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Control of Flexible Manufacturing Systems under model uncertainty using Supervisory Control Theory and evolutionary computation schedule synthesis

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ABSTRACT

A new approach for the problem of optimal task scheduling in flexible manufacturing systems is proposed in this work, as a combination of metaheuristic optimization techniques with the supervisory control theory of discrete-event systems. A specific encoding, the word-shuffling encoding, which avoids the generation of a large number of infeasible sequences is employed. A metaheuristic method, based on a Variable Neighborhood Search is then built using such an encoding. The optimization algorithm perform the search for the optimal schedules, while the supervisory control has the role of codifying all the problem constraints, allowing an efficient feasibility correction procedure, and avoiding schedules that are sensitive to uncertainties in the execution times associated with the plant operation. In this way, the proposed methodology achieves a system performance which is typical from model-predictive scheduling, combined with the robustness which is required from a structural control.

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1. Introduction

The task scheduling problem in a flexible manufacturing system (FMS) is of great importance in industry. A suitable solution for this problem would achieve an operation free of faults and high efficiency on the use of the resources available in the plant. Without the use of systematic techniques to create the production programs it is not possible to guarantee such features. For that reason, there has been a significant research effort in the last few years to develop systematic tools to deal with such a problem. The scheduling of FMS is a problem far more difficult than the ordinary scheduling of simpler manufacturing systems, due to the difficulty of building reliable models which are able to predict exactly the system behavior. This means that the model uncertainty should be considered in the design of schedules.

With regard to the uncertainty, scheduling problems are traditionally divided in two broad classes [3]: (i) deterministic scheduling problems, also called *model-predictive scheduling* [5,10,36], for which the system behavior is so predictable that it is possible to build models that, given a sequence of inputs, describe the sequence of system states with negligible error; and

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(ii) stochastic scheduling problems [23,27], in which the system is subject to unpredictable disturbances, rendering the system states predictable only in a statistical sense.

In recent years many authors have recognized that there are several manufacturing environments which are mostly deterministic but, notwithstanding, are unlikely to be predictable to the extent that would be required by the deterministic scheduling approaches. Some authors have even stated that the inability of much scheduling research to address the general issue of uncertainty may be considered as a major reason for the lack of influence of scheduling research on industrial practice. Those observations suggested that some efforts should be developed in order to extend deterministic approaches (or model-predictive approaches) to situations in which there is some type of uncertainty. For a review on those efforts, see the reference [3].

In particular, the FMS tend to be inherently susceptible to some uncertainty, due to their characteristic of involving a complex coordination of different operations. This tends to give rise to small differences between the states predicted by the model and the actual deployment of the plant operations, which accumulates over time – eventually leading to a loss of synchronism in the schedule [44]. However, the simple adoption of stochastic approaches would render the scheduling of operations in those systems rather inefficient, due to their complex structure that cannot be captured by simple rules.

Different approaches have been employed in order to solve scheduling problems in FMS in an efficient way. For instance, there are works based on Neural Networks [33], Fuzzy Logic [15] and Heuristic and Metaheuristic methods [2,19,22,35,40]. These approaches use artificial intelligence techniques in order to search for the optimal scheduling. However, in most cases, these approaches do not employ any formal technique that model the behavior of the FMS and assure the structural control[1] of it.

Usually, structural controllers are designed in a conservative way, leading to the rejection of some safe states, in order to enhance their ability to avoid forbidden states [25]. There is a class of works that implements the structural control of the FMS using some modeling technique of discrete-event systems, and uses together some optimization technique to search for optimal scheduling, for instance [16,21,42,45], among others. Those approaches rely on the Petri Nets to implement restrictions on the behavior of the system. In most cases, there is no hint on how to obtain such correct models. The focus of such works is on the integration of the information from the model into the algorithm.

The Supervisory Control of Discrete Event Systems (SCDES) has been developed to design structural controllers for discrete-event systems, automatically determining the commands that can be applied to the system avoiding its evolution to prohibited states, where the system can be damaged or enters in deadlock, while also ensuring that the resulting controller is minimally restrictive – allowing all possible legal command sequences [34]. There are some former works that deal with the problem of scheduling under the SCDES framework, such as [20,32,38], among others. Those works translate optimization problems into the framework of SCDES and propose theoretical solutions and algorithms for the problem. However, those translation procedures are problem-specific, and it is not known if they could be extended to generic FMS scheduling problems. Those procedures also may lead to a substantial increase of the computational burden of the controller design problem.

The problem to be solved in this paper is to find a scheduling that minimizes the makespan for the production of a batch of products, while ensuring the system robustness properties that are associated to the SCDES structural control. The purpose here is to perform an integration of a predictive scheduling (executed by optimization algorithms over a detailed discrete-event model of the plant) with a minimally-restrictive structural control (implemented by the SCDES methodology).

Due to the dynamic nature of the problem under consideration, in which the choices performed in each step determine the available choices in the subsequent steps, the formal setting for solving it up to optimality would be the dynamic programming methodology [6,28]. However, it is well known that such a methodology incurs in computational costs that grow rapidly as the problem size grows, becoming non-practical even for problems of moderate size [7,28]. Heuristic optimization techniques, on the other hand, have been developed as computational tools that can promote the enhancement of the solutions of combinatorial problems for which greedy heuristics lead to solutions far from the optimum and exact methods are excessively costly. Such techniques rely on stochastic procedures which are performed on candidate solutions, progressively converging to the regions of the solution space which feature the most promising solutions [17,37].

In the approach developed in this paper, a heuristic optimization method is applied on a model that implements the problem physical structure and the security and non-blocking constraints, using the SCDES paradigm. The model implements the least restrictive legal behavior using a systematic way to achieve it, based on the application of the Local Modular Supervisory Control of Discrete Event Systems [11], an extension of the classical Ramadge and Wonham Supervisory Control Theory [34]. A specific version of the metaheuristic technique Variable Neighborhood Search (VNS) is employed. This technique has been chosen, from eleven different metaheuristic techniques[2] which composed the portfolio of algorithms that were considered initially.

The methodology presented in this paper is tested on an example problem introduced in [12], and significant improvements have been observed in relation to strategies that are not optimization-oriented, which are typically produced by the greedy approach suggested in [8]. It is also shown that the resulting controller is robust, allowing significant errors in the system model times without compromising the correct functioning of the system.

This paper is organized as follows. The optimization problem is formally presented in Section 2, along with a summary of the proposed methodology. Section 3 presents the example plant that is used in this paper in order to illustrate the methodology. In Section 4, the modeling of the constraints is discussed. In Section 5, the optimization algorithm using the SCDES solution

[1] *Structural control* stands for the control layer that prevents the system entering an illegal (unsafe or blocking) state [3,25].

[2] Eleven algorithms have been considered including, in addition to VNS: two other versions of VNS algorithms, two Clonal Selection Algorithms, an Ant Colony algorithm, two versions of Iterated Local Search algorithms, two versions of a Variable Neighborhood Descent algorithm and a Tabu Search algorithm.

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