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A constraint programming model for the scheduling of flexible manufacturing systems with machine and tool limitations

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ABSTRACT

This contribution presents an integrated constraint programming (CP) model to tackle the problems of tool allocation, machine loading, part routing, and scheduling in a flexible manufacturing system (FMS). The formulation, which is able to take into account a variety of constraints found in industrial environments, as well as several objective functions, has been successfully applied to the solution of various case studies of different sizes. Though some of the problem instances have bigger sizes than the examples reported to date in literature, very good-quality solutions were reached in quite reasonable CPU times. This good computational performance is due to two essential characteristics of the proposed model. The most significant one is the use of two sets of two-index variables to capture manufacturing activities instead of having just one set of four indexes. Thus, dimensionality is greatly reduced. The other relevant feature is the fact that the model relies on an indirect representation of tool needs by means of tool types, thus avoiding the consideration of tool copies.

1. Introduction

Flexible manufacturing systems (FMSs) are considered as one of the most important production technologies to efficiently handle current changes in market requirements. An FMS is a network of workstations interconnected by material-handling devices, where a low or medium volume of parts can be manufactured. It combines an efficient use of resources such as machines, tools, and storage places, with high flexibility. Flexibility is a key issue in current manufacturing systems. It refers to the ability of the system to respond cost effectively and rapidly to changing production needs and requirements. This capability is becoming more and more important as FMSs do operate nowadays in highly variable, dynamic, and unpredictable environments.

In the context of FMSs, the current literature offers several competing definitions and classifications of flexibility types. According to Browne et al. (1984), there are eight different classes, which have been analyzed in various contributions. Two of the most important types are the possibility of performing an operation on more than one machine and the ability of a manufacturing system to use multiple alternative routes to produce a given part (Chan, 2001, 2003, 2004).

The main components of an FMS are shown in Fig. 1. This manufacturing environment has buffers for pre-processed and finished parts and machines have buffers for work in process. In order to execute the required operations on parts, machines need tools, which have a limited life-time and are grouped by type. The system employs one or more tool copies of each type and each copy requires a given number of slots to be placed in the machine tool magazine. Parts are transported from one machine to another by material-handling devices (MHDs).

The general FMS-scheduling problem, as most industrial scheduling problems, is NP-complete (Blazewicz et al., 1991) and only some particular cases do not belong to this category (Brucker, 2003). In fact, as pointed out by Gamila and Motavalli (2003), scheduling and control problems of FMSs are more difficult to solve than those of mass production systems. Their intrinsic complexity originates in the combinatorial nature of the many assignment (of machines, tools, and MHDs) and task (processing and transport) sequencing decisions to be faced. Besides, FMS scheduling has to take into account several technological, capacity, and availability constraints on the limiting resources: machines and their buffers, tools, MHDs, etc.

FMS scheduling embeds the following problems: machine loading, part routing, tool allocation, MHD assignment and routing, as well as task timing. Machine loading concerns the assignment of processing tasks to machines having a limited storage capacity in their associated buffers. Part routing establishes processing routes for the parts to be manufactured during the scheduling period. A processing route is defined as the

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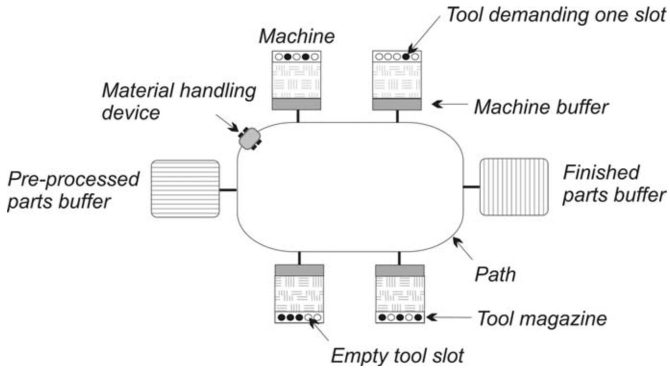

Fig. 1. Schematic representation of an FMS environment (four machines, tool magazines of five slots each, one material-handling device, and buffers for pre-processed and finished parts as well as machine buffers).

sequence of workstations that a given part must successively visit to have all its required operations executed. Tool allocation determines the number of tool copies of each type to be employed and assigns them to machines. On the other hand, MHD loading establishes the allocation of transport tasks to units having a limited transport capacity, whereas MHD routing determines the routes that each device has to follow. Finally, the various tasks (machining, transport, and storage) have to be given start and completion times. All these problems have to be tackled simultaneously while pursuing the optimization of a performance measure.

In industrial environments, schedules are influenced by part priorities and due dates, machine and part release times, cost bounds, machine availability and capability constraints, other resource (fixtures, transportation devices, etc.) availabilities, operation precedence restrictions, etc. In addition, FMS-scheduling problems are strongly affected by the number of tool copies at hand. Veeramani et al. (1992) and Mohamed and Bernardo (1997) emphasized that the lack of proper attention to this number can prevent manufacturing systems from achieving their maximum flexibility and may result in an unacceptable level of downtime, leading to a reduced FMS productivity. Thus, the tool planning subproblem, which determines the required number of tool copies to achieve the production requirements, is another critical issue associated with the problem.

An analysis of the most relevant contributions reveals that most of the approaches reported in literature decompose the FMS-scheduling problem and adopt assumptions that aim at making it tractable. Thus, proposals can be grouped under two categories: firstly, the ones that consider that MHDs represent a limiting resource and secondly, contributions in which tools appear to be the critical component.

Some of the most relevant and recent contributions related to the former case are the ones of Bilge and Ulusoy (1995), Ulusoy et al. (1997), Liu and MacCarthy (1997), Sabuncuoglu and Karabuk (1998), Smith et al. (1999), and El Khayat et al. (2006).

Bilge and Ulusoy (1995) presented two heuristics linked by an iterative solution procedure to deal with the machine and material-handling scheduling problems, without taking into account work in process buffers. The first one generates a machine schedule and the second one finds a feasible solution to the vehicle-scheduling problem given the machine schedule. Later, Ulusoy et al. (1997) developed a genetic algorithm approach that simultaneously addressed both problems. In turn, Liu and MacCarthy (1997) took into account aspects associated with part storage places. Their proposal presented a mixed integer linear programming (MILP) model. However, considering the weak performance of the approach, the authors developed a decomposition method of the type "loading then sequencing".

Other methodologies, different from the mathematical programming ones, have been suggested. Sabuncuoglu and Karabuk (1998) proposed a filtered beam search (FBS) algorithm for scheduling problems in which there is a limited machine buffer capacity. Smith et al. (1999) explicitly took into account loading and unloading tasks as well as transport activities by means of two alternative heuristic methods. More recently, El Khayat et al. (2006) addressed a class of scheduling problem associated with a setting that is common in industry. It corresponds to the case in which parts have fixed routings, each part operation can be executed by just one machine, and machine buffer capacities are not limiting. Two approaches were presented to tackle the scheduling problem: an MILP model and a constraint programming (CP) formulation, which also included a simple search strategy.

The second group of contributions considers that tools are the most critical resource of the system and leaves aside aspects related to MHDs and part storage places.

Within this category, Sarin and Chen (1987) and Atan and Pandit (1996) presented MILP models for the FMS machine loading and tool allocation problem. The first proposal aimed at finding part routings and allocating appropriate cutting tools at minimum machining cost. However, one of its main limitations is that it leaves aside the sequencing and timing problems. Furthermore, it assumes that each operation can be carried out in only one machine. Since the resulting model has a high dimensionality, authors proposed a solution procedure based on the Lagrangean relaxation and subgradient method. On the other hand, Atan and Pandit (1996) introduced a hierarchical method that first considers the machine loading problem, assuming that machines have access to all the required tools, and then tackles the allocation of tools to workstations. Similar to Sarin and Chen (1987), Atan and Pandit (1996) did not take into account the sequencing and timing problems. Their formulation aimed at minimizing the total number of tools.

Roh and Kim (1997) focused on the machine loading, tool allocation, and part-sequencing problems of a particular FMS in which each part stays in only one machine for its entire processing. Their proposal included three heuristic approaches that pursue the total tardiness minimization.

Later, Atmani and Lashkari (1998) presented an MILP model to tackle the tool assignment and machine loading problems. In contrast to Sarin and Chen (1987), these authors considered that a given operation can be assigned to various machines. The formulation minimizes the cost of machining, material handling, and set-ups while taking into account the tool magazine capacity and limited tool life. The resulting approach has the main disadvantage that large-size MILP formulations are obtained. The problem of largest size solved by Atmani and Lashkari (1998) consists of four parts to be scheduled, requiring at most three operations for each one, which should be executed in a manufacturing environment having six machines and seven tools.

More recently, Gamila and Motavalli (2003) addressed, by means of a decomposition approach, the loading and scheduling problems of an environment in which machines have tool magazines of limited capacity and tools have a given life-time. They proposed an MILP model to first solve the assignment of part operations and to determine the number of tools and their allocation to machines. As a second step, they employed a very simple heuristic to generate the detailed part scheduling. One of its main drawbacks is that the machine loading and tool allocation decisions are tackled before addressing the scheduling ones. Since the approach does not deal with the problem in an integrated way,