Auction-Based Mechanism for Job Allocation in Hybrid Manufacturing Planning and Control Architectures

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In modern manufacturing environments, effective allocation of production resources is crucial for addressing new market challenges. This work proposes an auction-based mechanism for horizontal bargaining within a semi-heterarchical architecture. The mechanism is built around three critical functions: activation, evaluation, and bidding. Particularly noteworthy are the two distinct evaluation approaches proposed to ascertain the value of jobs for auction. The first approach, inspired by a M/G/n queue model, aims to estimate the potential impact of a job on production line throughput. The second approach is strategically focused on strengthening the decision-making capabilities of the lower-level controller. It evaluates how the inclusion of the auctioned job could broaden the range of operational choices at the lower level, potentially optimizing system performance. Through a preliminary simulation study, we examined the effectiveness of this auction-based mechanism across a spectrum of scenarios. The results show that the proposed approach effectively aligns production processes, especially in settings where job distribution and processing time variability are critical.

Key words: Auction-based mechanism; Semi-heterarchical architecture; Manufacturing planning and control; Stochastic modeling

1. Introduction

The challenges posed by Industry 4.0 in manufacturing planning and control (MPC) require agile and responsive production systems that can efficiently allocate resources (Borangiu et al. 2020, Ivanov et al. 2018). Among various MPC architectures, semi-heterarchical architectures have emerged as a promising approach, combining the advantages of hierarchical coordination and decentralised reactivity (Antons and Arlinghaus 2022). In the architecture proposed by Grassi et al. (Grassi et al. 2020), High-Level Controllers (HLCs) coordinate production processes at a higher level of abstraction, while lower-level controllers focus on executing tasks and managing local resources. A key component of this architecture is the Job Ready Queue (JRQ), a virtual job queue positioned before the production system that contains jobs awaiting insertion by the dispatcher.

This work introduces an auction-based mechanism to facilitate horizontal bargaining between HLCs, enhancing job allocation and resource utilisation. The mechanism aims to improve decision-making and operational flexibility within semi-heterarchical structures by enabling HLCs to negotiate and exchange jobs based on their suitability and potential impact on production performance.

2. Proposed Auction-Based Mechanism

The proposed auction-based mechanism consists of three key functions: activation, evaluation, and bidding. A sealed bid second-price auction, also known as a Vickrey auction, was chosen for this mechanism because of its ability to ensure the highest degree of cooperation among participants.

2.1. Activation Function

The activation function is responsible for identifying the suitable jobs for auction. In the proposed case, the HLC monitors the JRQ and triggers the auction process when a job has remained in the queue for a pre-defined duration, indicating that it may benefit from being allocated to a different HLC.

2.2. Evaluation Function

The evaluation function plays a crucial role in determining the value of an auctioned job. In this work, we propose two distinct approaches to job evaluation, each grounded in stochastic modelling principles. The main conceptual difference between the two approaches lies in their focus: the first approach aims to estimate the impact of the auctioned job on the system's throughput, while the second approach focusses on enhancing the decision-making capabilities of the lower-level controller by considering the potential impact on the range of operational choices.

2.2.1. M/G/1 Queue Model Approach The first evaluation approach is inspired by the M/G/1 queue model, which assumes exponentially distributed interarrival times and generally distributed service times. The idea is to use the M/G/1 model to evaluate the cycle time before and after the addition of the auctioned job, in order to assess the impact on the line's throughput once the job has been accepted. The relative increase in throughput is the key metric in this approach.

- Calculates the cycle time of the queue (CT_{q_i}) for each machine i as follows:

$$CT_{q_i} = \left(\frac{1+c_i^2}{2}\right)\left(\frac{u_i}{1-u_i}\right)(t_i) \tag{1}$$

where u is the machine utilisation and t_i and c_i are the mean and the coefficient variation of processing time of jobs for machine i.

- Evaluate TH with Little Law with the auctioned job j (TH_j) and without (TH).
- Then the evaluation of the acution job j, P_j is obtained:

$$P_j = \frac{TH_j - TH}{TH} \tag{2}$$

2.2.2. Symmetric Point Analysis Approach The second approach is based on symmetric point analysis. For each HLC, a matrix containing the processing times of the jobs in the JRQ for each machine is considered. The evaluation function considers two points in space: I, which represents the point of imbalance of the job in the JRQ without the auctioned job, and I_j, which represents the auctioned job j. The evaluation function follows these steps:

- Calculate the average processing times (t_i) of the jobs in the JRQ for each machine i. This results in a $[1] \times [m]$ vector T containing the average processing times for each machine:

$$T = [t_1, \ldots, t_m] \tag{3}$$

- Define the desired Imbalance point I as:

$$I = -1 \cdot T \tag{4}$$

- Evaluate the distance P_l between I and I_j:

$$P_j = \sqrt{(i_{j,1} - t_1)^2 + (i_{j,2} - t_2)^2 + \cdots + (i_{j,m} - t_m)^2} \tag{5}$$

where $i_{j,k}$ represents the component of I for machine i and t_i represents the average processing time for each machine.

2.3. Bidding Function

The bidding function determines the value that each HLC proposes to an auctioned job based on the evaluation results and the HLC's current production goals and constraints. The bidding function considers three components: the evaluation result, the relative wealth of the HLC (R), and the ratio of the target cycle time to the actual cycle time (VAR_{CT}). The bid value is determined as follows:

$$Bid = P_j \cdot R \cdot VAR_{CT} \tag{6}$$

3. Conclusion

This work presents an auction-based mechanism for job allocation in hybrid manufacturing planning and control architectures. The proposed approach leverages the principles of auction theory and stochastic modelling to enhance decision-making and operational flexibility within semi-heterarchical structures. A preliminary simulation study evaluated the effectiveness of the auction-based mechanism across various scenarios with different distributions of job processing times and production line configurations. The results demonstrated that the auction-based mechanism outperformed traditional job allocation approaches, particularly in scenarios with high variability in job processing times. The mechanism's ability to dynamically allocate jobs based on their potential impact on production performance led to improved throughput and resource utilisation. The two evaluation approaches proposed in this work proved to be effective in capturing the stochastic nature of job processing times and providing valuable insight for informed decision making.

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