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Optimization of integrated preventive maintenance based on infinitesimal perturbation analysis

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ABSTRACT

This paper considers jointly the production control and preventive maintenance problem in a manufacturing system. This system is composed of a single unreliable machine that produces one or two types of products with constant and different demand, a customer and a buffer between the machine and the customer. Machine failures are time-dependent, i.e. the machine can fail at any time, so a block-type preventive maintenance policy is proposed to increase the system life. This policy is coupled with a hedging point policy which controls the machine production speed. Between each element of the system, constant transportation delays are considered, i.e. a conveyor between the machine and its downstream buffer and a transport between the buffer and the customer. Then, a continuous-flow model is proposed to represent the overall dynamics of the system. This model allows us to take into account explicitly the transportation delays. The main objective of this work is to find the optimal preventive maintenance period by means of infinitesimal perturbation analysis technique as well as the optimal hedging point in order to minimize the expected average cost function. For this, we find the gradient estimators of the cost function from a theoretical sample path study. Then we integrate them in a simulation algorithm to find a numerical estimation of the solution. Simulation results highlight our theoretical results.

1. Introduction

Since integrated production/maintenance strategy has been defined, it has become an important topic which catches growing attention, due to the total obtained cost savings (Colledani & Tolio, 2012). Indeed, the production planning and maintenance scheduling are two major issues which can hold quality and productivity in manufacturing companies even if uncertain conditions can occur such as failures, delays or client demands (Lu, Cui, & Han, 2015). On one hand, the use of a preventive maintenance policy has benefits such as the diminution of the probability of breakdowns and the increase of equipment life and availability of the system (Hadidi, Al-Turki, & Rahim, 2012; Van Horenbeek, Pintelon, & Muchiri, 2010). On the other hand, the chosen production control enables an increase of the quality service and customer satisfaction (Gershwin, 1994). The aim of this work is to implement both a preventive maintenance and a production control policy, in order to obtain a strategy which permits to minimize the average total cost. We suppose that the failures are time dependent. It means that the machine may fail even if it does not produce (Tan, 1998). Moreover, we assume that the failures have an increasing failure rate (Lu et al., 2015). Some strategies integrating production and maintenance focus on the scheduling of the production and the maintenance actions to minimize the delays in the execution of the jobs (Aramon Bajestani, Banjevic, & Beck, 2014; Gustavsson, Patriksson, Strömberg, Wojciechowski, & Önnheim, 2014; Liu, Wang, & Peng, 2015; Xiang, Cassady, Jin, & Zhang, 2014; Zammori, Braglia, & Castellano, 2014). Recently, other strategies combining the production and the maintenance have been proposed to control the quality of products (Bouslah, Gharbi, & Pellerin, 2014; Colledani & Tolio, 2012). The joint production control and maintenance problem has been addressed by many authors considering different preventive maintenance policies, such as age-based preventive maintenance, periodic preventive maintenance policy of block-type (Barlow & Hunter, 1960) or even condition based maintenance (Zhang, Ye, & Xie, 2014) and production control policies (Campos, Seatzu, & Xie, 2014). In an age replacement preventive maintenance policy, a corrective maintenance is made when a machine fails, or a preventive maintenance action is undertaken after T time units of use without a failure. By contrast, in a block preventive maintenance policy, a

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preventive maintenance action is performed every T time units, independently of the age of the machine. At the failure, a corrective maintenance is carried out. In economic terms, the age replacement preventive maintenance policy outperforms the block replacement preventive maintenance policy. Nevertheless, in practice, a block replacement preventive maintenance policy is easier to implement because there is no need to update the time of the next preventive maintenance after a maintenance action (Barlow & Proschan, 1975). Different variations of both policies, such as minimal repair at the failure (Chang, 2014; Chen, Xiao, & Zhang, 2015) or other variations on the maintenance costs are summarized in Nakagawa (2006). In the proposed approach, we choose a preventive maintenance of block-type due to its simplicity to implement and manage it.

Many of the strategies that integrate production control and maintenance scheduling are based on the construction of inventory buffers to avoid machines starvation in the production process or to fulfill the demands in periods in which machines fail. Some of these strategies are based on the average consumption of a product in a preventive maintenance cycle (Assid, Gharbi, & Hajji, 2015; Chelbi & Ait-Kadi, 2004; Gharbi, Kenné, & Beit, 2007; Rezg, Xie, & Mati, 2004; Salameh & Ghattas, 2001). Indeed, it has been shown that the construction of a buffer can be an optimal strategy in production systems, composed of machines subject to random failures. With this purpose, Kimemia and Gershwin (1983) introduce a pioneer work in which the authors show that it is possible to keep a low level of work-in-process inventory to meet demand while machines are unavailable. The proposed strategy is the well-known hedging point policy. Then, the optimality of this policy is proved in Akella and Kumar (1986) under certain conditions (constant demand, homogeneous Markov processes, etc.) for a single-product and a single-machine system. In their work, the optimal discounted inventory cost is obtained for the problem considered in Kimemia and Gershwin (1983). A counterpart of the solution proposed by Akella and Kumar (1986) is obtained in Glasserman (1995), in which additionally, the average inventory cost of this policy is considered. Martinelli and Valigi (2004) present another variation of this policy, considering bounds on the inventory and backlog costs. The authors prove that using these bounds does not affect the optimality of this policy.

The hedging point policy has been used coupled with an age preventive maintenance policy (Gharbi & Kenné, 2000; Gharbi & Kenné, 2005) or with a preventive maintenance of block-type (Berthaut, Gharbi, & Dhouib, 2011; Berthaut, Gharbi, Kenné, & Boulet, 2010; Gomez Urrutia, Hennequin, & Rezg, 2011), to propose joint production and maintenance strategies. For example, Gharbi and Kenné (2000) study several identical machines (i.e. identical transition rates of their stochastic process) producing a single-product. The states of the machines are represented by a Markov process. The same problem is studied for a manufacturing system with non-identical machines in Gharbi and Kenné (2005). Berthaut et al. (2010) define two hedging points. The first one controls the production rate and the second one controls the preventive maintenance actions. Thus, if the value of the inventory level is greater than the hedging point that controls the preventive maintenance actions, then the preventive maintenance is performed, otherwise, the preventive maintenance is skipped. In Berthaut et al. (2011) a hedging point policy is coupled with a modified block replacement preventive maintenance to study a manufacturing cell made up of a single machine. In this case, the preventive maintenance is skipped if the time elapsed between the last maintenance action and the preventive maintenance period is lower than a specific threshold of time. Gomez Urrutia et al. (2011) consider a production system composed of a single-machine producing a single-product. The authors couple a hedging point policy with a block replacement preventive maintenance policy.

Generally, most of the resolution methods for problems coupling production and maintenance are based on simulation approaches (for example, see Kröning & Denkena, 2013; Lynch, Adendorff, Yadavalli, & Adetunji, 2013; Roux, Duvivier, Quesnel, & Ramat, 2013; an interesting literature review is provided in Alrabghi & Tiwari, 2015). Other approaches combine analytical methods, design of experiments based on response surface methodology and simulation, such as in most of the aforementioned references, dealing with joint strategies of production planning and preventive maintenance (see, for example, Azadeh, Sheikhalishahi, Firoozi, & Khalili, 2013; Berthaut et al., 2010; Berthaut et al., 2011; Gharbi & Kenné, 2000; Gharbi & Kenné, 2005). Other works use analytical models combined with simulation to find approximate results of the optimal strategy such as in Rezg et al. (2004), Chelbi and Ait-Kadi (2004), and Chen, Ye, and Xie (2013). In the proposed approach, we make use of the advantages of the chosen analytical resolution method to combine analytical results with simulation. The analytical resolution method we choose is the Infinitesimal Perturbation Analysis (IPA). In this method, a sample path derivative is computed from two sample paths: the nominal and the perturbed sample path. The perturbed sample path is built from the nominal sample path applying a perturbation sufficiently small to the parameter with respect to which the sample path derivative is computed. This guarantees that the sequence of the events of the perturbed sample path does not change. The main condition to apply IPA is the unbiasedness of the derivative estimator. It makes possible the use of IPA for reliable sensitivity analysis or for the use in control and optimization methods (Sun, Cassandras, Wardi, Panayiotou, & Riley, 2004). Thus, the results obtained analytically using IPA can be integrated in a simulation algorithm. IPA has been first developed for queuing systems (Ho & Cao, 1983) and then extended to Markov systems (Cao, 2007). This technique is used in a stochastic flow model of a manufacturing workcenter in Yu and Cassandras (2002) to obtain gradient estimators of the throughput and buffer overflow with regard to threshold control parameters. Yu and Cassandras (2004) consider a manufacturing system consisting of a source supplying parts to a server. An intermediate buffer is considered to store the parts before being processed. The unbiased gradient estimates of the throughput and of the overflow rate are provided. In Paschalidis, Liu, Cassandras, and Panayiotou (2004), IPA is used to determine the inventory level that minimizes the expected inventory costs of each stage of a supply chain composed of two stages. The considered supply chain produces a single-product and the production is controlled by a base-stock policy. In Gomez Urrutia et al. (2011) IPA is used to determine the optimal hedging point and the preventive maintenance period that minimize the average total cost (inventory and maintenance costs). In the present work, the purpose is to extend the study of Gomez Urrutia et al. (2011), considering delays between each component of the manufacturing system. This feature in the study of the system complicates the definition of the hedging point, because the quantity of produced parts at a specific time is different of the quantity of parts arriving to the buffer.

Few works consider the delays explicitly, such as production or transportation delays in the model. The delays are taken into account explicitly for the first time in Van Ryzin, Lou, and Gershwin (1991) in a job shop with unreliable machines. In Xie, Hennequin, and Mourani (2013), delays are considered in a transfer line, in which the materials flowing out from the machines wait before arriving to the downstream buffer. The analytical model we choose is a Continuous Flow Model (CFM). Indeed, this model allows introducing the transfer and transportation delays. CFM is widely used to describe the behavior of the products flowing through the production lines in discrete manufacturing systems when there is an important number of products or to model