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Maintenance optimization of series systems subject to reliability constraints

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ABSTRACT

The extension of maintenance optimization methodologies used for single component to multiple component systems must take into account the interdependencies that may exist between the components. Such dependencies could arise when the maintenance optimization of the system over the time is subject to constraints. In this paper, a methodology using Lagrangian relaxation techniques embedded in dynamic programming is proposed for minimizing the maintenance costs of reliability constrained series systems. The methodology could be applied to deterministic and probabilistic dynamic programming problems, as well as to partially observable Markov Decision process. The computational complexity of the proposed approach is polynomial in the number Q of the system components. Theoretical and practical issues related to the existence, and the computation of the Lagrange multipliers are considered. The proposed methodology is illustrated by a numerical application considering maintenance planning of a pipeline.

1. Introduction

Maintenance optimization over time of multistate series systems is often complicated due to existing dependencies between the system components. If such dependencies would not exist, then the optimal strategy for the whole system would be the combination of the individual optimal strategies for each component, calculated independently from the other components. However, in practical settings, interdependencies among the components of a system arise from a multitude of sources. These interdependencies as classified by Dekker [14] can be either structural/functional, stochastic [7,32] or economic [15,18,38,45].

Interdependencies could arises between the components of a system, when the maintenance optimization of the system over time is subject to constraints. Such constraints could be for example the limited availability of budget [13], of maintenance capacity, of spare parts, etc., needed for the maintenance of the system during each time period of the planning horizon. In such case, the optimal maintenance decision of one component will depend on the state of that component, and also on the state of the other components which can potentially compete for the limited available resources.

The problem of optimizing the maintenance strategy, with respect to costs [8] or to reliability [10], subject to resources constraints (such as limited budget, limited labour availability, etc.) has been extensively dealt with in the literature. However, in practical settings, the manager of a system is compelled to minimize the maintenance costs of a system subject to reliability constraints during each time period of its projected lifetime. The reliability constraints are usually imposed by regulatory texts and standards related to specific industries. Hence, competition incite for cost minimization under target reliability levels.

In multicomponent systems, assigning one global reliability target for the whole system, for each time period, implies decision interdependencies between the components. The global reliability of a series system can be expressed as:

$$R = \prod_{i=1}^{i=n} r_i$$

where r_i is the reliability of component i. As such, optimizing the maintenance strategy of component i, with respect to cost, while meeting the imposed reliability constraints, cannot be done independently from the optimization of the other components.

Linear programming is often used to solve parallel Markov Decision Processes (MDPs) subject to global resource constraints for each time period [41,43]. However, this methodology has a major limitation; namely, it is restricted to homogenous systems (with respect to costs, types of activity, deterioration models, etc.); i.e. the different components of the system have to be essentially the same. Faddoul et al. [23] proposed an MDP-based methodology using Lagrangian relaxation

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techniques [21] to deal with the IM&R optimization of multi-structure inventories subject to economic interdependence induced by budget constraints. Lagrangian relaxation techniques are used to separate the initial combinatorial problem into smaller sub-problems. The system components do not have to be similar, different sets of feasible maintenance, inspection techniques, deterioration models and costs can be assigned to each component.

Elegbede et al. [20] present a methodology for allocating reliability during the design phase of a parallel-series system. Under the assumption that all the components, at a given stage of the system, have the same reliability cost function, it is shown that the optimum reliability allocation among the parallel components of that stage is an equally distributed reliability. Bae et al. [3] used a neuro-genetic methodology to optimize maintenance reliability allocation for urban transit break system. A genetic algorithm is used to minimize the square error between the target reliability and the reliability of the system evaluated from the components reliabilities. Bris et al. [8] used genetic algorithms to minimize the inspection-maintenance costs under availability constraints. Chen et al. [11] proposed group preventive maintenance model for lifecycle costs optimization under reliability constraints. Li and Brown [37] proposed a procedure to prioritize maintenance for multicomponent systems, by ranking maintenance tasks based on their marginal benefit-to-cost ratios, where the benefit is defined as improvement in system reliability. The manager selects maintenance tasks from the top of the ranking list until the cost limit is reached, or the reliability target is reached. The major shortcoming of this approach is that the optimal strategy is myopic and not dynamic. A similar approach was proposed by Bris et al. [9] where they choose the configuration with minimal cost that meet the reliability requirements.

Galante and Passannanti [28] described an exact algorithm for preventive maintenance planning of series–parallel systems. At predefined instants, a subset of system components is chosen to undergo maintenance according to the as good as new policy. The choice of the subset is made to minimize costs, while ensuring that the system reliability does not go below an accepted level until the next scheduled maintenance intervention. Loganathan and Gandhi [40] used particle swarm optimization to optimize the time interval for preventive maintenance. Doostparast et al. [17] used the simulated annealing algorithm to identify the optimal maintenance plan to minimize the total maintenance costs, with respect to a desired level of system reliability.

Flage et al. [27] investigate the effects of different formulation of reliability constraints on the cost minimization problem: (i) constraints are imposed on the subjective probability, or (ii) constraints are imposed on the subjective probabilities and the limiting probabilities. Barker and Newby [4] proposed a methodology for finding an optimal maintenance and inspection policy to minimize cost while ensuring a limit probability that a performance measure of the system does not permanently exceed a predefined limiting threshold. Khatab and Aghezzaf [34] developed a selective maintenance policy optimization procedure for multicomponent systems carrying out several missions with scheduled intermission breaks. The objective function is to minimize the total maintenance cost taking into account the required minimal probability of successfully completing the next mission. They end up solving a nonlinear and stochastic optimization problem. A similar problem was considered by Liu et al. [39] where the duration of the maintenance actions and of the breaks is stochastic. Jiang et al. [31] proposed a methodology for maximizing reliability benefit from maintenance selection and scheduling given constraints on financial and labour resources and network security. They used Lagrange relaxation for constrained linear programs. Once they find approximate Lagrange multipliers they formulate a new high dimensional knapsack problem. To reduce the computational complexity resulting from the high dimensionality, some percentage of the solution is obtained heuristically using ratio scores. Lai et al. [36] described an optimization framework with an alternative evaluator and an investment selector to determine an optimal investment plan with a specific allocation on cost, system reliability, and service reliability. They use a mixed-integer programming to minimize the cost model.

Tao et al. [44] proposed a methodology combining the theory of constraints (TOC) policy and variable lead-lag time window (VLLTW) policy to schedule opportunistic maintenance of the components of a series system where the components can be heterogeneous. Kang and Subramaniam [33] integrate production and opportunistic maintenance in a joint optimization problem. Feng et al. [26] integrate imperfect preventive maintenance in Flexible flowshop manufacturing cells methodology. Diallo et al. [16] introduce a two-phase approach combining efficient enumeration of patterns and a multidimensional multiple choice knapsack problem to optimally solve the selective maintenance problem for large serial k-out-of-n and complex reliability systems. Opportunistic maintenance and economic dependence for k-out-of-n systems were taken in account by Atashgar and Abdollahzadeh [2]. Yahyatabar and Najafi [49] propose an Invasive Weed Optimization algorithm to minimize periodic preventive maintenance cost for series-parallel systems were a global reliability constraint for the whole system is imposed. In Garbatov and Soares [29] pipelines are analysed as series systems where each segment is a component. Different failure modes are considered and the pipeline is considered failed if any the failures modes happen. Thus the system is in series with respect to the failure modes also. The failure modes are considered potentially correlated. In this study we assume that there is no correlation between the degradation rate of the segments of the system nor between its failure modes.

In this paper, the methodology proposed by Faddoul et al. [23] for the maintenance optimization of multiple structures under budget constraints is extended to the cost optimization of Inspection, Maintenance and Rehabilitation (IM&R) over time of a multi-component series system under reliability constraints during each time period of the planning horizon. Following Faddoul et al. [23], Lagrangian relaxation techniques are used to separate the initial combinatorial problem into k smaller sub-problems (k being the number of components). While the constraints in [23] were naturally additive, we will show in this paper that, by an appropriate variable transformation, one can transform the problem with reliability constraints to an additive problem which can be readily solved by the proposed methodology. The computational complexity of the proposed approach is polynomial $O(Q^c)$ in the number of system components Q.

Section 2 presents a brief overview of Markov decision process and dynamic programming. In Section 3, the proposed approach is formulated by extending dynamic programming to the multi-component level. Section 4 considers practical aspects concerning the computation of the Lagrangian multipliers. The paper ends with the presentation of a numerical example of IM&R optimization of five sections gun barrel oil pipeline.

2. Markov decision process and dynamic programming

Markov Decision Processes (MDPs) [42,48] and semi-Markov process [35] have been extensively developed and used in real world applications for IM&R optimization of deteriorating assets. Particularly for civil engineering structures, they are recognized as the industry standard decision support tools [14,30]. MDPs can be classified into (i) deterministic MDPs, where perfect inspections and perfect maintenance actions are implicitly assumed, (ii) probabilistic MDPs, where perfect inspections and uncertain maintenance actions are implicitly assumed; or (iii) Partially Observable Markov Decision Processes (POMDPs) [15,45], where the state of the system at each decision stage is not precisely known, and uncertain maintenance actions are assumed. In Faddoul et al. [24,25], further generalizations of POMDPs are developed to take into account possible epistemic uncertainties veiling the true values of inspection and/or maintenance transition probabilities.

The extension of deterministic MDPs to probabilistic MDPs and to POMDPs is straightforward, albeit requiring the manipulation of belief