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Full Length Article

Decision-making method of reconfigurable manufacturing systems' reconfiguration by a Gale-Shapley model

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ABSTRACT

The companies need to rapid response to new product introduction, mix and demand changes to stay competitive. A reconfigurable manufacturing system can quickly react to changes in products and market. The control method to reconfigure the machines of a reconfigurable manufacturing system is crucial for the performance level. This paper proposes a reconfiguration decision-making method based on a Game-Theory algorithm, and in particular the Gale-Shapley model. A periodic review strategy is used to create two sets: one set of machine over-loaded and one set under-loaded. The Gale-Shapley model forms a coupled of over-loaded and under-loaded machines. The reconfiguration concerns the under-loaded machine of the coupled adding also the task performed by the over-loaded machine. This paper presents a simulation environment developed to evaluate the proposed method and highlight the main topics. The simulation results highlight how the game-theory approach developed improves all the performance measures with controlled number of machines' reconfigurations.

1. Introduction

The frequent introduction of new products, unpredictable changes in demand and mix, changes in technology force the companies to react to these changes rapidly and at low costs. In this environment, the companies need to adopt manufacturing systems able to quickly react to the changes efficiently.

A reconfigurable manufacturing system (RMS) is able to rapid change in its structure (hardware and software items) to quickly response to market or intrinsic system changes [1]. RMSs can provide the functionality and capacity needed, exactly when needed (Bader et al. [39]). This allows to increase the responsiveness of the production systems and improve the competitiveness in the global context. The strategic goal of a RMS is to develop a responsive manufacturing system to cope with unpredictable market changes as: new products introduction; product demand changes; and, product mix changes [2]. The structure of these machines is modular and includes basic/essential modules and auxiliary modules [3]. The structure of the RMS machines provides the option of adding or removing auxiliary modules to the machine to change the functionality and process capability of the machine. The analysis of some machines with reconfigurable part available on the market highlighted how the reconfiguration time can be less than 2 h [4]. The costs bound the number of modules to reconfigure the machines of a production system. Thus, the allocation of the modules to the machines (configuration and capability of the machines) is important for the performance of the manufacturing system. The methods to select the optimal configuration of the RMSs suggested in literature are often difficult to apply in industrial cases [2]. However, the configuration of the reconfigurable machines of a manufacturing system facilitates or impedes the productivity, responsiveness, convertibility and scalability. Therefore, the numerical evaluation of the performance in different configurations is important before the investment in reconfigurable machines is made. The main directions of the past works related to this paper concern:

- The optimal reconfiguration policies that considers: the capacity scalability [5–8]; multiple objective optimization of RMS configuration based on convertibility; machine utilization and cost by applying genetic algorithm [9]; optimal reconfiguration policy to react to product changes [10]; and models based on Genetic Algorithms and Tabu Search, [11,12];
- the optimal configuration selection based on genetic algorithms [13] and approaches based on NSGA II, TOPSIS, Shannon entropy weights [3].

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Some works concern the reconfiguration when an exception occurs as machine failures. Bruccoleri and Pasek [14] studied the reconfigurations when failures occur detecting when the reconfigurations improve the performance; further, Bruccoleri et al. [15] included other exceptions for the reconfiguration supported by Multi Agent System architecture.

Another problem studied concerns the capacity scalability using reconfigurable machines. Deif and ElMaraghy [6–8] proposed several approaches to handle the capacity scalability with reconfigurable machines. They proposed a Genetic Algorithm that includes cost of the physical capacity unit and system reconfiguration. LaVie [16] proposed a model of capability reconfiguration to support the choice of reconfiguration mechanism. He provided an analysis of the types of nature of technological change and capability attributes for the reconfiguration mechanism selection. The model was only described but no analytical analysis is presented. Some works investigated the capacity scalability in different configurations of flow line by the simulation [17] or meta-heuristic global optimization technique as genetic algorithm and Tabu-Search [18,19]. The mathematical models proposed were complex (time consuming or even computationally intractable) and focused on a particular context (flow line with parallel machines).

This paper proposes a method to allocate the modules to the reconfigurable machines assigning the number of technological operations that a machine can make in a general job-shop context. The approach proposed is based on game-theory and, in particular, the Galey-Shapley algorithm is adapted to the case studied. This reduces the computational complexity and the time consuming to perform the model proposed. For example, one application of Game Theory was proposed for the case of reconfigurable enterprises [20] that cooperate in a production network [21]; these enterprises can be reconfigured to gather a specific production objective. The Gale and Shapley [22] algorithm is simple to apply and when preferences are strict, the deferred acceptance algorithm yields the unique stable matching in $O(n^2)$ time that is Pareto superior to any other stable matching from the viewpoint of the first proponent.

The referenced context of the manufacturing system is the same used in several Workload Control works [23,24] to evaluate the benefit compared to Workload Control policies. The main objective of this work is to propose a model that supports the reconfiguration activities of the machines to obtain an efficient configuration in terms of responsiveness and performance measures. The model proposed overcomes the limit of the workload control policies in general job-shop manufacturing systems.

The paper is organised as follows. Section 2 discussed the literature review about the Reconfigurable Manufacturing Systems. Section 3 describes the manufacturing system context investigated and the proposed model based on game-theory. The simulation model developed proposed is described in Section 4, while the numerical results are discussed in Section 5. Section 6 provides the conclusions and future research path.

2. Literature review

Some recent works underlined the importance of the integration of the RMS with other control strategies of the manufacturing system. For example, Jimenez et al. [25] collected data from 314 plants worldwide analysed by a series of canonical correlation analyses. The main results of the survey concern: the importance of the integration of RMS with other organizational programmes (JIT, HR, TPM and TQ) and technological program (group technology). In fact, the model proposed in this paper integrates the workload control policies used as a production control in the job-shop context.

Another problem addressed was the capacity scalability of the RMS when the demand and mix changes.

Koren et al. [26] studied the design-for-scalability principles to get the exact capacity needed to satisfy surging market demand. They proposed a model to reconfigure and rebalancing the RMS with capacity expansion (adding machines). A genetic algorithm with the optimization objective of minimising the total number of machines, or maximising the system throughput supports the model. The approach proposed in this paper reconfigures and rebalance the RMS without adding new machines in an operational time horizon.

Gupta et al. [27] developed a model to identifying and select the preferred system configurations based on performance in early phases of design. The configurations are analysed considering several criteria using the entropy-based analytical hierarchy process. Their work did not consider uncertainty in the input data values considering product families with varied demand.

Reza Abdi and Labib [28] addressed the impact of product family life cycle on the RMS's capacity adjustment. The model developed is based on Markov analysis considering end of product life cycle. They assumed that all the workstations have equal capacities to help prevent bottlenecks, and proposed the study of bottlenecks in future research.

The reconfiguration models to support the manufacturing systems in short-term planning concern mainly the cellular manufacturing systems composed by reconfigurable machines.

Renna and Ambrico [29] studied the cellular manufacturing systems composed of reconfigurable machines. They proposed three linked mathematical models for the design, reconfiguration and scheduling stages. Each mathematical model provides the information to the sequent model. The middle mathematical model performs the reconfiguration activities at fixed periods to handle the demand changes. The decomposition of the problem in three linked models reduces the computational complexity and use the proposed model with more complex manufacturing systems.

Eguia et al. [30] studied the module allocation in cellular manufacturing systems composed by reconfigurable machines. The modeled the problem by a MILP model to minimize the total costs and balancing the workload. As argued by the author, the main limits of the research are: proposed approach should be validated through simulation considering disturbances and the MILP may become impractical for large sized problems due to the excessive computation time required; this paper overcomes these two limits.

One of the risk of the reconfigurable models is the frequent changes of configuration reduces the possibility to control and plan the supply chain operations as highlighted by Chandra and Grabis [31]. Therefore, in this paper the number of reconfiguration changes is studied.

The previous works have limits and assumptions that have to be pointed out: several studies concern the design configurations and capacity scalability of RMSs; the models proposed using heuristic algorithms as GA or mathematical models with high computational complexity; few works concern the study of the reconfiguration to handle uncertain conditions in the working stage.

The researchers highlight how the mathematical and heuristic algorithms could be impractical for large sized problem and did not include the bottleneck analysis.

The research proposed in this paper overcomes the scientific literature in these issues:

- It is proposed a method to reconfigure the machines during the working stage of the manufacturing system to handle uncertain conditions; this method includes the bottlenecks and considers the comparison with workload control policy. Then, the proposed reconfiguration method shows how the introduction of reconfiguration machines could be competitive with production control policy proposed in literature (workload control).