Optimization of production strategies integrating occupational health and safety aspects: case of granite processing

Kevin Gildas DONGMO TAMBAH, Jean Pierre KENNE, Victor SONGMENE

Mechanical Engineering Department,
Production Technologies Integration Laboratory,
University of Quebec, École de Technologie Supérieure
1100 Notre Dame Street West, Montreal, Quebec Canada, H3C 1K3

Abstract. This article deals with the case of a granite processing line emitting silica particles that are harmful to the health of operators. This production chain is subject to deterioration over time that can lead to breakdowns. If nothing is done, these breakdowns will lead to equipment replacements. The manufacturing system consists of a machine, to which are grafted two protective equipments that reduce the particles emitted at the source. The silica particles emitted during production must respect the concentration limits provided by the regulations of the National Institute for Occupational Safety and Health (NIOSH). The goal of this work is to develop a production strategy to optimize the performance of the system while preserving the health of workers. The optimal conditions are obtained by applying the stochastic optimal control theory. The resulted optimality conditions are solved numerically to determine the control policies.

Keywords: Manufacturing system, optimization, silica particles, production planning, replacement policy, numerical methods

1. Introduction

According to the data from the International Labour Organization (ILO, 2019), 2.78 million of workers lose their live each year due to occupational accidents and diseases; 2.4 million of these deaths are attributable to occupational diseases such as silicosis. In addition, there are 378 million victims of work accidents and non-fatal occupational diseases each year. Fatal or not, these adverse events are responsible for several lost working days, which would represent on average four per cent of global Gross Domestic Product (Hämäläinen et al., 2017; Hämäläinen et al., 2014). The primary objective of companies is to make a profit, and this is achieved through the preservation of workers' health and a good optimization strategy. The manufacturing environment, particularly that of granite processing, is governed by laws such as the one limiting the concentration of silica particles that can be inhaled by the operator during production. The goal of this research is therefore to propose to manufacturing managers a dynamic model that allows them to make profits while respecting the exposure limit for silica particles set out by the legislation. In the past, several researchers such as Charlot et al. (2007) and Emami-Mehrgani et al. (2014) have studied the issue of production planning in a flexible manufacturing environment by integrating aspects such as the lockout, preventive maintenance or human errors. Very little or no work to date, has integrated the occupational disease prevention aspect into a dynamic model with a view to proposing a production planning strategy that allows the manufacturer to respect the limit of exposure. The manufacturing system studied in this article follows stochastic dynamics. This system is responsible for the production of silica particles which are considered as ultrafine in this paper. In order to protect the employees, we will have a lubrication unit and the local exhaust ventilation that will reduce at the source the particles that prevent employees from contracting silicosis. Therefore, this article will optimize production while integrating the occupational health and safety aspect. The paper is organized as follows: section 2 describes the manufacturing system and formulate the problem of this study. In section 3, we will provide a solution using a numerical approach. In section 4, we will analyze the results obtained, and finally make a conclusion in section 5.

2. Description and context of the study

The manufacturing system studied in this research consists of a production machine to which two units have been added, namely an exhaust ventilation room and a lubrication process (see figure 1) that will protect the employee by reducing the concentration of silica particles.

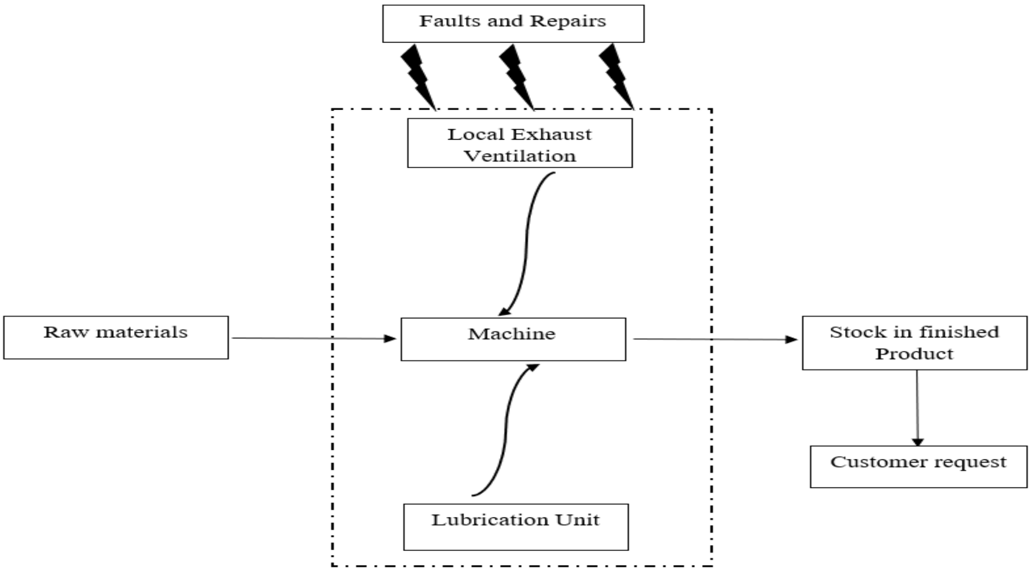


Figure 1. *structure of the production system*

At the entrance of the production line, we have the prefabricated granite blocks and at the exit, we have the modules of the finished products. During production, the manufacturing system deteriorates and becomes less and less efficient. This deterioration contributes to the increase in the concentration of silica particles. The more a machine is productive, the more the tools of this machine wear and contribute to the increase of particles emit (Songmene et al. 2008). Hence the importance of performing preventive maintenance on the system to keep it in good condition, which not only helps to reduce the concentration of emitted particles, but also to meet customer demand. Figure 3 shows the evolution of the concentration of particles in the working air as a function of the age of the manufacturing system. The probability of a failure increases with the age of the production unit. The more we produce, the more the failure probability of the machine increases (Nkeungoué, 2005). The failure rate depending on the age of the system is illustrated in Figure 2.

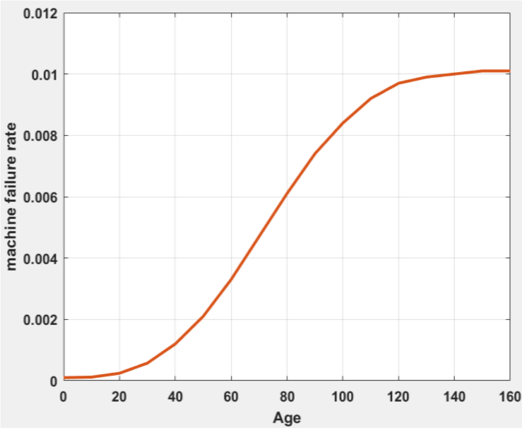


Figure 2. *machine failure rate*

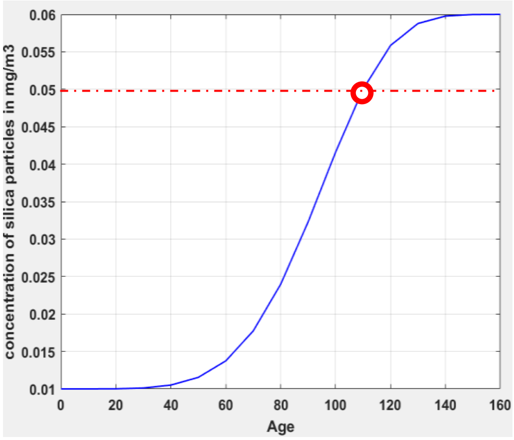


Figure 3. *silica particle dynamics*

The exposure limit for silica particles used in this work is that proposed by NIOSH, which is 0.05 mg/m^3

The dynamics of the system is described by a stochastic process defined by $\varepsilon(t)\epsilon B = \{1,2,3\}$ with $\varepsilon(t) = 1$ when the system is in production, $\varepsilon(t) = 2$ if at least one element of the system is not available and $\varepsilon(t) = 3$ if the system is under preventive maintenance. The transition from one mode to another is shown in figure 3. The decision variables are the production rate U_m, and the preventive maintenance dispatch rate W_{mp}. Let Q be the transition matrix given by :$Q = [q_{\alpha\beta}]$, with $q_{\alpha\beta}$ the transition from mode α to mode β, $q_{\alpha\beta} > 0, \forall\, \alpha \neq \beta$.

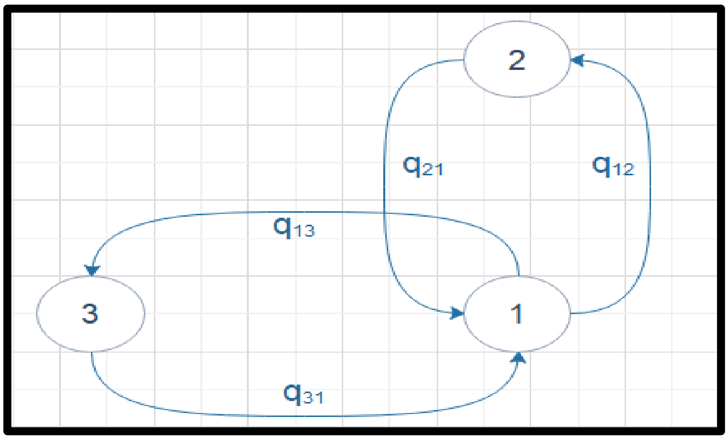


Figure 4. *states transition diagram of the system*

The set of admissible control variables is defined as follows:

$$\Gamma(\alpha) = \left\{(u_m, w_{mp}) \in R^2 / \; 0 \leq u_m \leq u_{max}, w_{mp}^{min} \leq w_{mp} \leq w_{mp}^{max} \right\} \qquad \textbf{(1)}$$

The dynamics of stock level and machine age are described below:

$$\text{Stock: } \frac{dx}{dt} = u(t) - d \qquad \text{Age: } \frac{da}{dt} = ku(t) \qquad \textbf{(2)}$$

In order to solve the problem, we have to make sure that we have the capacity to produce more than the demand, which is what we call the feasibility condition. Such a condition is expressed as follows:

$$\pi_1 \times u_1^{max} \geq d \qquad \textbf{(3)}$$

where π_1 is the average probability that the system is in mode 1 and d is the customer demand. The function of the instantaneous cost that allows to define the production cost is expressed in the following way:

$$g(x,a,\alpha) = c^{+}x^{+} + c^{-}x^{-} + c^{\alpha} \qquad \textbf{(4)}$$

where c^{α} is the cost incurred when the system is not in production especially in modes 2 and 3 and x defines the stock level.

$$x^{-} = \max(-x,0) \qquad and \qquad x^{+} = \max(0,x) \qquad \textbf{(5)}$$

The optimized total cost is given by:

$$J(x,a,\alpha) = E\left\{\int_0^{\infty} e^{-\rho t} g(x,a,\alpha)dt \,|\, x(t=0) = x,\ \ a(t=0) = a, \varepsilon(t=0) = \alpha\right\} \qquad \textbf{(6)}$$

where ρ is the discount rate.

The objective of the problem is to optimize this discounted cost, and this will be done through a function called the value function as in Charlot et al. (2007).

$$v(x,a,\alpha) = \underset{(u_{m,}w_{mp})\in\Gamma(\alpha)}{\operatorname{Inf}} J(x,a,\alpha) \qquad \forall\, \alpha \in B \qquad \textbf{(7)}$$

The optimum conditions for the problem under consideration are given by the Hamilton-Jacobi-Bellman (HJB) equations which are expressed as follows:

$$\rho v(x,a,\alpha) = \min_{(u_{m,}w_{mp})\in\Gamma(\alpha)} \left[g(x,a,\alpha) + (u-d)\frac{\partial v}{\partial x} + ku(.)\frac{\partial v}{\partial a} + \textstyle\sum_{\alpha\neq\beta} q_{\alpha\beta} v(x,a,\beta)\right] \qquad \textbf{(8)}$$

In the next section, we will propose a method that will allow us to solve the HJB equation 8.

3. Numerical approach

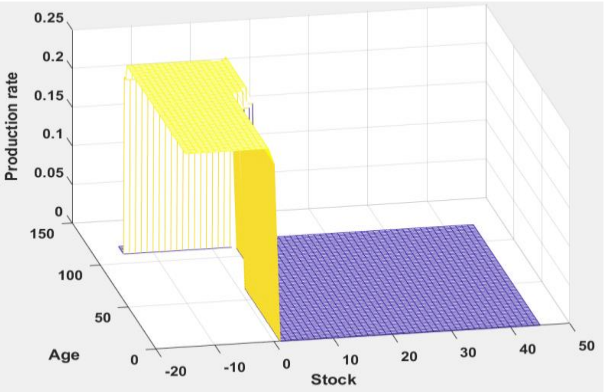
An analytical method for solving the HJB equation is currently non-existent. The approach used to solve the problem is the numerical method developed by Kushner and Dupuis (1992). This approach uses the notion of discretization steps (h_a, h_x) that we apply to equation (8). For this end, we shall now develop the numerical methods for solving the optimality conditions given by the HJB equations. Recall that the main idea behind this approach consists of using an approximation scheme for the gradient of the value function. This method has been used in several studies of this type, notably that of Nodem et al. (2011). By applying this technique, the previous equation (9) can be written in this form:

$$v^h(x,a,\alpha) = \min_{(u_{m,}w_{mp})\in\Gamma(\alpha)} \left[\begin{matrix} \left(\rho + \frac{|u_m-d|}{h_x} + \frac{ku}{h_a} + |q_{\alpha\alpha}|\right)^{-1} \times \\ \left(\begin{matrix} g(.) \\ + \frac{(u_m-d)}{h_x}\left\{\begin{matrix} v^h(x+h_x,\alpha)Ind\big((u_m-d)\geq 0\big) + \\ v^h(x-h_x,\alpha)Ind\big((u_m-d)<0\big) \end{matrix}\right\} \\ + \frac{ku}{h_a} v^h(x, a+h_a, \alpha) + \sum_{\beta\neq\alpha} q_{\alpha\beta} v^h(x,\beta) \end{matrix}\right) \end{matrix}\right] \qquad \textbf{(9)}$$

The discrete form of the HJB equations, given by (9), can be solved using either policy improvement or successive approximation methods. The reader is referred to Charlot et al. (2007) and references therein for details on such methods. The policy improvement technique is used in this paper to obtain a solution for the approximating optimization problem described in this section. The next section presents the analysis of the obtained results for a specific configuration of the system and for given data.

4. Analysis of results

Compliance with regulations on particle concentration requires good planning that considers the dynamics of the involved machines, especially those aimed at reducing the concentration of silica particles. The results obtained after simulation give us a production planning policy that considers the age of the machine and the silica particles. Figure (5) presents the strategy adopted to produce in a way to respect the health of the workers. This strategy shows that it is important to raise the critical threshold when the machine gets older. The second interpretation of this figure shows us that when the stock of finished product is negative, it is crucial to produce at the maximum rate in order to satisfy customer demand and build an inventory of finished products. Figure (6) present a preventive maintenance planning policy that allows us to make a profit and satisfy the customers but also to prevent silicosis among operators. It should be noted that this preventive maintenance is largely done when the machine is old enough and when the stock of finished products is quite comfortable. We have three areas, one where this maintenance is not done, another where it is done with a comfortable stock and another where it is done when the exposure limit is reached for which the manufacturing system must be sent immediately to preventive maintenance.



The production policy (figure 5) can be summarized as follows:

$$u(x,a,1) = \begin{cases} u_{max} & if \quad x(t) < Z(a) \\ d & if \quad x(t) = Z(a) \\ 0 & otherwise \end{cases}$$

Figure 5. *production policy*

The preventive maintenance policy (figure 6) is expressed as follows:

$$w_{mp} = \begin{cases} w_{max} & if\ (x,a)\ \epsilon\ zone\ B \\ w_{max} + W & if\ (x,a) \epsilon\ zone\ C \\ w_{min} & otherwise \end{cases}$$

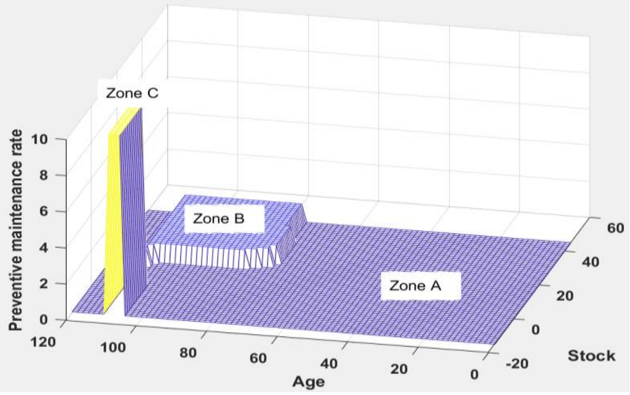


Figure 6. *preventive maintenance policy*

5. Conclusion

The objective of this study was to propose a production planning model for manufacturers that aims to optimize their revenues while providing a healthy work environment for their employees in order to prevent them from contracting silicosis. Through the results presented above, it can be said that the goal has been achieved. Companies in the granite processing sector can now plan their production over the long term while keeping the exposure limit for silica particles below the legislated limit. It should be noted that customer demand can vary according to several parameters. This variation in demand can therefore be considered in future work.

6. References

Bureau international du Travail. (2019). La sécurité et la santé au cœur de l’avenir du travail : mettre à profit 100 ans d’expérience. Première édition 2019.

Charlot, E., Kenne, J.P. and Nadeau, S. (2007). Optimal production, maintenance and lockout/tagout control policies in manufacturing systems. International Journal of Production Economics, vol. 107, issue 2, 435-450.

Emami-Mehrgani, B., Nadeau S. and Kenné J.P. (2014), Optimal lockout/tagout, preventive maintenance, human error and production policies of manufacturing systems with passive redundancy, Journal of Quality in Maintenance Engineering, vol. 20, no 4, 453-470.

Hämäläinen, P., Takala, J. and Boon Kiat, T. (2017): Global Estimates of Occupational Accidents and Workrelated Illnesses 2017. (XXIe Congrès mondial sur la sécurité et la santé au travail, Singapour, Workplace Safety and Health Institute).

Kushner, H. and Dupuis P.G. (1992). Numerical methods for stochastic control problems in continuous time, 24. Springer Science & Business Media.

National Institute for Occupational Safety and Health (NIOSH) and Occupational Safety and Health Administration, 2015 in Worker Exposure to Silica during Countertop Manufacturing, Finishing and Installation, hazard alert, publication number 2015-106

Nodem, FID. Gharbi, A. and Kenné J.P. (2011). Preventive maintenance and replacement policies for deteriorating production systems subject to imperfect repairs, International Journal of Production Research, 49 (12), 3543-3563

Songmene, V., Balout B. and Masounave, J. (2008). Clean machining: Experimental investigation on dust formation-Part II: Influence of machining strategies and drill condition. International Journal of Environmentally Conscious Design & Manufacturing. Vol. 14, No. 1.

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