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Integrated scheduling of resource-constrained flexible manufacturing systems using constraint programming

Juan M. Novas [1], Gabriela P. Henning *

INTEC (UNL-CONICET), Güemes 3450, S3000GLN Santa Fe, Argentina

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ABSTRACT

This contribution presents a novel approach to address the scheduling of resource-constrained flexible manufacturing systems (FMSs). It deals with several critical features that are present in many FMS environments in an integrated way. The proposal consists in a constraint programming (CP) formulation that simultaneously takes into account the following sub-problems: (i) machine loading, (ii) manufacturing activities scheduling, (iii) part routing, (iv) machine buffer scheduling, (v) tool planning and allocation, and (vi) AGV scheduling, considering both the loaded and the empty movements of the device. Before introducing the model, this work points out the problems that might appear when all these issues are not concurrently taken into account. Then, the FMS scheduling model is presented and later assessed through several case-studies. The proposed CP approach has been tested by resorting to problems that consider dissimilar number of parts, operations per part, and tool copies, as well as different AGV speeds. The various examples demonstrate the importance of having an integrated formulation and show the important errors that can occur when critical issues such as AGV empty movements are neglected.

1. Introduction

Flexible Manufacturing Systems (FMSs) are highly automated production systems, consisting of a computer-controlled integrated configuration of multipurpose workstations, storage buffers and one or more automated guided vehicles (AGVs). These manufacturing environments combine an important productivity with high levels of flexibility and an efficient use of limited resources, characteristics that are required to remain competitive in current markets. To increase the efficiency of the overall FMS, manufacturing activities, as well as transport and storage tasks, need to be properly scheduled. The FMS scheduling activity is affected by many features, such as the specific characteristics of the FMS, the plant in which it is located and its operational policies, the level of automation, as well as the resources belonging to the FMS (Grieco, Semeraro, & Tolio, 2001). The development of good quality schedules that consider all the FMS constrained resources, such as machines, AGVs, tools, buffers, is one of the main operational problems to be tackled in this kind of environment (Blazewicz, Eiselt, Finke, Laporte, & Weglarz, 1991).

FMS scheduling comprises the following problem elements: machine loading, part routing, manufacturing tasks scheduling, tool planning and allocation, as well as the generation of the buffers usage agenda and the AGVs schedule. The FMS loading problem is concerned with the assignment of manufacturing operations to machines, considering resource and technological constraints. Part routing determines manufacturing routes for parts, specifying the sequence of machines that each part visits throughout the system in order to be processed. Manufacturing tasks scheduling defines the start, duration and end times of each machining activity. Tool planning specifies the number of tool instances of each available type that are needed to achieve the production requirements, and the tool allocation problem tackles the tool assignment to the magazines of the various machines. Finally, buffers and AGVs scheduling specify the agenda of the buffers and the transport devices, respectively.

FMS scheduling problems have been extensively addressed during last decades. In order to reduce their complexity, researchers have usually resorted to decomposition approaches, not taking into account all the limiting resources at the same time and/or neglecting some others. Within the vast literature concerning FMS scheduling, there is a set of contributions that considers the tool-related limitations as the most important constraints, leaving aside the transportation issues, and another group that takes into consideration the AGVs as the main limiting resource, neglecting tool aspects. Thus, the literature review presented in this work organizes previous contributions in two main groups; first, the ones that address the job scheduling and tool allocation problems, and then, those that deal with the scheduling of vehicles and jobs in the FMS environment.

* Corresponding author. Tel.: +54 342 455 9175x2102; fax: +54 342 455 0944.
E-mail addresses: mnovas@intec.unl.edu.ar, jmnovas@famaf.unc.edu.ar (J.M. Novas), ghenning@intec.unl.edu.ar, gphenning@gmail.com (G.P. Henning).
[1] Permanent address: CIEM-CONICET/UTN-FRC, Ciudad Universitaria, X5000HUA Córdoba, Argentina.

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Most of the papers belonging to the first group, which tackle the loading machine and tool planning/allocation problems, were published in the last two decades. Atmani and Lashkari (1998) developed a mixed integer linear programming (MILP) model that addresses the FMS loading and tool allocation problem. The formulation takes into account constraints on tool magazines capacity and tools life-time, but does not consider the number of available tool instances. Another drawback concerns the large MILP formulations that are obtained.

Gamila and Motavalli (2003) proposed an approach to address the FMS machine loading, tool allocation and part scheduling problems, which consists of two steps. First, an MILP formulation solves the machine loading and tool allocation problems. Afterwards, a simple heuristic tackles the detailed part scheduling problem. Constraints regarding tool life-time and tool magazines of limited capacity are taken into account. Besides, it is assumed that only one copy per tool type is available, which is not always true in real settings.

Chan and Swarnkar (2006) presented a fuzzy goal programming approach to tackle the machine loading and tool selection problems, as well as the operations scheduling. They included constraints to consider tool magazine capacity, tool life-time, and machine resources as limiting features. The approach assumes that each tool magazine cannot hold more than a single copy of each tool type, which hampers its use in real settings.

Zeballos, Quiroga, and Henning (2010) proposed a constraint programming (CP) formulation that simultaneously considers machine loading, part routing, tool allocation and operation scheduling in FMS environments. It employs two different two-index variables in order to model machining activities, instead of a four index one. This feature considerably reduces the dimensionality of the approach and facilitates the modeling of machine and tool specific constraints. Furthermore, the proposal represents tool management features in terms of tool types. Indeed, the tool instances demand is calculated indirectly, based on tool type, tool life-time, and tool magazine constraints. Despite the fact that the work by Zeballos et al. (2010) is, to the best of our knowledge, one of the most complete contributions regarding tool loading and allocation issues, it has several shortcomings: it assumes that every part requires the same number of operations and ignores all part intermediate storage and transportation features. Simultaneously, Zeballos (2010) emphasized other aspects of the previous CP-based approach, presenting the search strategy that was used to reduce the computational time.

Regarding the second group of contributions, it is worth noticing that although there are many works on the AGV scheduling problem, there are few contributions on the simultaneous scheduling of AGVs and manufacturing activities (Ganesharajah, Hall, & Sriskandarajah, 1998; Vis, 2006). One of the first attempts was made by Blazewicz et al. (1991), who were motivated by an actual FMS environment. To address the machine scheduling and vehicle routing problems, two situations were considered. In the first one, the assignment of jobs to machines is assumed to be known and the goal is to find a feasible vehicle schedule. The second one aims at finding a solution by simultaneously taking into account the assignment of operations to machines and the vehicle routing problem. For the former sub-problem, a simple polynomial-time algorithm was developed, whereas for the later a pseudopolynomial-time algorithm based on dynamic programming was proposed. This algorithm obtains a minimum length schedule with its corresponding feasible AGV schedule. The main shortcoming consists in considering single-operation parts and identical parallel machines. Besides, the proposal was only tested with small size problems.

Bilge and Ulusoy (1995) developed an iterative procedure to address the scheduling of jobs and vehicles. The problem was decomposed into two sub-problems, which were iteratively solved by means of two algorithms. First, machine schedules are generated by means of a set of dispatching rules. Afterwards, for each machine agenda, a feasible AGV schedule is obtained by means of a heuristic based on a sliding time window. In a later work, Ulusoy, Sivrikaya-Serfioglu, and Bilge (1997) presented a genetic algorithm (GA) to simultaneously address the scheduling of machine jobs and automated transport vehicles. In 59% of the test examples, the GA proposal outperformed the solutions reported by Bilge and Ulusoy (1995). The reverse was true for only 6% of the problems.

Liu and MacCarthy (1997) developed an MILP-based model with the aim of addressing storage and AGV related aspects. Its main shortcomings are its size and complexity, even for small problems. Despite these features, the analysis of the formulation provided the basis for the development of two heuristic algorithms, named "loading then sequencing" and "global heuristic procedure", which are also presented in the paper. It was shown that the iterative global heuristic procedure is much more effective than the "loading then sequencing" one.

In recent years, El Khayat, Langevin, and Riopel (2006) developed a mathematical programming model and a constraint programming formulation to tackle the integrated scheduling of production and material handling activities. The two approaches do not cope with the machine loading problem; i.e. it is assumed that jobs have predefined routes. In addition, they consider that machine buffers have unlimited storage capacity. The mathematical and the CP approaches were tested and compared by means of examples proposed by Bilge and Ulusoy (1995), considering two and three vehicles as limiting resources. The CP approach rendered better results in terms of makespan minimization and computational times.

Jerald, Asokan, Saravanan, and Rani (2006) addressed the concurrent scheduling of parts and AGVs using an adaptive GA-based approach. In the environment being considered machines are grouped into cells, which are connected by means of two AGVs. The approach does not cope with the machine loading problem, since part routes are already fixed. Thus, transport times are also prescribed beforehand and considered as part of the processing times. However, it is not clear how deadlocks are prevented. These assumptions make the proposal of little practical use. More recently, Caumond, Lacomme, Moukrim, and Tchernev (2009) presented an MILP formulation that considers one automated vehicle and adopts a "first in first out" (FIFO) buffer management rule. The proposal considers limited input/output machine buffers, but it does not address the part routing problem since each operation can be executed only by a single machine, which is already defined. The proposal does not ensure that a part waiting in the input buffer of a machine will start its operation as soon as the unit becomes idle. Small problems are successfully solved by the MILP formulation, while a heuristic is proposed for larger ones.

As it was previously pointed out, due to simplicity reasons, decomposition-based approaches do not simultaneously consider all the FMS scheduling elements. Some proposals tackle loading and sequencing problems assuming there are no other critical features to address (Prakash, Chan, & Deshmuck, 2011). However, it will be shown in Section 2 that neglecting some of the FMS main features might lead to schedules that cannot be implemented in practice. Therefore, to obtain good quality solutions of industrial relevance, an integrated approach simultaneously coping with all the FMS scheduling sub-problems is required. This work addresses this challenge by presenting a novel CP contribution that holistically tackles the problem. In fact, the proposed formulation simultaneously takes into account the following subproblems: (i) machine loading, (ii) manufacturing activities scheduling, (iii) part routing, (iv) machine buffer scheduling, (v) tool planning and allocation, and (vi) AGV scheduling, considering both the loaded and the empty movements of the device.