Selective maintenance model for mission-oriented systems considering heterogeneous missions and budget constraints

L. Ribeiro* and C. Cavalcante**

* *Departamento de Eng. de Produção, Universidade Federal de Pernambuco, Brazil- lucasfredericoeing@hotmail.com*

** *Departamento de Eng. de Produção, Universidade Federal de Pernambuco, Brazil- cristiano@ufpe.br*

Abstract. Maintenance planning is a challenge for organizations. This is particularly evident for mission-oriented systems, since maintenance must to be performed within stoppages. In this sense, models indicate a set of actions to be performed in each stoppage by considering the operational dynamics of a system. We propose a model that address this issue in an innovative way, by considering a system working under different operational conditions – i.e. heterogeneous missions – and subject to a budget constraint. We used genetic algorithm (GA) in order to solve this problem have. Finally a case study illustrates the model applicability.

1. Introduction

System's performance is dependent on effective assistance. This is a challenge for mission-oriented systems since interventions have to be done during stoppages between missions (LIU, XIE and KUO, 2016). Maintenance models, however, usually neglects the system's operational dynamics as well as constraints on the maintenance resources (DO and BARROS, 2017; RICE, CASSADY and NACHLAS, 1998). These aspects, however, limit the set of actions that may be executed (RICE, CASSADY and NACHLAS, 1998; MAILLART et al., 2009).Thus, one should elect, the actions that best improve system's performance, not violating such aspects (KHATAB and AGHEZZAF, 2016).

In this sense, one contribution of this paper is adopting a limited maintenance budget. Moreover, we deal with maintenance costs in an innovative way considering a penalty fee related to system failures during missions. We also consider a system working under different operational conditions - heterogeneous missions.

Further, we explore service-oriented systems. In this context, stoppages implies in loss of service to customers; so its duration must be minimized. Despite this objective is uncommon in literature (CASSADY, POHL and MURDOCK, 2001), it may increase system's efficiency.

2. Problem formulation

First, it is necessary to point that a great part of this section is derived from Ribeiro, Cavalcante and Rodriguez (2017).

Consider a system S composed by n subsystems S_i ($i=1, ...,n$) connected in series, each consisting of N_i components C_{ij} ($j=1,...,N_i$) arranged in parallel. This system must perform a sequence of M missions, with known duration $U(m)$ such that between two consecutive missions must to be a stoppage, also with known duration $D(m,l)$ ($l=m+1$).

Components may be in operational or failed state. Failure occurs within a mission and is related to component's virtual life (NAKAGAWA, 1998). Setting $A_{ij}(m)$ and $B_{ij}(m)$ the virtual ages of component C_{ij}, respectively, at the beginning and at the end of the m-th mission, the reliability $R_{ij}(m)$ of component C_{ij} is determined by the equation:

$$R_{ij}(m) = \mathrm{o(m)} \exp\left(-\int_{A_{ij}(m)}^{B_{ij}(m)} h_{ij}(t)dt\right). \tag{1}$$

where $h_{ij}(t)$ corresponds to the risk function of component C_{ij}. The parameter o(m), in turn, models heterogeneity through the relation between the designed and the expected system's operation condition, i.e. it assumes values smaller than one if the expected operation condition is harder than the designed one. This parameter generalizes the problem stated in Ribeiro, Cavalcante and Rodriguez (2017) and modifies the subsystem S_i and system S reliabilities, respectively denoted by $R_i(m)$ and $R(m)$, impacting in following equations.

$$R_i(m) = 1 - \prod_{j=1}^{N_i}\left(1 - R_{ij}(m)\right). \tag{2}$$

$$R(m) = \prod_{i=1}^{n} R_i(m). \tag{3}$$

Such system is minimally repaired, if a component fails during a mission. This intervention restores the operational satete of the component, has negligible duration and a cost cmr_{ij} inherent to component C_{ij}. Within a stoppage, components can be preventively maintained, either perfectly or imperfectly. These effects are modeled by an age reduction coefficient $\alpha(p) \in [0,1[$, inherent to action p, that updates components' virtual ages.

The set of the P preventive actions that can be performed on system's components is displayed in vector $VPM = [a_1,...,a_p, ..a_P]$. Every action a_p ($p = 1,...,P$) it attached to age reduction coefficient $\alpha(p)$, a cost $cpm(a_p)$ and a duration $dpm(a_p)$, as well as a set of components on which the action can be performed $Comp(a_p)$.

Additionally to system's reliability, it is important to highlight others indicators. Thus, total maintenance cost C_{total} consists in the sum of three parcels: the minimal repair cost CMR; the preventive maintenance cost CPM; and a penalty cost $CPAR$, related to the system failure probability during a mission.

$$CMR = \sum_{m=1}^{M} \sum_{i=1}^{n} \sum_{j=1}^{N_i} cmr_{ij} \int_{A_{ij}(m)}^{B_{ij}(m)} h_{ij}(x)dx. \tag{4}$$

$$CPM = \sum_{i=1}^{n} \sum_{j=1}^{N_i} \sum_{m=1}^{M-1} \sum_{p=1}^{P} \left(cpm(a_p).a_p(C_{ij},m) \right). \tag{5}$$

where $a_p(C_{ij},m)$ is a binary decision variable which assumes non-zero value if the action a_P is performed on component C_{ij} at the m-th stoppage.

$$CPAR = \sum_{m=1}^{M} \left(1 - \prod_{j=1}^{n} (1 - \prod_{j=1}^{N_i} \left(1 - R_{ij}(m) \right)) \right) cpar. \tag{6}$$

where $cpar$ is a fee, related to system failure probability.

Total maintenance duration DPM is given by the expression:

$$DPM = \sum_{m=1}^{M-1} \sum_{p=1}^{P} \sum_{i=1}^{n} \sum_{j=1}^{N_i} dpm(a_p).a_p(C_{ij},m). \tag{7}$$

In the case of service-oriented systems, performance is indirectly described via stoppage duration. Still, system's reliability $R(m)$ should not be smaller than technical recommendations $R(l)$ nor the maintenance budget BGT should be trespassed. Thus, determine a subset of VPM that minimizes the total maintenance duration (8), enables the achievement of the desired reliability levels (9) and honors the budget constraint (10).

$$P1: Minimize\ DPM \tag{8}$$

Subject to:

$$R(m+1) \geq R(l) \tag{9}$$

$$C_{total} \leq BGT \tag{10}$$

$$\sum_{v=1}^{P} a_v(C_{ij},m) \leq 1 \tag{11}$$

$$a_v(C_{ij},m) \in \{0,1\} \tag{12}$$

$$i = 1, \dots, n; j = 1, \dots, N_i; p = 1, \dots, P; m = 1, \dots, M-1; l = m+1 \tag{13}$$

Constraint (11) stands that no more than one action can be performed on a component within a stoppage. Further, we have chosen genetic algorithm as solution approach. For details, also refer to Ribeiro, Cavalcante and Rodriguez (2017).

3.Illustrative case

In order to demonstrate models' applicability, we took advantage of the coal transportation system described in (LIU, XIE and KUO, 2016). The system consists of five subsystems compound, respectively, by 3, 2, 3, 2 and 4 components. Components' lives follow Weibull(β,η) distributions which parameters and minimum repair costs cmr_{ij} are displayed in Table 1.

Table 1. System components' parameters.

C_{ij}	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}	C_{41}	C_{42}	C_{51}	C_{52}	C_{53}	C_{54}
β_{ij}	1.5	2.4	1.6	2.6	1.8	2.4	2.5	2	1.2	1.4	2.8	1.5	2.4	2.2
η_{ij}	37.5	57	42	60	42	51	39	42	39	52.5	60	52.5	45	67.5
cmr_{ij}	3	4	3	5	2	3	6	5	3	6	7	4	6	3

This system is oriented to perform a sequence of 15 missions whose durations, operation conditions and reliability aspiration levels are shown in Table 2.

Table 2. Durations, operation conditions and reliability levels for system.

U(m)	11	12	11	13	11	13	10	10	13	11	11	13	13	10	13
o(m)	1	1.05	1	1.1	1	1.1	0.95	0.95	1.1	1	0.9	1	1	0.85	1
R(m+1)	0.8	0.8	0.8	0.8	0.8	0.75	0.75	0.75	0.75	0.7	0.7	0.7	0.7	0.7	-

The set of the preventive actions that can be performed on system's components and their features are presented in Table 3.

Table 3. Parameters of the *P* preventive actions that can be performed in the system.

P	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Comp(p)	C_{11}	C_{11}	C_{12}	C_{12}	C_{13}	C_{13}	C_{21}	C_{21}	C_{22}	C_{22}	C_{31}	C_{31}	C_{32}	C_{32}
α(p)	0.6	0	0.46	0	0.52	0	0.68	0	0.41	0	0.36	0	0.55	0
cpm(p)	6.9	14.1	8.2	18	6.9	14.1	9.7	15.5	9	14.2	8.1	16	8.3	16.25
dpm(p)	0.25	0.55	0.35	0.65	0.25	0.37	0.3	0.58	0.37	0.75	0.25	0.75	0.87	1.5

P	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Comp(p)	C_{33}	C_{33}	C_{41}	C_{41}	C_{42}	C_{42}	C_{51}	C_{51}	C_{52}	C_{52}	C_{53}	C_{53}	C_{54}	C_{54}
α(p)	0.62	0	0.61	0	0.49	0	0.6	0	0.43	0	0.25	0	0.43	0
cpm(p)	7.3	16.5	8.3	12.5	9.2	15.4	6	13.9	7.9	12	6.7	14	7.8	16.5
dpm(p)	0.75	1.65	0.25	0.42	0.38	0.8	0.25	1	0.45	0.95	0.45	1.15	0.52	1.55

The fee *cpar* resulting from the system's failure probability during a mission was settled in 100 currencies and the maintenance budget in 1900 currencies. As previously announced, we choose Genetic Algorithm as solution technic. Table 4 displays the maintenance plan obtained for the formulation in comparison to the homogeneous conditions case (P2).

Table 4. Maintenance plans obtained for cases P1 and P2.

Case/ Stoppage	P1	P2
1	3,10,11,18,20,22,27	5,9,15,17,21,25
2	1,8,10,14,16,20,22	7,10,12,13,18,20,22,23,26,27
3	1,4,6,8,10,14,16,18,22,23,27	2,5,9,11,18
4	3,5,7,10,11,21,26,27	2,3,6,7,12,17,19,21,24,26,28
5	1,4,13,19,23,26	1,10,11,13,15,19,22,24
6	2,5,7,10,14,15,18,19,21,23,28	6,7,11,19,25,28
7	2,3,5,7,9,12,20,24	1,4,6,8,15,20,21,24,25,28
8	1,6,8,10,11,13,21,25	2,10,11,16,18,19,21,23,26,28
9	3,6,8,10,13,20,22,25	3,7,11,18,22,23
10	1,4,5,8,9,11,22	1,5,7,9,23
11	4,5,7,10,15,17,19,21,25	1,5,8,10,17,21,23,26,28
12	1,5,7,9,11,13,16,17,20,25	4,6,7,9,14,19,22,23,25,27
13	2,5,9,14,16,18,21,23,26,27	1,3,5,15,18,26,28
14	2,6,7,14,17,26,27	2,7,11,13,16,18,19,22,23,25

At a first glance, there is no pattern between plans, however the total interventions number is similar in cases P1 (117) and P2 (113). The amount of perfect actions are also very similar between plans (55 for P1 and 48 for P2). This little difference may be explained by the necessity of more effective interventions in the missions in which the system is subject to severe operational conditions.

The more effective the intervention (replacement) the more expensive it is. Despite replacements are more frequent in case P1, its total maintenance cost is similar to the P2 cost (table 5). This is a consequence of a balance between severe and soft operational conditions for P1 (table 2). Thus it is necessary a skew to consider the effects of heterogeneity in models.

Table 5. Expected performance values for cases P1 and P2.

Case / Indicator	P1	P2
Maintenance Cost	1590.38	1586.36
Maintenance Duration	71.31	67.42
Average Reliability	0.91	0.90

4. Conclusions

Although a proper maintenance policy is essential to system's performance, organizations adopt models that despise its dynamics of operation. Selective maintenance models deals with such simplification. This paper contributes to that category of models, in part, by considering the system working under different operational conditions - heterogeneous missions. This assumption, however, should reflect the system's operating conditions, since adopting it brings unnecessary complexity to model in the case of homogeneous missions or balanced condition horizons.

Acknowledgement

The research of L. Ribeiro have been supported by Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco (FACEPE); and C. Cavalcante research is funded by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

References

Cassady CR, Pohl AE, Murdock WP (2001) Selective maintenance modeling for industrial systems. *Journal of Quality in Maintenance Engineering* 7(02), pp.104–117.

Do P, Barros A, (2017) Maintenance grouping models for multicomponent systems. In *Mathematics Applied to Engineering* (Ran and Davim, Eds), Academic Press, pp. 147 -170.

Khatab A, Aghezzaf EH (2016) Selective maintenance optimization when quality of imperfect maintenance actions are stochastic. *Reliability Engineering and System Safety* 150, pp. 182 – 189.

Liu B, Xie M, Xu Z, Kuo W (2016) An imperfect maintenance policy for mission-oriented systems subject to degradation and external shocks. *Computers and Industrial Engineering* 102, pp. 21–32.

Nakagawa T (1998) Sequential imperfect preventive maintenance policies. *IEEE Transactions on Reliability* 37(3), pp.295-308.

Ribeiro L, Cavalcante C, Rodriguez, T (2017) Selective maintenance for multi mission oriented systems. In: *Risk, Reliability and Safety: Innovating Theory and Practice* (Walls, Revie & Bedford, Eds) pp. 1179-1184.

Rice WF, Cassady CR, Nachlas JA (1998) Optimal maintenance plans under limited maintenance time. In: *Proceedings of the Seventh Industrial Engineering Research Conference,* s.d.