons colliding. This assumption is reasonable in large multicomponent systems and with modular design.
(5) The duration of the break is longer than the longest component repair time. This is reasonable as the contrary would automatically make the component non-eligible and out of consideration for optimization.

To establish the SM optimization model, we first define the decision variables, then develop the expressions of the reliability of a component selected from a mixed population, the total maintenance costs and durations.

In the formulation of the proposed SM optimisation model, the binary decision variables z_{ijk} and w_k are defined and used along with the binary status variable x_{ij} and y_{ij} defined above.

$$z_{ijk} = \begin{cases} 1, & \text{if } E_{ij} \text{ is replaced by repairperson } k \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

$$w_k = \begin{cases} 1, & \text{if repaiperson } k \text{ is hired/utilized} \\ 0, & \text{otherwise.} \end{cases} \quad (4)$$

2.1 System and components reliability during the next mission

A component E_{ij} is said to have an age $\tau_{ij}(\tau_{ij} \geq 0)$ if either it has accumulated τ_{ij} units of operating time without failure or the component has operated longer and, at a certain time instant, has been reconditioned to age τ_{ij}. If $\tau_{ij} = 0$, then the component is reconditioned back to a "*as good as new*" state. Accordingly, for the next mission of duration u, the reliability $r_{ij}(u)$ of any component E_{ij} selected from a mixture of new and reconditioned spare parts is computed as follows:

$$r_{ij}(u) = q_{ij} R_{ij}(u) + p_{ij} \frac{R_{ij}(u + \tau_{ij})}{R_{ij}(\tau_{ij})} \quad (5)$$

where $R_{ij}(t)$ is the unconditional reliability function of a new component E_{ij}.

At the beginning of the scheduled break, if component E_{ij} is failed (functioning) then it is selected (not selected) for a replacement. Thus, its reliability $R^c_{ij}(u)$ during the next mission is given by:

$$R^c_{ij}(u) = \sum_{k=1}^{K} \left[q_{ij} R_{ij}(u) + p_{ij} \frac{R_{ij}(u+\tau_{ij})}{\tau_{ij}} \right] \cdot (1-x_{ij}) \cdot z_{ijk} + \frac{R_{ij}(u+a_{ij})}{R_{ij}(a_{ij})} (1 - z_{ijk}) \quad (6)$$

where a_{ij} is the age of component E_{ij} if it is still functioning at the end of the current mission.

The reliability $\mathcal{R}$ of the whole system during the next mission is evaluated from the individual component reliabilities $R^c_{ij}(u)$ according to the system reliability block diagram. For the series-parallel configuration considered, the reliability $\mathcal{R}$ is obtained as:

$$\mathcal{R} = \prod_{i=1}^{N} \left(1 - \prod_{j=1}^{N_i} \left(1 - R^c_{ij}(u)\right) \right). \quad (7)$$

2.2 Total maintenance cost and time computation

When a component is not selected for a replacement, neither maintenance cost nor duration are incurred. However, if a component, say E_{ij}, is selected for a replacement, it incurs a maintenance cost and duration. The expressions of the total maintenance cost and duration incurred are computed in what follows.

The total replacement cost is computed as:

$$\sum_{i=1}^{N} \sum_{j=1}^{N_i} \sum_{k=1}^{K} \Psi(\tau_{ij}, p_{ij}) + c^v_k \cdot t_{ijk} \cdot (1-x_{ij}) \cdot z_{ijk}, \quad (8)$$

where t_{ijk} and c^v_k are respectively the time and the cost per unit of time for repairperson k to replace component E_{ij}. The term $(1-x_{ij})$ implies that replacements are available only for failed components, and $\Psi(\tau_{ij}, p_{ij})$ is the acquisition cost of the component selected from the mixed pool of spare parts used to replace E_{ij}. The acquisition cost is formulated as a function of both mixture proportion p_{ij} and age τ_{ij} of the reconditioned component E_{ij}. In the numerical experiments section, a particular cost structure of the acquisition cost will be given and discussed.

The total fixed cost for hiring the repairpersons is:

$$\sum_{k=1}^{K} c^f_k \cdot w_k, \quad (9)$$

where c^f_k is the fixed cost incurred if repairperson k is hired.

The grand total maintenance cost $\mathcal{C}$ is the sum of the replacement and hiring costs:

$$\mathcal{C} = \sum_{i=1}^{N} \sum_{j=1}^{N_i} \sum_{k=1}^{K} \Psi(\tau_{ij}, p_{ij}) + c^v_k \cdot t_{ijk} \cdot (1-x_{ij}) \cdot z_{ijk} + \sum_{k=1}^{K} c^f_k \cdot w_k \quad (10)$$

Given that there is no risk of repairpersons colliding during the repairs (see assumption 4), the total time T_k spent by each repairperson k $(k = 1, \ldots, K)$ to carry out their assigned replacements is given by:

$$T_k = \sum_{i=1}^{N} \sum_{j=1}^{N_i} t_{ijk} \cdot (1-x_{ij}) \cdot z_{ijk} \quad (11)$$

3. THE JOINT SM AND REPAIRPERSONS ASSIGNMENT OPTIMISATION MODEL: SMRAOM

In the present paper, the objective is the joint selection of the set of failed components to replace and the repairpersons assignment to replacement tasks to maximize the reliability of the system during the next mission while taking into account the limited maintenance resources: break duration, budget and the number of maintenance staff. The proposed joint SM and repairpersons assignment optimisation model (SMRAOM) is then given by the following MINLP:

SMRAOM:

Max $\mathcal{R} =$

$$\prod_{i=1}^{N} \left(1 - \prod_{i=1}^{N_i} \left(1 - \sum_{k=1}^{K} \left[q_{ij} R_{ij}(u) + p_{ij} \frac{R_{ij}(u+\tau_{ij})}{\tau_{ij}} \right] \cdot (1-x_{ij}) \cdot z_{ijk} + \frac{R_{ij}(u+a_{ij})}{R_{ij}(a_{ij})} \cdot (1-z_{ijk}) \right) \right. \quad (12)$$

Subject to:

$$\sum_{i=1}^{N} \sum_{j=1}^{N_i} \sum_{k=1}^{K} \Psi(\tau_{ij}, p_{ij}) + c^v_k \cdot t_{ijk} \cdot (1-x_{ij}) \cdot z_{ijk} + \sum_{k=1}^{K} c^f_k \cdot w_k \leq \mathcal{C}_0 \quad (13)$$

$$\sum_{i=1}^{N} \sum_{j=1}^{N_i} t_{ijk} \cdot (1-x_{ij}) \cdot z_{ijk} \leq \mathcal{D}_0, \quad \forall k \quad (14)$$

$$z_{ijk} \leq 1 - x_{ij}, \quad \forall i, j, k \quad (15)$$

$$\sum_{k=1}^{K} z_{ijk} \leq 1, \quad \forall i, j \quad (16)$$

$$y_{ij} = x_{ij} + \sum_{k=1}^{K} (1-x_{ij}) \cdot z_{ijk}, \quad \forall i, j \quad (17)$$

$$z_{ijk}, w_r, y_{ij}, R^c_{ij} \in \{0, 1\}, \quad \forall i, j, k \quad (18)$$

In the above optimization model, Equations (13) and (14) are, respectively, the maintenance budget and time constraints. Provided that a repairperson is utilized, constraints (14) guarantees that their total repair times is no more than the break duration. If the repairperson is not hired, then they cannot perform any repair. Equations (15) refers to constraints according to which replacement/repair are allowed only for failed components. For each component E_{ij}, Equations (16) states that only one replacement can be performed if the component is to be maintained. The constraint (17) allows to update the operating status of components et the beginning of the next mission. The last constraints define the binary decision variables used in the formulation.

The proposed MINLP was coded and solved using the standard nonlinear and global solvers in the academic version of the solver LINGO Release 18.0. The Global solver finds a guaranteed global optima to non-convex, nonlinear and integer mathematical models using the branch and bound/relax approach (Lin and Schrage, 2009).

In the following section, numerical experiments are conducted to show how the use of reconditioned spare parts impacts the joint selective maintenance and repairpersons assignment decisions.

4. NUMERICAL EXPERIMENTS

The spare parts acquisition cost structure is first provided before carrying out the numerical experiments. It is reasonable to assume that the acquisition cost of a component of age τ is a decreasing function of its age up to a certain value, from where it will start to increase to account for the increased disassembly and other cleaning efforts (rust, dust, etc.) In the present work, we consider the acquisition cost of component E_{ij} of age τ_{ij} as initially defined in (Chari et al., 2016):

$$\Theta_{ij}(\tau_{ij}) = \frac{O^0_{ij}}{(1+\tau_{ij})^{\alpha_{ij}}} + \tau_{ij}^{\gamma_{ij}}, \tag{19}$$

where $O^0_{ij} = \Theta_{ij}(\tau_{ij} = 0)$ is the cost of (or equivalent to that of) a new component E_{ij}, and α_{ij} and γ_{ij} are parameters of non-negative real values. Parameter $\alpha_i j$ affects the discount rate offered on old components, while parameter γ_{ij} allows to model an increase in cost due to aging. The average acquisition cost of a component, randomly selected from the pool of new and reconditioned spare parts, is then function of its age τ_{ij} and the mixture ratio p_{ij} and given by:

$$\Psi(\tau_{ij}, p_{ij}) = (1 - p_{ij})\, O^0_{ij} + p_{ij}\Theta_{ij}(\tau_{ij}). \tag{20}$$

4.1 Experiment #1 :

In this first experiment, the system investigated is composed by identical components whose time to failure are Weibull distributed with shape and scale parameters respectively set to $\beta = 1.5$ and $\eta = 30$. The system is composed of $N = 3$ subsystems with the respective number of components are $N_1 = 3$, $N_2 = 5$, $N_3 = 4$ (see Figure 1). The maintenance time required to replace failed components is 0.6. We consider a single repairperson ($K = 1$) with a fixed and variable costs set at $c^f = 3$ and $c^v = 0.2$, respectively. The status x_{ij} and the age a_{ij} of component C_{ij} ($i = 1, \ldots, 3;\ j = 1, \ldots, N_i$) at the end of the current mission are given in Table 1. The two parameters α and γ in the acquisition costs of Equation (19) and (20) are set to $\alpha = 2$ and $\gamma = 0.2$, while the cost of a new component is set to $O^0 = 2$. All remanufactured components have age $\tau = 2$. The next mission duration is $u = 15$ and the break duration is fixed to $\mathcal{D}_0 = 2$.

Let us assume the maintenance budget is set to $\mathcal{C}_0 = 10$. To show the impact on the SM decisions of using the reconditioned spare parts, we compare the two SM plans obtained with and without resorting to such spare parts. To model the case when reconditioned parts are not used, one has to set the mixture ratio to $p = 0$. The optimal SM plan obtained suggests to replace component E_{12} resulting in a maximal system reliability of 62.05% with a total cost of 5.12. Now, to deal with the case where reconditioned parts are used, let the mixture ratio be $p = 0.2$. The optimal SM plan allows to perform more replacements if compared to the case where only new spare parts are used. Indeed, when using reconditioned parts, both components E_{12} and E_{34} are replaced with a total maintenance cost of 9.98 which is nearly equal to the total allotted maintenance budget. The resulting maximal achievable reliability is of 72.50% which is indeed larger than that obtained in the first case. From this result, and given the data used, one may conclude that resorting to the remanufacturing options can be beneficial in maintenance decisions, in general, and in SM problems, in particular.

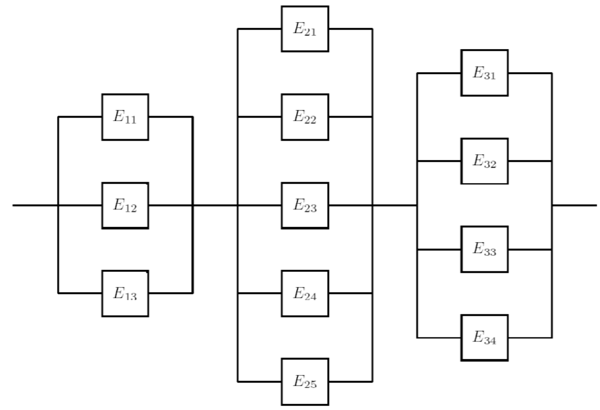

Fig. 1. Reliability block diagram of the series-parallel system

Table 1. Components status and age: case of Experiment #1.

Components E_{ij}	Status variable x_{ij}	Age a_{ij}
E_{11}	1	15
E_{12}	0	10
E_{13}	1	08
E_{21}	0	15
E_{22}	0	15
E_{23}	1	10
E_{24}	1	8
E_{25}	0	5
E_{31}	1	8
E_{32}	1	15
E_{33}	0	15
E_{34}	0	10

4.2 Experiment #2 :

This experiment investigates the same system used in the first experiment except that its components are now considered as non-identical. Table (2) lists the data for all system components. Because, 4 repairpersons of different skills are available, Table (2) gives the repair times required to replace a component by a given repairperson. Repairpersons 2 and 3 are considered to have standard skills and have the same repair times. Repairperson 1 is more skilled thanks to his short repair times, his is therefore more expensive to hire. Repairperson 4 has low qualification (i.e., a trainee). Thus, his repair times are longer than the standard ones but his is cheaper to hire. Table (3) gives the fixed and variable costs of each of the repairpersons considered. For each component E_{ij}, the mixture proportion p_{ij}, the initial age τ_{ij} and the parameters (O^0_{ij}, α_{ij} and γ_{ij}) of its corresponding acquisition cost are shown in Table (4).

Table 2. Components data: Experiment #2.

E_{ij}	β_{ij}	η_{ij}	x_{ij}	a_{ij}	Repair time t_{ijk}			
					$k=1$	2	3	4
E_{11}	1.5	30	1	15	0.6	0.7	0.7	0.8
E_{12}	1.5	30	0	10	0.3	0.4	0.4	0.5
E_{13}	3	40	1	8	0.5	0.6	0.6	0.7
E_{21}	3	40	0	15	0.2	0.3	0.3	0.4
E_{22}	1.5	30	0	15	0.1	0.2	0.2	0.3
E_{23}	1.5	35	1	10	0.5	0.6	0.6	0.7
E_{24}	3	45	1	8	0.6	0.7	0.7	0.8
E_{25}	2	20	0	5	0.3	0.4	0.4	0.5
E_{31}	1.5	30	1	8	0.4	0.5	0.5	0.6
E_{32}	3	55	1	15	0.2	0.3	0.3	0.4
E_{33}	3	25	0	15	0.6	0.7	0.7	0.8
E_{34}	1.5	35	0	10	0.7	0.4	0.4	0.5

Table 3. Fixed and variable costs of repairpersons: case of Experiment #2.

Repaiperson k	1	2	3	4
Fixed cost c^f_k	5	4	4	3
Variable cost c^v_k	0.8	0.4	0.4	0.2

Table 4. Components mixture, age and acquisition cost parameters: case of Experiment #2.

E_{ij}	O^0_{ij}	τ_{ij}	α_{ij}	γ_{ij}	p_{ij}
E_{11}	2	2	2.2	0.2	0.15
E_{12}	3	1	3.3	0.3	0.15
E_{13}	1	2	1.1	0.1	0.15
E_{21}	4	3	1.4	0.4	0.15
E_{22}	2	1	2.2	0.2	0.15
E_{23}	1	2	1.1	0.1	0.15
E_{24}	3	2	3.3	0.3	0.15
E_{25}	4	3	2.4	0.4	0.15
E_{31}	3	1	3.3	0.3	0.15
E_{32}	5	1	1.5	0.5	0.15
E_{33}	2	1	2.2	0.2	0.15
E_{34}	2	2	2.2	0.2	0.15

In Experiment #2, the next mission has duration $u = 25$ and the break length is set to $\mathcal{D}_0 = 1.5$. The overall results are drawn while varying the predetermined maintenance budget $\mathcal{C}_0$ to reflect the options available to the decision maker.

First let us assume that the maintenance budget is set to $\mathcal{C}_0 = 3$. In this case, if we assume that spare parts used are new, i.e. repairpersons use only new components to perform replacements, the optimization model finds no optimal SM plan and the reliability of the system is then left as is (i.e. 46.30%) without any possible improvement. However, if the repairpersons resort to reconditioned components, the optimal SM plan is provided and suggests to assign the trainee (repairperson 4) to the replacement of component E_{34} by a component selected from the corresponding mixed pool of new and reconditioned spare parts. The resulting maximum achievable reliability is evaluated to 52.37%. Once again, the example comforts the conclusion of the first experiment and demonstrates that resorting to remanufacturing products in maintenance activities can constitute a good deal to the system owner, both at financial and sustainable point of views, especially when the maintenance budget is low. Indeed, if the spare parts are all reconditioned components (this case can be obtained by setting $p_{ij} = 1$ for all $i = 1, \ldots, N$, and $j = 1, \ldots, N_i$), the optimal SM plan allows to reach a maximum achievable reliability of 55.01% resulting in a reliability improvement of 2.64%. This improvement is obtained by replacing the component E_{34} which is indeed more reliable than component E_{34}.

For different values of the maintenance budget, the overall results obtained are reported in Tables (5) and (6). Results in Table (5) are drawn in the case where only new spare parts are used in the maintenance activities, while results in Tables (6) corresponds to the case where both new and reconditioned spare parts are used.

Table 5. Results of Experiment #2.: Only new spare parts.

$\mathcal{C}_0$	k^*	Repairpersons				$\mathcal{R}^*(\%)$	TMC*	Parts replaced
		1	2	3	4			
5	1				✓	55.36	4.1	E_{12}
6	1				✓	57.95	5.16	E_{21}, E_{34}
8	1				✓	62.69	6.2	E_{12},E_{34}
10	1				✓	69.29	8.26	E_{12}, E_{22} E_{34}
20	2			✓	✓	77.87	18.62	3: E_{12}, E_{34} 4: E_{21}, E_{22}
30	2	✓			✓	78.23	27.20	1: E_{21}, E_{22} E_{33} 3: E_{12}, E_{25} E_{34}

Table 6. Results of Experiment #2.: mix of new and reconditioned spare parts.

$\mathcal{C}_0$	k^*	Repairpersons				$\mathcal{R}^*(\%)$	TMC*	Parts replaced
		1	2	3	4			
5	1				✓	57.86	4.97	E_{22}, E_{34}
6	1				✓	62.56	5.84	E_{12}, E_{34}
8	1				✓	69.12	7.82	E_{12},E_{22} E_{34}
10	1				✓	69.12	7.82	E_{12}, E_{22} E_{34}
20	2			✓	✓	77.61	17.87	3: E_{12}, E_{33} 4: E_{21}, E_{22} E_{34}
30	2	✓		✓	✓	77.96	26.98	1: E_{33} 3: E_{12}, E_{22} E_{34} 4: E_{25}

The results reported in the above two tables show that resorting to reconditioned components may offer a financial opportunity only when the maintenance budget does not exceed the threshold value of 8. Indeed, when the maintenance budget is, for example, set to 6, the optimal SM plan using only new spare parts allows a maximum achievable reliability of 57.95%, while when the alternative of mixed new and reconditioned components is used, the optimal SM plan allows to reach a maximum achievable reliability of 62.56% resulting in a difference of 4.61% in reliability improvement.

Similar conclusions made in (Diallo et al., 2018b; Khatab et al., 2018a; Diallo et al., 2017) also hold in the present work. First, a clear trend can be observed from the results of Tables (5) and (6). Both the number of repairpersons that can be hired, and the number of components that can be replaced increase as the maintenance budget increases. Thus, the maximum achievable reliability increases with the budget.

Second, one can also observe that depending on the maintenance budget, the proposed model will always give priority to the skilled repair-person as they are capable to repair more components during the fixed break duration. Additional repairpersons are added as permitted by the budget to complement the work of the more skilled repairperson.

5. CONCLUSION

In this paper, we proposed a novel variant of the joint selective selective maintenance and repairpersons assignment problem in a multicomponent system when spare parts used are composed of new and reconditioned ones. Current models in the literature usually assume that only new components are available to perform replacements activities. A novel integrated mixed integer nonlinear programming model was developed and optimally solved. Numerical experiments demonstrate the validity of the proposed approach and clearly show the economic and sustainable benefits of resorting to remanufacturing processes in spare parts management when dealing with maintenance decisions, in general, and particularly in the the joint selective maintenance and multiple repairpersons assignment problem.

Future extensions that the authors are working on include a generalization to more general reliability structures under imperfect maintenance. Most models study the selective maintenance problem with reliability as the performance indicator. Considering system availability would also be an important issue to investigate.

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