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Controlling delivery and energy performance of parallel batch processors in dynamic mould manufacturing

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ABSTRACT

Given the mounting concern about service levels and environmental sustainability, mould industry is facing growing pressure to improve delivery reliability and energy efficiency. While heat-treatment operation is a bottleneck that affects related performances in mould manufacturing. Effective production control of this operation is essential to improve the on-time delivery and reduce the energy consumption of the mould. The operation often involves parallel batch processors and incompatible jobs, which allows for simultaneous processing yet with same job family and different weights and due dates. This paper considers the batch process control of parallel processors for dealing with such non-identical jobs in dynamic environments. An event-driven look-ahead batching strategy called MLAB-DE has been proposed. In MLAB-DE, the individual decisions for each family excluding the effects of these decisions on other families are suggested firstly. Then each alternative decision by including its effects on all families is evaluated. MLAB-DE is used to control two kinds of conflicting objectives related to the delivery and energy performances and finally achieve trade-off based on two-level compromise programming model. Simulation study is conducted to verify the effectiveness of the MLAB-DE strategy and show that the results are promising as compared to benchmark rules.

1. Introduction

In the mould industry, there is always a need to meet customers' demands in terms of higher quality, shorter due date and lower cost to survive in the competitive business environment. As a critical tool for the manufacturing process, the delivery time of a mould is a key determinant of the final product's time-to-market [1]. Currently, however, one of the biggest challenge faced by the mould industry is to improve delivery performance. Late delivery seriously leads to lost sales and loss of goodwill. On the contrary, companies offering more reliable delivery have a better chance of retaining customers and receiving subsequent orders.

In recent years, mould manufacturing enterprises are also facing growing pressure to reduce their carbon footprint given mounting concerns related to climate change. This pressure will become even more significant in the future due to the increasing cost of energy, resulting from both likely taxes and regulations related to carbon emissions as well as increasing energy demands from developing countries [2]. These environmental and economic factors provide motivation for substantial initiatives directed at improving energy performance in mould industry.

Many studies have shown that effective production control has a huge influence on the delivery performance of manufacturing enterprises (e.g. Stevenson and Hendry [3], Land and Gaalman [4]). Manufacturing scheduling strategies are crucial to help mould enterprises meet increasingly high customer demands and expectations as mould market become more competitive in the present manufacturing climate. On the other hand, previous research related to improving energy performance has largely centered on developing more energy efficient machines and processes [5]. Rather than focusing on updating individual machines or processes to be more energy efficient, attention should be directed at system-level changes that could realize significant energy benefits [6]. Moreover, optimized shop schedules should require fairly small capital investments relative to hardware changes in system/process equipment. But such efforts have not yet received adequate consideration.

One of the key issues of mould production planning and control systems with delivery and energy objectives is to control the heat-treatment processing. In mould manufacturing process, heat-treatment is needed by most parts of mould production between conventional machining and finish machining [1]. This processing operation largely affects the precision, intention and life-span of the finished mould. The processing time of mould heat-treatment

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are generally long, to ten hours, or even several tens of hours. Moreover, the heat-treatment furnace is a kind of exiguous resources and thus often becomes the bottleneck resource leading to frequent delay of heat-treatment operation. In addition, heat-treatment is a high-energy operation. According to the China Heat Treatment Association, more than 50% of the energy is consumed by the heat treatment operation in mould manufacturing, auto parts production and other industries. However, the energy efficiency of the heat-treatment production is still low in China (average unit energy consumption is up to 600 KW h/t). Therefore, developing appropriate scheduling approaches to improve delivery and energy performance of heat treatment production is an urgent practical problem mould industry is currently facing.

The production control problem of mould heat-treatment shop is very complex due to several factors. Firstly, heat-treatment furnaces that can produce multiple parts of moulds are referred to as batch processors (the one that produces one part are referred to as serial processor). Batch capacity is limited by the maximum loading weights of the furnace. Once the processing starts a batch, it cannot be interrupted in the sense that no part can be inserted into or removed out from the furnace until the processing is completed. If a batch weight equals to the batch processor's capacity, it is referred to as a full batch, and otherwise a partial batch. 'To start the machine now or to wait for the next part to arrive' is the typical decision problem, which is called batch process control in the literature. Secondly, stochastic factors in mould manufacturing further increase the complexity of the batch process control. Each potential mould order is made according to the client's specification, which tends to be for a differing number of units, due-date, BOM structure and requires varying routings and capacity requirements through the production facilities (see Silva et al. [7] and Liu et al. [8]). Hundreds of different moulds compete for the same resources at the same time and require different materials. One kind of material is referred to as job family. The mould parts with different families cannot be processed in a batch. Heat-treatment operation is in a sequential production system in which parts arrive to the batch shop after their process is completed at the upstream operations. Due to the non-repetitive characteristics of mould manufacturing, the production lead time of parts in the upstream operations can only be determined gradually rather than accurately known in advance. Various emergencies stochastically occur in manufacturing process, e.g. repairing and due date changing. Thus batch process control for mould heat-treatment has to face strongly dynamic and uncertain environments of job arrival. Finally, the delivery and energy performance objectives must be considered at the same time.

This research focuses on the dynamic control of parallel batch processors in the uncertain environments of job arrival, which is subject to incompatible jobs with different weights and due-dates. Dynamic batch process control is the use of real-time strategies that review the state of the batch processor system at specific decision points to find the best batching scenario [9]. Decision points are the time epochs on which either the batch processor becomes available while there are jobs waiting in its buffers or an arrival occurs at its buffers while the batch processor is available. The best batching scenario can achieve the optimisation of the performance measures. The control has to focus the upcoming jobs whose future arrival time can be relatively accurately predicted from the upstream operations in the uncertain environments. Look-ahead batching (LAB) is a very popular dynamic batch process control strategy in the literature, as it includes a limited amount of forecast data on near-future arrivals in deciding on the contents of the next batch to be loaded [10]. In this paper, we propose a dynamic batch process control strategy using look-ahead batching to control the delivery- and energy-related performance measures in the mould heat-treatment production. In the remainder of this paper, the new control strategy will be called MLAB-DE (Mould: Look-ahead batching for delivery and energy objectives) strategy.

The rest of the paper is organised as follows. In Section 2, a short review of the batch process control is provided. In Section 3, the mould batch processing system is described with the problem definition, where the uncertain parameter model for determining the arrival time of jobs and the performance measures for batch process control are introduced. The MLAB-DE strategy for the optimisation control of mould batch processors is introduced in Section 4. To show the effectiveness of the proposed strategy, a simulation experiment is designed and the outcomes are analysed in Section 5. Conclusions and future works are given in Section 6.

2. Related literature

Production control of batch process has attracted wide interests. The motivation for batching jobs is the gain in efficiency—it may be cheaper or faster to process jobs in a batch than to process them individually [11]. The control of batch processors used in many manufacturing environments has received much attention in the literature, e.g. food processing, semiconductor manufacturing and mould manufacturing, see Mathirajan and Sivakumar [12], Tajan et al. [13], Liu et al. [1] and Cheng et al. [14]. Early researches in this domain mainly focus on cycle-time related performance objectives, e.g. minimising makespan. But last decade, as the market competition becomes more intense, and manufacturing systems become more complex, some other optimization objectives have been receiving more and more attention. Where delivery-related performance objectives are emphasized most, e.g. minimising weighted tardiness (e.g. Gokhale and Mathirajan [15], Xu et al. [16], Chiang et al. [17]). Very recently, little researches also have begun to focus on environmental sustainability-related performance, e.g. minimising carbon dioxide emissions, see Liu et al. [6].

The control problem for parallel batch processors is an important branch of the field of batch process control in the literature. The developed strategies for controlling parallel batch processors could be classified as follows. Literature in the static problem domain mainly focuses on the scheduling issues. All the jobs are ready at the beginning and the scheduling problem is how to form the batches for the jobs and determine their sequence. Lu and Yuan [18] focuses on minimising makespan for unbounded parallel batch scheduling with job delivery. Kashan et al. [19] introduce a scheduling problem of parallel identical batch processors with arbitrary job sizes. They develop a hybrid genetic heuristic (called HGH) to minimise makespan objective for the problem. Li et al. [20] propose several heuristics based on best fit longest processing time for scheduling unrelated parallel batch processing machines to minimise makespan. Li and Zhang [21] present a serial batch scheduling on uniform parallel machines to minimise total completion time. The application related researches is quite limited in mould manufacturing, because the information of the future arrivals is in fact dynamic and uncertain.

To make the batch process control closer to the real world, the situation of dynamic arrival should be considered. The principle is to evaluate the related performance measures at different time instants after starting the batch operations. The dynamic problem domain can be categorised into two groups based on the available amount of future arrival information:

The jobs are deterministic dynamic arrivals. Full knowledge on future arrivals is assumed to be available to the decision maker. This group can degenerate into a global deterministic scheduling problem. Due to the complexity issues, only special cases of the problem with limited size can be solved. Various approximation algorithms appear to be dominant in this field, e.g. metaheuristics. Malve and Uzsoy [22] develop a genetic algorithm for minimising