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Joint maintenance-inventory optimisation of parallel production systems

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ABSTRACT

We model a joint inspection and spare parts inventory policy for maintaining machines in a parallel system, where simultaneous downtime seriously impacts upon production performance and has a significant financial consequence. This dependency between system components means that analysis of realistic maintenance models is intractable. Therefore we use simulation and a numerical optimisation tool to study the cost-optimality of several policies. Inspection maintenance is modelled using the delay-time concept. Critical spare parts replenishment is considered using several variants of a periodic review policy. In particular, our results indicate that the cost-optimal policy is characterised by equal frequencies of inspection and replenishment, and delivery of spare parts that coincides with maintenance intervention. In general, our model provides a framework for studying the interaction of spare parts ordering with maintenance scheduling. The sensitivity analysis that we present offers insights for the effective management of such parallel systems, not only in a paper-making plant, which motivates our modelling development, but also in other manufacturing contexts.

1. Introduction

The optimisation of maintenance operations offers economic benefits [1] and therefore maintenance is increasingly highlighted as an integral part of production and business in both the research literature [2] and the practitioner literature [3]. Typically, in the literature, a maintenance interval that yields the minimum cost is determined assuming infinite availability of spare parts [4]. This implies that spares are either highly standardized and readily replenished, or so inexpensive that large quantities can be stored. However, in reality, spares are often highly customized and their procurement lead-time is relatively long [5]. Therefore, maintenance analysis and decision-making [6] without the consideration of spare parts inventory may result in sub-optimal decisions.

The literature on joint modelling of maintenance and spare parts inventory is developing rapidly. However, little of this research considers systems with two or more machines, operated in parallel [7]. Indeed Van Horenbeek et al. [8] state that single-machine systems are oversimplified and do not reflect the interactions in real manufacturing systems. Scarf [9], in an "appeal to maintenance modellers to work with maintenance engineers and managers on real problems", acknowledges that "too much attention is paid to the invention of new models, with little thought, it seems, as to their applicability". This latter observation remains valid since evidence suggests that little research on the optimisation of maintenance is applicable to real industrial systems [10].

We aim to address these shortcomings in our study, and we model the maintenance and spare parts inventory of an industrial plant comprising two parallel machines. In this context, an important objective of maintenance is the elimination, or at least minimisation of simultaneous downtime. In this way, we suppose that simultaneous downtime has serious consequences for the performance of production and upstream and downstream processes. Note, this is in contrast to say offshore-windfarm maintenance [11], where opportunistic maintenance of wind turbines in parallel is ideal in order to minimise significant set-up costs [12].

Viewed separately, maintenance models broadly fall into two sets: time-based, including block-replacement and age-based replacement [13]; and condition-based [14,15], including models of periodic inspection whereby only those components that are defective are replaced. An inspection policy, provided it is effective [16], offers a cost advantage over time-based policies where items are replaced regardless of their condition or state. The classic model of inspection maintenance is the delay-time model [17], reviewed by Wang [18], developed by many ([19–22]), and used in case studies (e.g [23]). We shall use the delay-time model in our study and suppose that the parallel machines are subject to regular inspections that aim to identify defects and carry out consequent replacements.

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We consider our inspection policy in conjunction with a periodic review replenishment policy. We choose this particular inventory policy because the inventory literature (e.g [24]) and previous research studies [25] suggest that this policy complements a periodic maintenance policy. Shared inventory imposes a logistical interaction between the machines in the parallel system, so that in principle we model a multi-component system with dependence. Further logistical interaction arises because we suppose that the costs of individual machine downtimes are not additive, in that simultaneous downtime of machines incurs a severe penalty. These logistical dependencies are distinct from economic dependence that arises from shared set-up costs for maintenance interventions [26].

The joint policy is considered in two variants. In these variants, the timing of orders may be such that spare parts delivery coincides with inspection (*just-in-time* ordering) or ordering itself coincides with inspection (*coincident* ordering). Further, the frequency of inspection and the frequency of replenishment may be the same or different.

The joint optimisation of maintenance and inventory is reviewed in [8] and this review is updated in [25]. Therein, there exist studies of joint optimisation of inspection and spare parts inventory that use the delay-time model [25,27,28], and that do not [5,29], but these do not consider parallel machines. On the other hand, studies that do consider parallel machines do not consider joint optimisation of maintenance and inventory [30]. There exist studies of joint optimisation for single-component systems [31,32], but these are for series systems, and there are studies of joint policies that do not consider inspection (joint block replacement policies are studied in [10,33–40], and joint age-based replacement policies are studied in [32,41]). Furthermore, studies of joint inventory and condition-based policies exist [42,43], but these studies do not consider parallel lines. Therefore, as far as we are aware, our paper is the first to consider joint optimisation of maintenance and spare parts for parallel production systems.

Finally, turning to solution methodology, the use of simulation to analyse joint policies is common for realistic settings [33,37,44–46]. Simulation has the flexibility to address the increasingly complex and dynamic nature of maintenance optimisation, and inventory optimisation adds to this complexity.

The layout of the paper is as follows. The next section describes the context that motivates our model. In Section 3, we describe the maintenance and inventory policies and their assumptions, and the cost structure of the joint policy. Our simulation methodology is described in Section 4. Section 5 presents the results and discussion of these, and also includes a sensitivity analysis of the policy to model parameters. We finish with concluding remarks.

2. Problem description

The specific industrial situation considered is a paper mill consisting of two machines working in parallel. Beside relatively low-cost cutting blades, bearings are the *critical* components in this plant. Bearings are used extensively in paper-making machines and, apart from general risks to safety, their failure can incur costs due to repair or replacement, and unplanned machine downtime. Folger et al. [47] describe several conditions under which bearings can fail unexpectedly and catastrophically, and Jacobs et al. [48] and Collins [49], for example, describe engineering models of bearing life (e.g. the "L10-life"). The notion of the L10-life is consistent with the three-state failure model that we use for bearing life, whereby a bearing degrades from the good to the defective to the failed state. A bearing operates when it is defective and the defective state is revealed only by inspection. This is the delay-time concept, and the sojourns in the good and defective states are random variables. The sojourn in the defective state is called the *delay-time*, and is similar to the notion of the *P-F* (potential to functional failure) interval in reliability-centred maintenance [50,51].

We suppose a common inventory exists for bearings for both machines. Paper machinery typically have many identical bearings. In our model, it is supposed that inventory planning is concerned only with these bearings. That is, inventory control for a single stock keeping unit will be considered.

The delay-time model implies that failures occur at random times and that at inspection a random number of defects will be found. Thus, despite that inspection times are known, the times of demands for spare parts are unknown. Consequently, when, relative to inspection, and in what quantity spares should be ordered is an interesting question.

Survey data [45] provide information about: possible defect arrival patterns, *delay-times*, and their distributions; inspections; preventive replacements; failure replacements; current maintenance and replenishment policies for replacing critical components; lead-times; and costs. The data were provided by maintenance and inventory control experts and paper manufacturers, who completed a questionnaire on their experience of paper making machinery and the critical components therein. This ensured that the model and simulation experiments were realistic and not based on some arbitrary data. This process also ensures that our modelling approach is relevant to other (similar) settings. Furthermore, variability in the values of model parameters was quantified in order to reflect a range of opinion about maintenance "inputs and outputs" where it existed. We also used [28], in which maintenance optimisation for a paper-making plant is also considered, to guide model parameter specification. The values and ranges of model parameters are given in the relevant sections.

3. The joint maintenance and spare parts inventory model

3.1. Notation

$C_{d(ind)}$ Cost-rate of individual machine downtime
$C_{d(sim)}$ Cost-rate of simultaneous machine downtime
C_f Cost of a failure replacement (per item)
C_r Cost of a preventive replacement (per item)
C_h Cost-rate of inventory holding
C_i Cost of an inspection
C_m Cost-rate of one maintenance technician
C_o Cost of an order including delivery
C_{sh} Cost of an emergency order including delivery
C_u Cost of one item (unit cost of a bearing)
C_∞ Long-run total cost per unit time, or cost-rate
d_f Downtime due to a failure replacement
d_r Downtime due to a preventive replacement
D_∞ Long-run total downtime per unit time, or downtime-rate
L_o Normal delivery lead-time
L_{sh} Emergency delivery lead-time
R Order review period; a decision variable
S Order-up-to level; a decision variable
T Inspection interval; a decision variable; $T = kR$, for $k > 0$

U *Time-to-defect* arrival; initial time from new (or as new) until a defect that could be identified by inspection arises; a random variable

u Particular realisation of U

H *Delay-time*; time between a defect arising and the subsequent failure if left unattended; a random variable

$F_H(h)$ Cumulative distribution function (cdf) of H, independent of