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Optimizing production and imperfect preventive maintenance planning's integration in failure-prone manufacturing systems

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ABSTRACT

This paper investigates the issue of integrating production and maintenance planning in a failure-prone manufacturing system. It is assumed that the system's operating state is stochastically predictable, in terms of its operating age, and that it can accordingly be preventively maintained during preplanned periods. Preventive maintenance is assumed to be imperfect, that is when performed, it brings the manufacturing system to an operating state that lies between 'as bad as old' and 'as good as new'. Only an overhauling of the system brings it to a 'as good as new' operating state again. A practical integrated production and preventive maintenance planning model, that takes into account the system's manufacturing capacity and its operational reliability state, is developed. The model is naturally formulated as a mixed-integer non-linear optimization problem, for which an extended mixed-integer linear reformulation is proposed. This reformulation, while it solves the proposed integrated planning problem to optimality, remains quite demanding in terms of computational time. A fix-and-optimize procedure, that takes advantage of some properties of the original model, is then proposed. The reformulation and the fix-and-optimize procedure are tested on some test instances adapted from those available in the literature. The results show that the proposed fix-and-optimize procedure performs quite well and opens new research direction for future improvements.

1. Introduction

The current technological sophistication of the modern manufacturing systems creates a natural interdependence between production and maintenance activities on these systems. In automotive industry for example, some assembly lines are fully integrated and a failure of one of its machines or workstations may cause the full line to stop creating delays with considerable technical and economic consequences. In such environments, operating a manufacturing system that is not appropriately maintained, or even preventively maintained but at less opportune time periods, may result in significant productivity losses and additional costs which are among others caused by poor product quality and avoidable production overtimes. Thus, any system's deterioration in these highly automated and fully integrated production lines impacts not only the system itself but also the quality of the product, which may either require rework or is simply scrapped if it cannot be reworked. Consequently, the integration of production and preventive maintenance planning is essential to keep the manufacturing system operating optimally and at the desirable productivity level.

When a manufacturing system is operating, its various components are subject to degradations due either to age or usage. Some of these degradations can be modeled or approximated by some stochastic processes, which can be used to optimally integrate production and preventive maintenance plans. In practice however, production and maintenance are usually planned independently. Maintenance is scheduled and carried out based only on the system's reliability data, neither the forecasted production orders nor planned product mix are taken into account. Production planning is then carried out within the limits imposed by the system's maintenance schedule. This results often in production and maintenance plans which are not optimal with respect to the overall objective of minimizing the combined production and maintenance related costs.

This paper proposes an aggregate production planning model, which in addition to the relevant production data and parameters also takes the system's reliability statistics into account, to generate optimal tactical production plans that specify optimal periods for preventive maintenance as well. This planning integration is carried out at the

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tactical level to allow the planner to efficiently and effectively plan the required production and preventive maintenance tasks while taking advantage of the available information on expected product-mix orders and system's operating state. The actual scheduling of maintenance is then carried out, at the operational level, during those specified opportune periods. The model attempts to achieve an optimal trade-off between production related costs and maintenance related costs while fulfilling the aggregate production requirements. The model assumes that maintenance is imperfect and is first formulated, in its natural variables, as a mixed integer non-linear optimization problem. It is then shown that it can be reformulated as mixed-integer linear problem, which can be solved with the readily available solvers. However, the numbers of variables and constraints in this reformulation are too large. An approach to approximately solve the problem, while taking advantage of the linearity of the large reformulation, is also proposed and discussed.

The remainder of this paper is organized as follows: Section 2 briefly overviews relevant literature. Section 3 discusses in detail the development of an optimization model, and its properties, to generate optimal integrate production and imperfect preventive maintenance plans. Section 4 presents an extended mixed-integer linear reformulation of the problem. Section 5 presents a fix-and-optimize procedure to solve the problem using some well-constructed relaxed mixed-integer linear sub-problems, stemming from the reformulation discussed in Section 4. Then, the results of the reformulation and the fix-and-optimize procedure on some test instances are reported and discussed. Finally, some concluding remarks are presented in the conclusion.

2. A brief review of the literature

During its operation, a manufacturing system and its components are subject to random degradations which are inherent to either their age, usage or both. Maintenance must be regularly performed to assess the level of degradations and then, if necessary, attempt to bring the system and/or its critical components back to good operating conditions. As a result, researchers started investigating the issue of developing maintenance strategies for the stochastically degrading manufacturing systems. Maintenance of the system can be performed either preventively before or correctively after its failure or failure of one of its components. Preventive maintenance and replacement policies have been extensively investigated in the literature, starting with the preventive maintenance framework introduced by Barlow and Hunter in their seminal paper [1] (see also Barlow and Proshan [2]). Surveys summarizing the research status in this area at different epochs can be found in, among others, McCall [3], Pierskalla and Voelker [4], Sherif and Smith [5], Jardine and Buzacott [6], Valdez-Flores and Feldman [7], Cho and Parlar [8], Dekker [9], Pham and Wang [10], Van Der Duyn Schouten [11], Dekker et al. [12] and Lugtigheid et al. [13]. Recently Nakagawa and Mizutani, [14], extended the well-known results of periodic replacement with minimal repair policy as well as those of block replacement policy from infinite into finite time horizon setting. For more details about preventive maintenance policies made within finite time horizon see Nakagawa [15].

The major part of the available research literature, dealing with production and preventive maintenance integration, focuses on operations scheduling. The proposed integrated production and preventive maintenance scheduling models assume that the periods during which preventive maintenance is to take place are known in advance, and are mainly formulated as deterministic scheduling problem with availability constraints. These models are usually solved using adapted versions of the solution methods used for scheduling problems, see among others, Lee [16–18], Kubiak et al. [19], Lee and Chen [20] and Cassady and Kunatoglu [21].

During the last two decades, however, the research literature addressing the issue of integrating production and preventive maintenance, at the tactical planning level, witnessed a significant intensification. Starting with the paper of Wienstein and Chung [22], in which the authors presented a three-parts hierarchical production planning and scheduling model that also considers system's reliability. The first part in the model is an aggregated production planning model formulated as a linear program. The second part is a master production schedule with the objective of minimizing the weighted deviations with respect to the goals specified at the aggregate production planning level. The third part in the model deals with work center loading requirements, which are used to simulate equipment failures during the planning horizon. Several experiments are carried out to test the significant factors such as category of maintenance activity, maintenance activity frequency, failure significance, maintenance activity cost, and aggregate production policy for maintenance policy selection. In Aghezzaf et al. [23], the authors proposed an integrated production and preventive maintenance planning optimization model to generate optimal integrated production and preventive maintenance plans at the tactical level. The model assumes that the system is minimally repaired when it fails randomly during a production period. That is, the systems is returned to an operating state without altering its failure rate. When the system is preventively maintained it returns to an as good as new state. Its failure rate is the same as the that of a new system. It also assumes that any maintenance action, minimal repair or preventive maintenance, reduces the available production capacity of the system. This work is extended in [24] to deal with simultaneous optimization of production and preventive maintenance in multiple-lines stochastic degrading manufacturing system. Najid et al. [25] extended the model in [24] to include demand time windows and shortage cost. Nourelfath and Chatelet [26] discussed the same planning problem for a production system composed of a set of parallel components, in the presence of economic dependence and common cause failures. Zhao et al. [27] assume order-dependent-failure (ODF) and proposed an iterative method to solve the problem on a single-machine system. Fitouhi and Nourelfath [28] extended the model [23] to multi-state systems. Recently, Yalaoui et al. [29] proposed some very interesting exact and heuristic algorithms to efficiently solve moderate to larger instances of the model proposed in [24]. Liu et al. [30] studied the economic production quantity problem on a system, producing multiple items, and requiring preventive maintenance. Preventive maintenance is carried out during set-up times of some items. The authors analyzed the issue of jointly determining the optimal lot sizes and the preventive maintenance policy. Other versions of this latter model, including inventory, are discussed in the literature.

The model discussed in this paper extends the one proposed in [23] and its subsequent variations. It deals, though, with the non-periodic and imperfect preventive maintenance. When an imperfect preventive maintenance operation is performed it brings the system to an operating state that is between the two extreme operating states, namely the 'as bad as old' and the 'as good as new' states. Along the same lines as in [23] and [24], it is assumed that each imperfect preventive maintenance improves the available production capacity of the system and this according to the degree at which the maintenance is performed. However, the deterioration rate of the manufacturing system after each imperfect preventive maintenance increases and the production capacity decreases more rapidly due to more frequent minimal repair tasks. When the deterioration rate reaches an unacceptable level, the systems is overhauled and returns to an 'as good as new' state.

To model imperfect preventive maintenance, Malik [31] proposed an age reduction model based of the concept of system's 'virtual age' according to which a system becomes 'younger' whenever it undergoes an imperfect preventive maintenance. In other words, after an