Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Volume 13, Issue 01 January 2024

Maintenance Strategy Optimization in Mineral Processing Multi-Component Systems: A Case Study of Slurry Filtration Plant

D. Kabeya Nahum, Allen Tam, Gopi Chattopadhyay, Leonard K. Mukeba
Institute of Innovation, Science and Sustainability, Federation University Australia
Institut Supérieur de Techniques Appliquées, ESU-ISTA Kinshasa, DR Congo

***Abstract*— Development of Maintenance Strategy in Mineral Processing Multi-Component Systems is a complex process, and its optimization helps in reducing costs and risks and enhancing performance of assets. A slurry filtration plant is considered as case study. Individual component's failure rate and MTBF are determined to facilitate the development of a cost-effective maintenance plan. A cost function for predictive and preventive maintenance are proposed for the overall system, considering multi-component inter-dependence. The reliability of critical components is analyzed with Weibull model. Single-component age-specific maintenance-based algorithm is used to determine the preventive replacement times of all components reducing the total cost by reducing the total downtime of the system. This paper presents a general approach for the optimization of a mineral processing multi-component system in a context of economic dependence based on maintenance execution strategy. Illustrative example analyses MTBF for decisions on when the preventive maintenance can take place based on interactive data acquisition from SCADA on asset performance.**

***Keywords*— Modelling, optimization, multi-component system; economic dependence; maintenance strategy**

I. INTRODUCTION

Engineering systems are generally subject to deterioration with age and/or use. For some systems (power plant, transport, etc.), the concern for safety makes it extremely important to make every effort to avoid failure in service to reduce the loss of production and/or profit. Maintenance of systems improves reliability and enhances safety. An optimal maintenance strategy is developed based on required availability and equipment integrity at the lowest possible costs (Wang H. 2002). A well-developed single-component maintenance plan facilitates the multi-component systems' reliability management. In a multi-component asset, inter-dependence between components can be due to economic dependence, structural dependence, and stochastic dependence and/or failure interactions (Thomas, 1986), (Dekker, R., et al., 1997). Economic dependence means the costs can be reduced when multiple components are maintained in a coordinated manner for economies of scheduling scale (R. Laggoune, 2007). If several components are structurally linked, structural dependence applies for maintaining one component along with others linked components. Stochastic dependence occurs when the condition of one component influences the lifespan distribution of other components (Dekker, R., et al., 1997) or when external forces cause failures of more than one component at the same time (R. Dekker and R. Wildeman, 1997). The literature research shows majority of researchers work with systems by simplifying the problem with assumptions to keep mathematical modelling less complicated. Markov's analysis, based on the state space grows exponentially with the number of system components (R. Laggoune, 2007). Hence, heuristic models are developed for systems with several components. These models address unique cases (structure, constant failure rate, ...). This paper presents a general method for the optimization of a multi-component system in series by developing an optimal maintenance plan as shown in figure 2. Equations (12) and (13) provide preventive and corrective maintenance cost. The preventive replacement intervals for each component are calculated to reduce the overall cost whilst taking the system's total downtime into account, as expressed in equation (14).

II. MODELLING OF THE MULTI-COMPONENT SYSTEM

Let the system consist of n components subjected to k stresses. The given strengths of the components $X_1, X_2, \dots, X_n, X_{(n+1)}$ with parameters l_i, $i = 1, \dots, n$. Each component is subjected to a given n stresses $Y_1, Y_2, \dots, Y_k, Y_{(k+1)}$ with component's parameters μ_i, $i = 1, \dots, n$. Stresses and strengths are assumed to be independent and are given as $X, Y \in \boldsymbol{E}$. In this application strengths and stresses refer to component's design-performance and operation solicitations causing failure respectively. The reliability of both systems, parallel and series arrangements of the components can be determined using the below theories.

A. Reliability of the parallel systems

For parallel multi-components, the reliability of the system is given by:

$$R_1 = P\left[max\left(X_1, X_2, \dots, X_n, X_{(n+1)}\right) > max\left(Y_1, Y_2, \dots, Y_k, Y_{(k+1)}\right)\right] = P[Z > H] = \int_0^{\infty} \bar{F}_z(h) dF_H(h) \quad (1)$$

where $Z = max(X_1, X_2, \dots, X_n, X_{(n+1)})$, $H = \max\,(Y_1, Y_2, \dots, Y_k, Y_{(k+1)})$ and P the probability function. The expression of parallel system reliability in equation (1) takes into consideration the sub-component stresses and strengths where strengths remain higher over the system life. The survival function $\bar{F}$ under strength condition given in equation (2) is defined for $h \in [0, \infty]$.

$$\bar{F}_z(z) = P[Z > z] = \sum_{i,l=1}^{n} (-1)^{i+1} \sum_{1 \le i_1 < \dots < i_l \le n} P(X_{i_1} > z, X_{i_2} > z, \dots, X_{i_l} > z) \quad (2)$$

$$\bar{F}_z(z) = \sum_{s=1}^{n} (-1)^{s+1} \sum_{1 \le j_1 < \dots < j_s \le n} \exp\left(-\left(l_0 + l_{j_1} + \dots + l_{j_s}\right)z\right) \quad (3)$$

Survival functions given in equations (2) and (3) apply in the determination of the multi-component system's efficiency under cumulative stress distribution.

Considering H, the cumulative distribution $Y_1, Y_2, \dots, Y_k, Y_{(k+1)}$ F of H given in equation (4) is expressed in terms of system's strengths over the operation life:

$$F_H(h) = 1 - \sum_{s=1}^{k} (-1)^{s+1} \sum_{1 \le j_1 < \dots < j_s \le k} \exp\left(-\left(\mu_0 + \mu_{j_1} + \dots + \mu_{j_s}\right)h\right) \quad (4)$$

Substituting with (3) and (4) into (1), the reliability of a multi-component system can be expressed with consideration stresses and strengths from commissioning to operation in its entirety as given in equation (5).

$$R_1 = \sum_{s=1}^{n} (-1)^{s+1} \sum_{1 \le j_1 < \dots < j_s \le k} \left(\mu_0 + \mu_{j_1} + \dots + \mu_{j_s}\right) \left\{ \sum_{l=1}^{n} (-1)^{l+1} \times \sum_{1 \le j_1 < \dots < j_s \le k} \left(l_0 + l_{j_1} + \dots + l_{j_s} + \mu_0 + \mu_{j_1} + \dots + \mu_{j_s}\right)^{-1} \right\} \quad (5)$$

With μ_0 design-parameter independent of component's run time and l_o the stresses parameters at an initial state, i.e., commissioning phase.

B. Reliability of the series systems

For series multi-components, the reliability of the system is:

$$R_2 = P(\min(X_1, \dots, X_k) > H) = P(M > H) = \int_0^{\infty} \bar{F}_M(h) dF_H(h) \quad (6)$$

where $M = min(X_1, \dots, X_n)$ and exponentially distributed with l. The survival function $\bar{F}$ of M is expressed in equation (7).

$$\bar{F}_M(h) = \exp\,(-lh) \quad (7)$$

This equation is applied to determine component's life under conditions. From (7) and (4) in (6) the reliability of series system can be written as

$$R_2 = \sum_{s=1}^{n} (-1)^{s+1} \sum_{1 \le i_1 < \dots < i_l \le n} \frac{(\mu_0 + \mu_{j_1} + \dots + \mu_{j_S})}{(l + \mu_0 + \mu_{j_1} + \dots + \mu_{j_S})} \quad (8)$$

With $\sum_{1 \le i_1 < \dots < i_l \le n} \frac{(\mu_0 + \mu_{j_1} + \dots + \mu_{j_S})}{(l + \mu_0 + \mu_{j_1} + \dots + \mu_{j_S})}$ the system strength ratio considering sub-component's life cycle under strength conditions. If the variable time is considered, the reliability of such a system at a given time t can be expressed in a contracted form as:

$$R_{sys}(t) = 1 - F_{sys}(t) = \prod_{i=1}^{n} R_i(t) \quad (9)$$

With $R_{sys}(t)$ the reliability of the system, $F_{sys}(t)$ the probability function of system failure and $R_i(t)$ the reliability of component i.

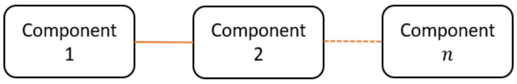


Figure 1: Serial system with components

The below figure illustrates a preventive maintenance plan for a serial system with n components.

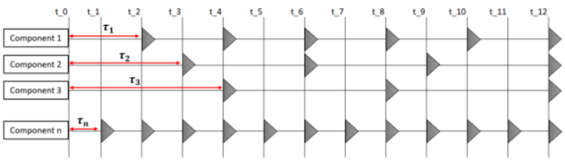


Figure 2: Preventive Maintenance strategy

The times t_1, t_2, t_3, …, t_n are calculated between preventive replacements of components 1, 2, 3, ...,n (Laggoune, R. et al. 2009). The decision when to shutdown such a system to pre-emptively replace other components, is based on the decrease in reliability and the increase of risk of failure incurred before the next scheduled time. During a corrective replacement of an i component, the opportunity is seized to anticipate the replacement of other j components. The total maintenance cost per unit of time is obtained by using (12) and (13) into equation (11):

$$C_T(t) = \frac{\left(C_0^c + C_i^c + \sum_{j=1}^{n_h} C_j^p\right) F_{sys}(t) + \left(C_0^p + \sum_{r=1}^{n_p} C_r^p\right) R_{sys}(t)}{\int_0^t R_{sys}(u)du} \qquad (10)$$

This equation is the total maintenance cost of the system per unit of time before streamlining the repair time. This mathematical approach does not consider strengths and stresses under operation conditions but instead the failure time. i indicates the component that fails first: $T_i = \min(T_j)$ (j = 1, 2, …). The opportunistic policy proposes grouping replacements so as not to penalize the total availability of the system, this grouping is obtained by rearranging the times of replacement by: $t_i = k_i . t$ where i an integer; $t_i = \min(t_j)$; j = 1, 2, ..., n (Figure 2). The expression of the total cost then becomes:

$$C_T(\tau, k_1, k_2, \dots, k_n) =$$

$$\frac{\sum_{\alpha=1}^{k_{max}} \sum_{i=1}^{n} \left(\left(C_0^c + C_i^c + \sum_{j=1}^{n_h} C_j^p\right) F_{sys,i}(t_\alpha) + \left(C_0^p + \sum_{r=1}^{n_p} C_r^p\right) R_{sys}(t_\alpha) \right)}{\int_0^{k_{max}\tau} R_{sys}(u)du} \qquad (11)$$

where $F_{sys,i}$ is the probability of system failure due to component i. In comparison of equation (10), the expression given in equation (11) is the total maintenance cost of the system relative to component's stresses.

III. MAINTENANCE COST STRUCTURE OF MULTI-COMPONENT SYSTEM

The maintenance cost consists of the fixed part relating to the system and the variable part for each component. With C_0^c: fixed cost induced by a corrective maintenance operation, C_0^p: fixed cost induced by a preventive maintenance operation, C_i^c cost of the patch for component i and C_i^p cost of preventive care relating to component i. The cost of preventive replacement of n_p system components is given by:

$$C_{sys}^P = C_0^p + \sum_{i=1}^{n_p} C_i^p \qquad (12)$$

The cost of preventive replacement expressed in equation (12) is applied to determine individual component's cost. The cost of the system patch following the failure of component i, including the cost of the preventive replacement of the n_h components during the opportunity is:

$$C_{sys,i}^c = C_0^c + C_i^c + \sum_{j=1}^{n_p} C_j^p \qquad (13)$$

IV. MAINTENANCE STRATEGY OPTIMIZATION

The proposed model is based on the age-specific maintenance strategy for a single-component system and used in the algorithm process (Piresa C.R., 2019) to determine ages for each component's preventive maintenance. The total expected replacement cost rate is expressed in equation (14).

$$c(T) = \frac{C_p R(T) + [1 - R(T)] C_d}{\int_0^T R(t)dt} \qquad (14)$$

With $C_p R(T) + [1 - R(T)] C_d$ the expected preventive replacement cost per equipment cycle and $\int_0^T R(t)dt$ the expected length of a failure cycle, T the age of preventive replacement, C_p the cost of preventive replacement, C_d the cost of failure and $R(t) = 1 - F(t)$ the reliability function (Bassem S. et al., 2006), (Scarf P. A., Deara M., 1998). In this approach, the optimization consists of determining the t_i replacement times that would minimize the total cost rate. The resolution is obtained numerically by the Monte Carlo simulation according to the iterative algorithm shown in figure 3.

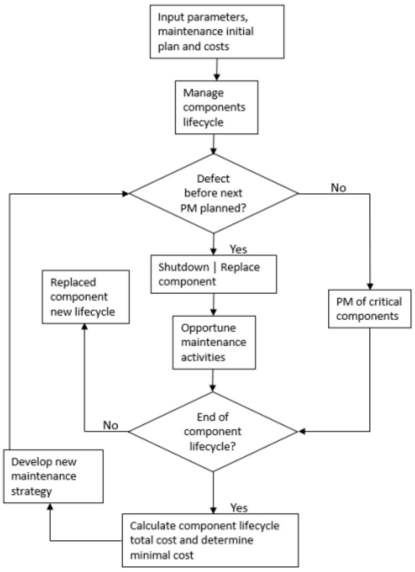


Figure 3: Maintenance optimization model

When component i fails at time t_i, the opportunity to replace component j as preventive maintenance is based on the analysis of its cost/profit balance according to the decision criteria: $C_j^p \left(R_j(t_i) - R_j((k+1)_\tau)\right) < \left(C_0^c + C_j^c\right) F_j((k+1)_\tau)$. This condition indicates the opportunity to inspect and/or replace component j. The opposite condition restricts the component to stay in place until next scheduled replacement.

V. INDUSTRIAL CASE STUDY

The application of the proposed filtration process is found in upstream concentrate mineral processing wet plant. Filtration plant is a multi-component system in which the technology mainly incorporates fluid and electric power to enable the separation of minerals in fine form from water through a porous polyethylene cloth used as filtering agent by pressing and blowing slurry feed in cake chamber. From metallurgy perspective, five filtration process steps can be considered as indicators to determine sub-components performance: (a) cake formation, (b) moisture reduction, (c) cake washing, (d) cake discharge, and (e) medium washing (B. Wills, et al., 2016). Based on the theory of Darcy and Poiseuille, the basic filtration equation can be written as (Dahlstrom, 2003): $n = \frac{1}{A}\frac{dV}{dt} = \frac{\Delta P}{\mu\left(\alpha w \frac{V}{A}\right)}$ where the element of slurry volume is function of run time and the variation of blowing pressure is taken from minimal to maximal pressure input. This mathematical expression is basically a process approach for filters sizing and is applicable for filtration plant reliability in design phase. In addition, the mechanical deterioration of sub-components can be deducted from pressure and slurry flow aspects. The filtration plant considered in this case study has recorded several downtime affecting daily production key performance indicators as shown in Table 1. An asset management system to capture all downtime and main causes was implemented to facilitate the development of an effective maintenance strategy. Since this filter is multi-components system, a 6-month observation were conducted for failure rate and MTBF determination. A process operation investigation was also conducted to examine the root-cause of those failures. However, the operational analysis results are Considered negligible in this approach. Relation (9) was applied to determine components failure and MTBF.

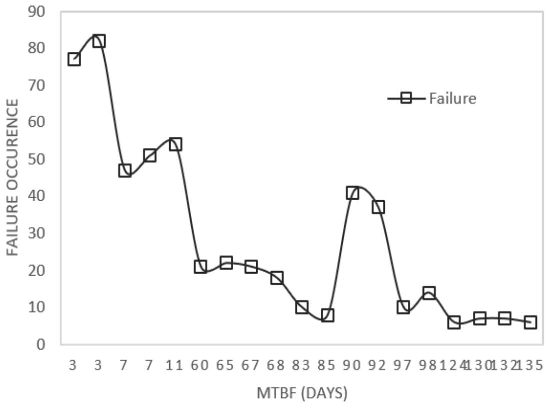


Fig. 4(a): Failure and MTBF for sub-components

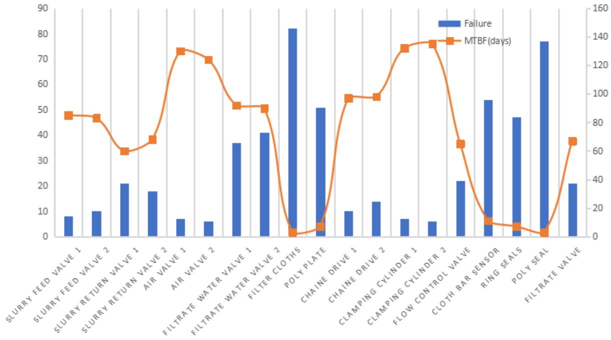


Fig. 4(b): Overall failure in a period of 135 days

Figure 4 illustrate the filtration plant performance and Weibull distribution over a period of 135 days before maintenance strategy optimization. The numerical data given in table 1 were analysed in MS Excel.

Table 1: Operational data

Equipment description	Failure	MTBF	C_correct. ($)	C_prev. ($)
Poly seal	77	3	98765	1870
Woven	82	3	104000	37300
Ring seals	47	7	89670	3750
Poly plate	51	7	107560	33450
Cloth bar sensor	54	11	57200	21800
Slurry return valve 2	18	68	106570	3200
Slurry return valve 1	21	60	65160	1200
Filtrate valve	21	67	88540	3490
Flow control valve	22	65	101345	2430
Slurry feed valve 1	8	85	97740	2700
Slurry feed valve 2	10	83	93450	2450
Chaine drive 1	10	97	83100	940
Chaine drive 2	14	98	79800	940
Filtrate water valve 1	37	92	115430	4560
Filtrate water valve 2	41	90	112345	5300
Air valve 2	6	124	78970	2750
Clamping cylinder 2	6	135	76500	865
Air valve 1	7	130	89045	4950
Clamping cylinder 1	7	132	74056	940
Total	**539**	**1357**	**1719246**	**134885**

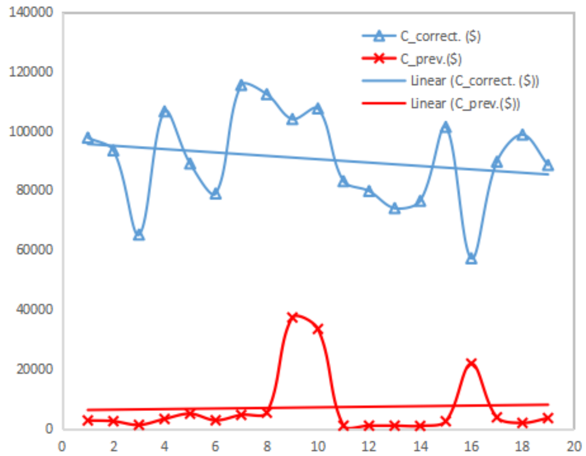
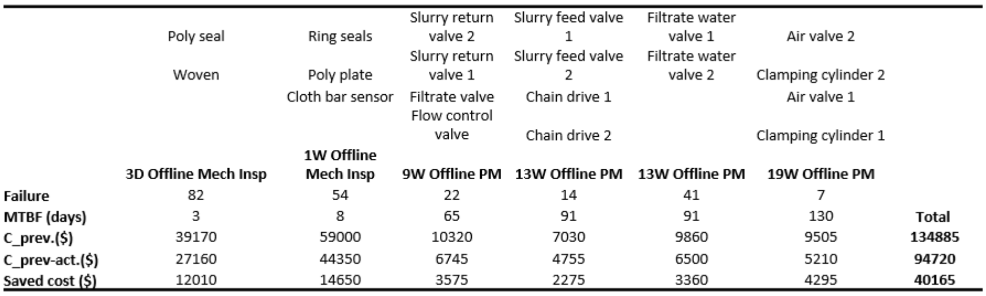


Figure 5: Actual preventive and correct maintenance costs over a period of 6 months

Table 2: Optimized maintenance plan



	3D Offline Mech Insp	1W Offline Mech Insp	9W Offline PM	13W Offline PM	13W Offline PM	19W Offline PM	
	Poly seal Woven	Ring seals Poly plate Cloth bar sensor	Slurry return valve 2 Slurry return valve 1 Filtrate valve Flow control valve	Slurry feed valve 1 Slurry feed valve 2 Chain drive 1 Chain drive 2	Filtrate water valve 1 Filtrate water valve 2	Air valve 2 Clamping cylinder 2 Air valve 1 Clamping cylinder 1	
Failure	82	54	22	14	41	7	
MTBF (days)	3	8	65	91	91	130	**Total**
C_prev.($)	39170	59000	10320	7030	9860	9505	**134885**
C_prev-act.($)	27160	44350	6745	4755	6500	5210	**94720**
Saved cost ($)	12010	14650	3575	2275	3360	4295	**40165**

The costs of corrective and preventive maintenance are calculated by relation (14) considering downtime, labour, parts, and other relative costs. Filter clothes and clothes bar sensor's preventive maintenance cost reveal to be higher than the corrective maintenance cost, whilst the poly plates both costs look slightly the same. The below figures show the established ratio between the two costs for every single component. The application of multi-component systems maintenance plan in figure 2 allows to develop the horizontal pressure filter serial components maintenance plan and schedule based on their failure and MTBF; Table 2.

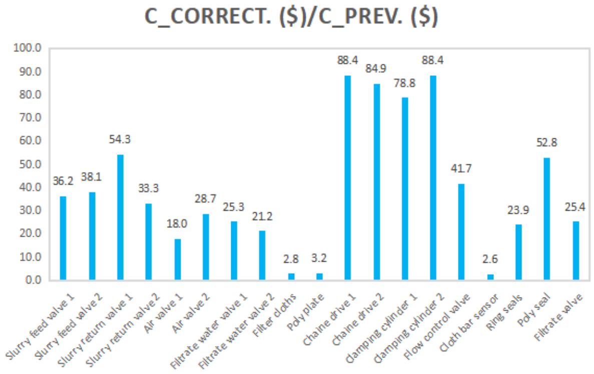


Figure 6: Corrective and preventive maintenance costs ratio

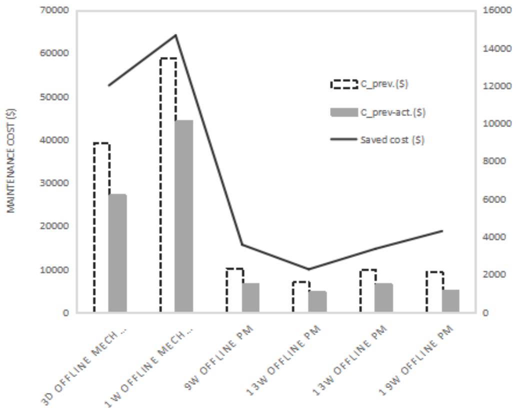


Figure 7: Saved cost on initial and actual preventive maintenance cost.

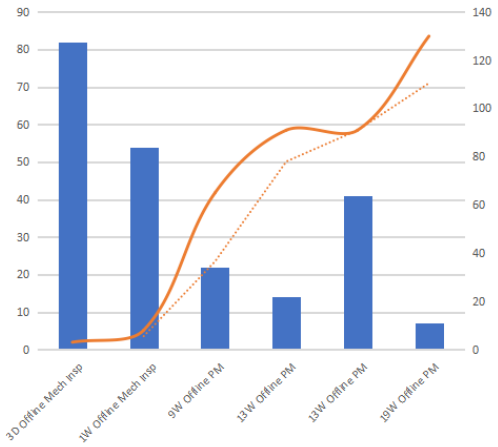


Figure 8: Components failure and MTBF trend per scheduling group.

The initial preventive maintenance cost and the actual cost are differentiated to determine the saving cost per scheduled component group and the overall business cost saved; Figure 8. Approximately 34% of preventive maintenance cost is saved per scheduled group-components with an overall cost saving of 29%.

VI. CONCLUSION

The application of reliability improvement in a slurry pressure filter proved to be cost effective for interdependent serial components. The Weibull graph of Figure 4(b) plotted based on real data illustrates the continuous probability distribution of approximately 52% possible premature downtime within the first 100 operation days. The implementation of the preventive maintenance plan for serial systems with n components shown in Table 2, demonstrates the effective strategy with a cost saving of $40165 in five months. The algorithm here presented can provide a framework to guide future maintenance optimization. In future root cause analysis of component failures can be combined for enhanced life-cycle management of systems.

REFERENCE

[1] Wang, H. (2002). A Survey of Maintenance Policies of Deteriorating Systems. European Journal of Operational Research, 139, 469-489. http://dx.doi.org/10.1016/S0377-2217(01)00197-7

[2] Dekker, R. et al. (1997). Review of Multi-Component Maintenance Models with Economic Dependence. Mathematical Methods of Operations Research (1997) 45:411-435

[3] Thomas, L. (1986). A survey of maintenance and replacement models for maintainability and reliability of multi-item systems. Reliability Engineering 16:297–309.

[4] Laggoune, R. and Aissani, D. (2007). Optimisation du plan de maintenance d'un système multi-composant. Laboratoire de Modélisation et d'Optimisation des Systèmes. Séminaire sur les Techniques et Management de la Maintenance, STMM 2007

[5] Barry A. Wills and James A. Finch, (2016). Will's mineral processing technology. An introduction to the practical aspects of ore treatment and mineral recovery. 8th Edition, Elsvier, Canada.

[6] Pires C.R. et. al., (2019). Mathematical model for maintenance planning of machine tools. 29th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2019), 2019, Limerick, Ireland.

[7] Bassem S. et al. (2006). A suitable inspection policy definition for system with two modes of degradation. IFAC Proceedings Volumes. Elsevier, Volume 39, Issue 13, Pages 789-794

[8] Scarf P. A., DEARA M. (1998). On the development and application of maintenance policies for a two-component system with failure dependence, IMA Journal of Management Mathematics, Volume 9, Issue 2, March 1998, Pages 91–107, https://doi.org/10.1093/imaman/9.2.91

[9] Khairy a. H., D. N. Prabhakar D.N. Complex System Maintenance Handbook - Reliability Engineering – Springer.

[10] Laggoune R. et al. (2009). Opportunistic policy for optimal preventive maintenance of a multi-component system in continuous operating units. Computers & Chemical Engineering, Volume 33, Issue 9.

[11] Alain Ratle et al. (2013). Availability Optimization for Series/ Parallel Systems using Evolutionary Algorithm, Inter-university Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT) and Department of Mechanical Engineering, 1065, Quebec, Canada.