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A Comparison of Different Solution Approaches to Simultaneous Manufacturing Kanban Design and Scheduling

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ABSTRACT

This paper evaluates several artificial intelligence heuristics for the simultaneous Kanban system design and scheduling on flexible manufacturing systems. The objective of the problem is to minimize the total production cost that includes due date penalty, inventory, and machining costs. We show that the simultaneous Kanban design and scheduling decisions are critical in minimizing the total production cost (approximately 40% cost reduction over scheduling without Kanban design decision). To identify the most effective search method for the simultaneous Kanban design and scheduling, we evaluated widely known artificial intelligence heuristics: genetic algorithm, simulated annealing, tabu search, and neighborhood search. Computational results show that the tabu search performs best in terms of solution quality. The tabu search also requires much less computational time than the genetic algorithm and simulated annealing.

1. INTRODUCTION

This paper investigates the use of artificial intelligence heuristics as a means of concurrently determining Kanban design and production schedule of customers' orders. The decision problem is defined as follows. A manufacturing system employs a Kanban-based pull system with a flexible manufacturing system. The flexible manufacturing system consists of a series of work centers. Each order consists of multiple units of finished products. The machines in the system are dedicated to processing at most one unit of each order, and the unit can be processed on at most one machine at any time. The customers' orders must be processed in the same sequence by each of the serial machines, given the processing times of the unit of each order on each machine. Kanban is used to control the work-in process (WIP) inventory. There are a limited number of Kanban containers between work centers. Each Kanban container can contain a certain amount of WIP inventory. Kanban containers move WIP parts between work centers. The objective of the above decision problem is to make Kanban design and scheduling decisions to minimize the total production costs.

Traditionally, process design and scheduling have been considered two separate manufacturing decisions. Decision flows sequentially from an upstream design and engineering function to a downstream manufacturing function. Engineering function determines plant layout and process design based on the product design and products' sales estimates. Subsequently, manufacturing function determines production schedules based on the actual demand or demand forecast of products. Due to the sequential nature of the decision-making, the feedback from the manufacturing to engineering is long and costly. In make-to-order production system, production schedules change dynamically based on the market needs with a fixed manufacturing process. Recently, computer integrated manufacturing has opened an opportunity for a rapid integration of process design and scheduling.

The objectives of our research are three-fold: (1) to design a solution representation for artificial intelligence heuristics that incorporates both Kanban design and scheduling decisions; (2) to perform a sensitivity analysis on the number of Kanban containers, due date penalty cost, and inventory cost; and (3) to compare and improve the performance of artificial intelligence heuristics. The rest of the paper is organized as follows: In section two we discuss the Kanban-based manufacturing facility and decision problems. In section three we compared sequencing with Kanban design and sequencing without Kanban design on some sample problems. In section four we compare four artificial intelligence heuristics and present the improved two-phase tabu search for the Kanban design and sequencing problems.

2. KANBAN DESIGN AND DECISION PROBLEM

The motivation of this study comes from integrating Kanban design and scheduling decisions for customer orders to minimize the total production cost. Kanban design is typically concerned about deciding the number of Kanban containers and the capacity of each Kanban container. Scheduling is concerned about determining production sequence of customers' orders. While these two decisions are typically made independently of each other, they can have a tradeoff effect on the total production cost. For example, the primary objective of Kanban design is to minimize inventory cost and improve product quality. On the other hand, the objective of the sequencing is to minimize the makespan or due date penalty cost. Since these two objectives usually conflict with each other, the decisions should be made simultaneously to minimize the total production cost. In the following, we discuss the problem in the context of a metal part manufacturing system followed by the discussion of the objective function.

The system consist of the sequence of a saw machine, a drill, an inspection machine, a plasma burn, a harden furnace, a temper furnace, a paint booth, and a banding and palletizing machine. A certain number of Kanban containers are located between machines. The system uses these containers between the workstations to regulate inventory and production. When a container reaches its maximum capacity, the upstream workstation stops producing that part type. A simple pull system is used to trigger the upstream production of metal parts. Customer orders trigger production of metal parts at the banding and palletizing machine. As soon as a Kanban container is empty at the banding and palletizing machine, the container moves to a paint booth and joins a queue waiting for part painting. Within this system, machines located along the production line only produce desired amount of work-in-process metal parts when they receive an empty Kanban container. At the top, raw bar stock is fed into at the saw machine from the inventory site. All metal parts require identical process routings but different processing times. The time required to set up a machine for processing a specific metal part usually depends on the kind of metal part processed previously on the machine. In other words, the setup times on the machines are sequence-dependent.

Recently, more and more manufacturing companies are using an electronic Kanban system instead of a paper-based Kanban system. They have deployed advanced manufacturing technologies such as computerized process control, automatic guided vehicles (AGV), and computerized short setups for change of jobs. Large manufacturing companies such as GM and Ford have used Electronic Data Interchange (EDI) technology to achieve an effective Just-In-Time inventory control and supply chain management.

In this paper, the objective function measures the total production cost with three decision variables: the number of Kanban containers between work centers, the capacity of each Kanban container, and the sequencing of customer orders. Each order is an indivisible production element that needs to be delivered to customers on the due date. Each order triggers successive production events from downstream to upstream according to the production process. If a Kanban-triggered production is completed, there is no delay in moving the Kanban container to its downstream work center. A final assembly for a specific order starts after all required parts arrive at the assembly stage. In the scheduling of metal fabrication and assembly tasks, due dates play a significant role in minimizing the overall production costs. Substantial due date penalty cost may occur when products are delivered late, and unnecessary inventory carrying costs can occur when component or assembly tasks finish early (Faaland and Schmitt 1987). It is also important to minimize machining cost in order to reduce the total production cost. The total production cost function assumes an implicit tradeoff since minimizing due date penalty cost may increase inventory carrying costs and machining costs.

3. A PRELIMINARY STUDY OF KANBAN DESIGN AND SCHEDULING

In order to study the impact of the simultaneous Kanban design and sequencing decisions on the production cost, we compared the performance of (1) sequencing with Kanban design and (2) sequencing without Kanban design on sample problems. The objective function determines the production sequence, the number of Kanban containers, and the capacity of each Kanban container to minimize the total cost.

The scheduling task involves determining the production sequence of customers' orders. We assume that there are five work centers and four spaces between two workcenters where Kanban containers are located. The work centers have to be set up when the type of job changes and the time for setting up the work centers depends on the type of job that was processed last. The number of Kanban containers and the capacity of the Kanban containers are also represented in an integer form.

In our preliminary experiments, we assume that a manufacturing system processes 8 to 25 different orders, each order requiring order units of 20 to 60. The maximum number of Kanban containers is set to 20 and the maximum capacity of each Kanban container is set to 20 units. The manufacturing system consists of five serial work centers, each processing a single operation. The sequence-dependent setup times of the order types were generated randomly from the range [25, 125]. The processing times for each unit product within an order were generated randomly from the range of [2, 6]. Due date for each order was randomly generated with a formula of the due date tightness factor* {uniform distribution of [1, 0.5 * (average setup time + total processing time for all orders)]}. Note that a smaller number of due date tightness factor results in shorter due dates for orders.

To understand the effect of simultaneous Kanban and scheduling decisions on the production cost, a tabu search method was used to develop an optimal/near-optimal solution to the problem where sequencing with a Kanban design and sequencing without a Kanban design were considered, respectively. Due date tightness factor was set at 0.5. The experiments replicated 10 problems for each problem size. Sequencing with a Kanban design decision has a significant performance improvement over sequencing without a Kanban design decision (24.24% to 42.90% performance advantage). This result strongly suggests that the scheduling decision without considering a Kanban design may be suboptimal at best under a dynamic market environment.

4. A COMPARISON OF HEURISTICS FOR KANBAB DESIGN AND SCHEDULING

Several well-known artificial intelligence heuristics such as genetic algorithm, simulated annealing, and tabu search have been used to solve complex optimization problems such as sequencing and traveling salesman problems. Since it is known that in solving certain problems, certain heuristics are more suitable than other heuristics, a question arises what kind of heuristics are most suitable for the problem we discussed. We compare four heuristics described in section three: tabu search (TS), simulated annealing (SA), genetic algorithm (GA), and neighborhood search (NS).

Results were evaluated using the consistency of solution quality and computational time. In all comparisons, the pair-wise t-tests were performed at a significance level of 0.05. We evaluated the consistency of the solution quality using an average relative percentage deviation (ARPD) from the best-known solution returned in all the runs.

We examined 24 problem sets of varying sizes. Each problem set had 10 replications. The 24 problem sets were obtained by varying the number of orders (8, 10, 13, 15, 20, and 25) and the number of work centers (3, 4, 5, and 6). The results of 10 runs for each problem set have been averaged.

The solution quality of the tabu search was better (significance level of 0.05), with less computational time, than that of the simulated annealing and genetic algorithm across all problem sizes. As expected, the neighborhood search performed worst, but needed the smallest computational time. When the number of orders was small, the overall solution quality of the genetic algorithm was comparable to that of the simulated annealing but the genetic algorithm took more than two times longer than the simulated annealing. We also observed that the solution quality of the genetic algorithm deteriorated rapidly as the number of orders increased from thirteen to twenty five.

As the number of work centers increased, the overall solution quality deteriorates in all heuristics except for the tabu search. All heuristics needed more computational times. This result may be attributable to the fact that as the number of work centers increases, the problem complexity increases. While the previous heuristics have shown to be effective in escaping local optima, it is well known that when the solution space is extensive, premature convergence may occur. Based on the experimental results, the tabu search was selected to further improve the solution quality and computational time. We name the previous tabu search as one-phase tabu search.

To further improve the solution quality and computational time, we present a two-phase tabu search. To enhance a tabu search capability, a domain-specific knowledge is used to ramp-start the solution search process. The two-phase tabu search incorporates the order-based sequencing. The order-based sequencing for customers' orders focuses on minimizing due date penalty costs. Starting from the order-based sequencing which minimizes the due date penalty, the subsequent search focuses on minimizing the total production cost.

The solution quality of the two-phase tabu search was better (significance level of 0.05), with less computational time, than that of the one-phase tabu search, except for seven problem sets out of twenty four problem sets. On average, the two-phase tabu search was 0.72% better in solution quality with 3.24% less computational time. The difference in the solution quality was especially pronounced at the early stage of the search. The results can be attributable to the synergy between the order-based sequencing and tabu search: the order-based sequencing minimizes the due-date penalty more effectively, and the second-phase tabu search minimizes the total production cost.

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