European Journal of Operational Research 000 (2017) 1–14

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Production, Manufacturing and Logistics

Integrating meta-heuristics, simulation and exact techniques for production planning of a failure-prone manufacturing system

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ARTICLE INFO

Article history:
Received 2 June 2015
Accepted 28 October 2017
Available online xxx

Keywords:
Genetic algorithms
Combinatorial optimization
Production planning
Simulation-based optimization
Uncertainty modelling

ABSTRACT

This paper considers a real-world production planning problem in which production line failures cause uncertainty regarding the practical implementation of a given production plan. We provide a general formulation of this problem as an extended stochastic knapsack problem, in which uncertainty arises from non-trivial perturbations to the decision variables that cannot be represented in closed form.

We then proceed by describing a combination of exact optimization, simulation and a meta-heuristic that can be employed in such a setting. Specifically, a discrete-event simulation (DES) of the production system is developed to estimate solution quality and to model perturbations to the decision variables. A genetic algorithm (GA) can then be used to search for optimal production plans, using a simulation-based optimization approach. To provide effective seeding to the GA, we propose initialization operators that exploit mathematical programming in combination with the DES model.

The approach is benchmarked against integer linear programming and chance-constrained programming. We find that our approach significantly outperforms contestant techniques under various levels of uncertainty.

1. Introduction

Our work is motivated by a production planning problem encountered at the tactical level in a collaborating manufacturing company. The key features of the application are as follows: (i) The basic deterministic planning problem (without uncertainties) can be modelled using a standard mathematical programming approach. (ii) Uncertainties within the system impact on the implementation of a given production plan, which results in perturbations to the original values of the decision variables (i.e. the quantity produced of each product) and the objective function (i.e. the profit realized). (iii) These uncertainties are of sufficient complexity to prohibit their modelling through a closed-form expression. On the other hand, the overall system (including its uncertainties) is understood at a level that allows for the mapping from a given production plan to profit through a discrete-event simulation (DES) model or an alternative numerical tool.

The primary purpose of this study is to explore the relative strengths of mathematical programming and heuristic optimization in this specific optimization context, and to investigate possible synergies between the two classes of approaches. In order to underline the practical origin and value of our work, we provide an overview of the specific features of the real-world problem underpinning our research. A full description is beyond the scope of this paper but has been provided elsewhere (Diaz, 2016, pp. 30–42). To help position our research and highlight the wider applicability of our approach, we derive a general formulation for this setting in the form of an extended knapsack problem. Finally, we present a solution approach that employs a combination of DES, mathematical programming and a meta-heuristic to provide an effective optimizer for this setting, and we evaluate its performance in comparison to more established approaches.

The remainder of this paper is structured as follows. This introductory section continues with a summarized description of the failure-prone manufacturing system motivating our research, and a discussion of the optimization challenges arising from this setting. Section 2 provides a review of relevant literature, and highlights our contributions in that context. The general formulation of the problem is given in Section 3, while Section 4 describes our optimization methodology. In Section 5, we discuss results obtained on the real-world problem, and benchmark our approach against integer linear programming (ILP), chance-constrained programming (CCP) (Charnes & Cooper, 1959) and a baseline meta-heuristic optimizer. Finally, the conclusions derived from this study, limitations and future research directions are given in Section 6.

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https://doi.org/10.1016/j.ejor.2017.10.062

1.1. Production planning in a failure-prone manufacturing system

The real-world problem motivating our research is the production planning problem of a manufacturing company with insufficient capacity to fully cover demand requirements. See Diaz (2016, pp. 30–42) for a detailed description of this manufacturing system.

Under their current operating model, the company has to purchase the materials needed for the next working month before the beginning of the production period. A production plan for the following month must therefore be available in order to make adequate purchasing decisions. This is a challenging task because, at the time when the production plan needs to be developed, specific due dates of orders are still unknown and only demand forecasts are provided. Since due date information is not yet available during the specification of a production plan, scheduling decisions are not considered here.

The production lines in this system are failure-prone which complicates the design of adequate production plans. In particular, the occurrence of production line failures has the net effect of reducing the total number of products that can be manufactured and sold, as labour and production line capacity are limited resources. Once a production plan has been decided and a failure occurs, corrective actions (at the operational level) may combat, but will likely not fully eliminate, negative consequences in terms of production volume, profit and possible penalties. Here, we do not yet explicitly consider the possibility of corrective actions, or the individual types of negative repercussions. Instead, we incorporate the generic presence of negative repercussions by penalizing any deviation from a given production plan.

Given the above, the company in question aims to develop production plans that are not only profitable but are also expected to perform robustly under different realizations of breakdown events. In other words, not only profitability and system constraints have to be considered during the specification of a production plan, but also the uncertainty around the occurrence of failures in production lines.

The specific manufacturing system considered here is a batch processing system where a set-up is required before the manufacturing of every product lot (even between consecutive lots of the same product) and where the technical lot[1] of every product is fixed. Each technical lot has been specified by the company so that an entire lot can be manufactured within one shift. Specifically, a shift has a length of 8 hours, which corresponds to the daily number of hours that an operator needs to work. Therefore, the theoretical manufacturing time for every product lot is defined as 8 hours. This theoretical manufacturing time already considers set-up time and time spent in transportation of necessary resources to and within the production line involved, but it does not consider unexpected events such as delays caused by failures of production lines.

1.2. Model formulation and outline of the methodological approach

In this paper, we provide an extended knapsack formulation of the above problem. The model describes the general situation in which each specific item can be loaded into a set of different knapsacks, but not all knapsacks can carry every item. Furthermore, it allows for the presence of complex uncertainties that affect the implementation of the solution at the level of the individual decision variables.

Given the specific impact of uncertainty at the decision variable level, our formulation also incorporates the ability to explicitly consider deviations from the original packing plan and to penalize those deviations. Moreover, our model introduces several relaxations in relation to the usual linear constraints considered in knapsack problems. This serves to extend the range of applications, as it enables us to consider the case of complementary products, maximum demand levels and marginal costs of products used as raw materials.

In situations involving a significant amount of uncertainty, simulation-based optimization (SBO) provides a suitable mechanism to incorporate complex system features. Specifically, this eliminates the need for a closed-form formulation of certain aspects of the problem. While linear constraints can be incorporated directly into our knapsack formulation, additional non-linear constraints, uncertainties or other complex features may be considered by direct incorporation into the simulation component (see Section 4 for more details).

The absence of a closed-form description of the production system necessitates the use of a black-box optimizer such as a meta-heuristic to search for near-optimal solutions. In this study we describe an SBO approach that combines DES with a genetic algorithm (GA). The optimization performance of our GA is boosted by specialized initialization operators that combine DES, deterministic ILP and CCP in a variety of ways, as described in Sections 4.2.1 and 4.2.2. We demonstrate that our approach is able to outperform the solutions obtained from the separate application of meta-heuristics and mathematical programming approaches.

1.3. General aspects of the problem

Generally, uncertainties in an optimization problem may arise from perturbations on decision or environmental variables, or they may be more closely linked to aspects of the objective function (Jin & Branke, 2005). As explained above, the primary uncertainty in our problem arises from perturbations to the decision variables, which can be modelled via DES.

Given the non-trivial uncertainties inherent to the system, addressing the problem through mathematical programming approaches may require a number of assumptions that are overly stringent, and could impact on the validity of the resulting solutions (Gnoni, Iavagnilio, Mossa, Mummolo, & Di Leva, 2003; Goh & Tan, 2009; Nikolopoulou & Ierapetritou, 2012). The severity of the impact will depend on the levels of uncertainty present in the system or/and on the appropriateness of the assumptions made.

Here, we aim to develop a methodology that is applicable in situations when the uncertainty arises from non-trivial perturbations to the decision variables, but can be described using some form of numerical model (such as DES). An additional prerequisite of our approach is the existence of a suitable exact optimization model for a simplified version of the problem (obtained e.g. through the elimination of all uncertainties). In principle, possible applications of our approach are therefore thought to extend beyond the class of knapsack problems formalized here, and include other combinatorial optimization problems that meet the above two criteria, such as assignment problems.

Section 1.1 has outlined a number of features of the real-world system considered here. It is important to note that the majority of these are not prerequisites for the use of our formulation and methodology. In particular, alternative problem features (such as sequence dependent set-ups, non-fixed technical lots and different manufacturing times across different product lots), could be incorporated through the numerical (simulation) component of the approach (see Section 4 for more details), and through linear constraints in the problem formulation. It is evident that the complexity of the features may impact on the applicability of mathematical programming approaches, and, potentially, on the effectiveness of the initialization strategies introduced in this paper.

[1] The number of items produced per product lot.

Please cite this article as: J.E. Diaz et al., Integrating meta-heuristics, simulation and exact techniques for production planning of a failure-prone manufacturing system, European Journal of Operational Research (2017), https://doi.org/10.1016/j.ejor.2017.10.062