PROCESS DESIGN FOR EFFICIENT SCHEDULING

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Abstract: For manufacturing, management needs to make rapid, informed strategic decisions to react to changes in the market place. In many of these cases the decisions will give rise to a redesign of the manufacturing processes (layout, changes in product mix and volumes), which in turn changes the nature of the scheduling problems associated with the production facilities. However, the necessary skills and time in bridging the gap between design and scheduling are not available to allow managers to evaluate the many different high level decisions. In this paper, we propose an architecture which brings some scheduling capabilities to managers and planners. This approach is evaluated on two real-life design scenarios considered by a manufacturing company.

Keywords: Design, Process models, Scheduling, Constraint satisfaction problems

1. INTRODUCTION

Manufacturing environments are never static: technology becomes obsolete, demand fluctuates, rapidly changing markets dictate the necessity to vary the range of products, reduce inventory or deploy new resources. Indeed, agility [Nagel et al., 1991] and adaptability [Katayama and Bennett, 1999] of a manufacturing enterprise are increasingly pointed to as key ingredients for long term economic success. A critical component for making agility and adaptability a reality, is the ability to quickly assess how changes to production processes, factory design and scheduling policies influence the efficiency and cost of their production processes. After all, a design change may introduce several constraints which may not become apparent until scheduling time.

'Design for X' is a comparable area, with 'process design for schedulability' being the relationship investigated. Consequently, there has been research in the areas of building [Papamichael et al., 1997] and product design [O'Sullivan, 2001], but little or no published work has been carried out in how process design influences schedules. Perhaps the closest examples are in the area of construction [Wakelam et al., 2005] and [Gray and Little, 1986]. Both systems create a schedule from a generated set of activities corresponding to fea-

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tures of a building. However they do not consider the effect of resource availability on the schedule. This is a feature, important in manufacturing, which makes finding valid schedules much more difficult.

Other research has addressed the question of linkage between process design and scheduling. The approach Sadeh et al. [1998] took, was if the scheduling problem is too difficult, information about resource bottlenecks that often contribute to scheduling difficulty, is made available to the process planner. As a result, process plans can be dynamically re-designed. Although that system allows the factory to react to particular load characteristics of the current orders, it is not capable of reasoning about large-scale resource changes such as machine placement or existence of storage facilities. The long-term goal of the research is to examine the broader strategic question of making decisions that cannot be reactively modified, for example, due to costs of stopping production to reconfigure the physical layout of the factory. This paper is a first step in that direction. Existing commercial scheduling systems provide what-if comparisons, but these are based at a lower scheduling level in which a full detailed schedule is calculated. This research addresses a much higher level in which the process of scheduling is more suitable for use by planners and managers.

The paper is organised as follows; section 2 provides a description of the company's manufacturing process. In section 3, the different manufacturing scenarios are presented. In section 4, a constraint-based architecture is described for evaluating these scenarios in scheduling terms. Section 5 presents an implementation of this architecture and consequently the scheduling results. Section 6 derives conclusions and looks towards further extensions within the architecture.

2. MANUFACTURING PROCESS

The manufacturing process is aimed at producing optical lenses of known types, in given quantities, by specified due dates. The process includes two sequential steps; moulding followed, after a stabilisation delay, by casting. Other stages such as changeovers, testing and packaging are also present, but are not considered significant to the schedule. Between these two processes there is a holding inventory (kanban) of completed moulds. Depending on the level of its content, casting can begin immediately without waiting for moulds to be produced. The company operates with a fixed maximum batch size and tries to achieve this level for as many runs as possible. This maximum value though, can be changed. The Key Performance Indicators; manufacturing time, risk of stock out, resource utilisation and inventory costs, can all be obtained from the schedule either explicitly or implicitly by the scheduler.

2.1 Moulding

At the moulding stage, pairs of moulds are produced that determine the shape of the lens during casting. Moulds of different types are made within cavities on mould injection machines that operate in cycles. Each machine has a number of cavities. The tools for making the moulds are very similar and so the production rates are essentially equivalent across all mould types. Moulds can be stored in order to minimise the risk of not being able to produce lenses in time. This may be due to a failure in the casting process and not having sufficient time to make new moulds and re-cast. The inventory levels within the kanban can be kept so as to continuously provide for casting. The main disadvantage of this approach is the cost of maintaining possibly high inventory levels and increased risk of moulds becoming too old.

2.2 Casting

During casting, two different types of mould are clamped together and plastic is injected between them to produce a lens. The moulds themselves have a minimum and maximum stabilisation interval during which they are suitable for casting. The casting machines produce all lenses at the same rate.

3. SCENARIOS

In this section, two different scenarios are described whose scheduling implications we wish to assess. The two scenarios are evaluated on three sets of weekly demand data. The instances differed in the number of orders (175, 60 & 2) but, nonetheless, have approximately the same overall quantity of production (around 1,400,000 per 7 days), as shown in Table 1.

Table 1. Dataset Characteristics

Data Set	Total orders	Number of SKUs
1	1,373,763	175
2	1,345,818	60
3	1,386,988	2

3.1 Scenario 1: Coupling Processes

The amount of holding inventory between the moulding and casting process can vary. With zero stock, the casting has to wait until moulds have been produced. This is called a coupled process. It incurs the highest risk. Alternatively a fully de-coupled process has enough ready to use moulds available for all the casting. In this way, the risk is much lower, but the inventory costs are higher. Between these two coupling scenarios is the partially coupled scenario, where there is stock held, but this is less than the full casting requirement. Here the moulding is done, both for replenishing stock and for casting. Naturally the inventory costs are lower, but the risks are higher than the de-coupled case. In the evaluation, the amount of mould stock is varied in terms of total weekly demand; that is, 0, 3.5 and 7 days stock are considered.

3.2 Scenario 2: Raw Material and Stabilisation Delay

The minimum and maximum duration of the stabilisation delay between moulding and casting can also be varied. The different values considered correspond to different types of resin that are used to produce moulds and that, consequently, require different durations for chemical and physical stabilisation. In the evaluation, the minimum stabilisation delay is reduced from 48 hrs to 12 hrs, and separately reduce the maximum stabilisation delay from 504 hrs to 120 hrs.

4. PROCESS DESIGN CONSTRAINT-BASED ARCHITECTURE

To describe and evaluate the different design scenarios, a prototype design workbench is developed, based on an architecture illustrated in Fig. 1. An implementation of the framework allows different designs to be evaluated through a flexible user interface. The user interface provides a variety of design components which can be combined in many ways; these include the degree of process coupling, min/max stabilisation delay, machine performance, number of machines, in-lining of machines and allocated machines to products. These are an initial set of design components obtained from the company through discussion on current and future changes to their manufacturing.

A process design specification is described in a data file, stored in Microsoft Excel and passed via the workbench to ILOG OPL Studio 3.7, a constraint-based problem solving technology used for scheduling [Baptiste et al, 2001]. A scheduling model is chosen automatically and that design instance scheduled within an acceptable time limit (default 10 min CPU). A standard load balancing heuristic is used to allocate tasks to machines. This is based on scheduling together, the three activities in making a lens (two moulding and casting activities) and allocation of machines based on availability. Where there are both coupled and decoupled tasks we prioritise the scheduling of the coupled tasks, as they are more constrained than the other tasks. The choice of these heuristics has been validated empirically.

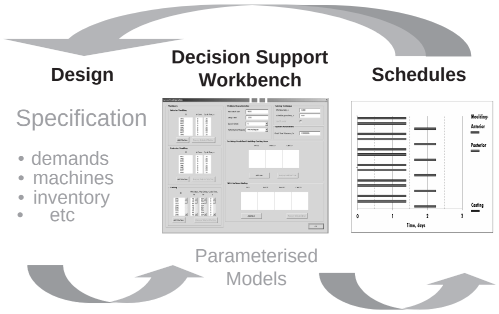

Fig. 1. An Architecture for Design Evaluation

5. EXPERIMENTS AND RESULTS

The due date provided by the company was within 7 days. Since we are looking to minimise the manufacturing duration in the models, this was relaxed in order to obtain schedules even when the duration was greater than 7 days. This gave us important feedback on how close the schedules were to feasibility. For comparison between designs, we consider that a full cycle is measured; so exactly as many moulds are replenished as are removed for casting, as well as having them in the same original state of stabilisation. In the case of the partially coupled or the decoupled scenario, we also assume that the schedule begins with the moulds ready for casting. The moulding and casting processes for any batch of lenses is assumed to be continuous, therefore moulds need to be available throughout the process. For these experiments the maximum batch size was set to 6000.

Table 2 shows how mould stock influences the schedule. Two manufacturing duration values are presented; actual and company-viewed. In the schedule we consider one period of production activities, and so at the end of the cycle we have replaced all moulds which we have used, including time for stabilisation. In a continuous process, there is additional stock held in buffers so the next casting does not need to wait until the moulds are ready. Assuming the amount of mould stock equals or exceeds what the company produces, the company-viewed makespan is the 'actual makepan minus the stabilisation delay' in those cases where the last activity in the schedule is moulding for stock replenishment. If the last activity is not

Table 2. Makespan and Resource Utilisation for Different Couplings

Dataset	Scenario	Actual manufacturing duration, days	Company-viewed manufacturing duration, days	Moulding utilisation, %	Casting utilisation, %
1	coupled	7.11	7.11	96.3	88.2
1	partial	7.51	5.51	90.5	85.6
1	decoupled	7.18	5.18	96.3	99.3
2	coupled	6.92	6.92	86.9	89.4
2	partial	7.65	5.65	86.7	81.0
2	decoupled	7.64	5.64	86.8	99.2
3	coupled	7.43	7.43	90.2	83.1
3	partial	7.57	5.57	90.2	85.8
3	decoupled	7.57	5.57	90.2	90.3

Table 3. Makespan and Resource Utilisation for Different Min Stabilisation Delays

Dataset	Scenario	Min delay, hrs	Actual manufacturing duration, days	Average ant. moulding usage, %	Average post. moulding usage, %	Average casting usage
1	coupled	48	7.11	96.3	96.3	88.2
1	partial	48	7.51	90.5	90.5	85.6
1	decoupled	48	7.18	96.3	96.3	99.3
1	coupled	12	-	-	-	-
1	partial	12	-	-	-	-
1	decoupled	12	5.68	96.3	96.3	99.3
2	coupled	48	6.92	87.3	86.4	89.4
2	partial	48	7.65	87.1	86.2	89.2
2	decoupled	48	7.64	87.3	86.4	99.2
2	coupled	12	-	-	-	-
2	partial	12	-	-	-	-
2	decoupled	12	6.14	87.3	86.4	99.2
3	coupled	48	7.43	90.3	90.1	83.1
3	partial	48	7.57	90.3	90.1	85.8
3	decoupled	48	7.57	90.3	90.1	90.3
3	coupled	12	-	-	-	-
3	partial	12	-	-	-	-
3	decoupled	12	6.07	90.3	90.1	90.3

Table 4. Makespan and Resource Utilisation for Different Max Stabilisation Delays

Dataset	Scenario	Max delay, hr	Actual manufacturing duration, days	Average ant. moulding usage, %	Average post. moulding usage, %	Average cast. usage, %
1	coupled	504	7.11	96.3	96.3	88.2
1	partial	504	7.51	90.5	90.5	85.6
1	decoupled	504	7.18	96.3	96.3	99.3
1	coupled	120	7.11	96.3	96.3	88.2
1	partial	120	n/a	n/a	n/a	n/a
1	decoupled	120	-	-	-	-
2	coupled	504	6.92	87.3	86.4	89.4
2	partial	504	7.65	87.1	86.2	89.2
2	decoupled	504	7.64	87.3	86.4	99.2
2	coupled	120	6.92	87.3	86.4	89.4
2	partial	120	7.65	87.1	86.2	89.2
2	decoupled	120	-	-	-	-
3	coupled	504	7.43	90.3	90.1	83.1
3	partial	504	7.57	90.3	90.1	85.8
3	decoupled	504	7.57	90.3	90.1	90.3
3	coupled	120	7.43	90.3	90.1	83.1
3	partial	120	n/a	n/a	n/a	n/a
3	decoupled	120	-	-	-	-

moulding for stock replenishment, the company-viewed makespan value equals the actual value.

With a completely coupled scenario there is the likelihood that the due date of 7 days will be missed. However, increasing the stock holding to a partially coupled scenario, allows for all the lenses to be produced in time. In terms of utilisation, the partially coupled scenario is often lower for both machine types. This is as a consequence of the gap in time between the two different casting processes (casting from stock and casting from moulding). Therefore the company should hold some buffer stock, but it is up to the planner to determine the level of risk / inventory level they wish to have.

In Tables 3 and 4, different stabilisation limits influence the schedule. In the case of changes to the mimimum stabilisation delay (Table 3) for any coupled or partially coupled scenario with a minimum delay of 12 hrs, there exists no solution. The analysis showed that any solution would necessarily violate the casting continuity constraint, which says there should be exactly one continuous casting activity for each batch. For coupled activities, the following relationships must hold for continuous casting, see Fig.2 where C_M and C_C are moulding and casting cycle times, B is the batch size and D_{min} is the minimum stabilisation delay. The batch size is taken as the maximum specified by the user.

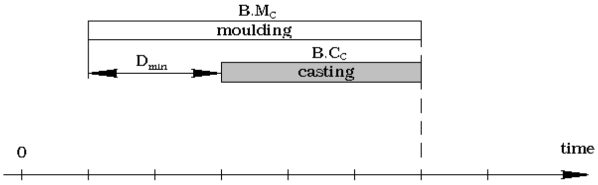

Fig. 2. Relationships between Moulding and Casting for Continuous Processes.

If we want to make the coupled or partially coupled scenarios in Table 3 feasible, we would consider decreasing the maximum allowed batch size or consider more physical changes of increasing the minimum stabilisation delay and/or decreasing the moulding cycle time and/or increasing the casting cycle time.

In Table 4, with changes to the maximum stabilisation delay, it can be observed that there is no solution to the decoupled scenarios. Further analysis showed that for decoupled activities all casting (from stock) should start within the period $[0, D_{max} - D_{min})$, where D_{min} and D_{max} are the minimum and maximum stabilisation delays. This assumes that the moulds in stock are ready for casting from the start. In those scenarios where it was not possible to do all casting from stock within that time frame, this inventory constraint is violated. To make the decoupled scenarios in Table 4 feasible, one can consider increasing the performance of casting machines.

The results also show that in some of the partially coupled instances no solution was found in the allotted CPU time interval (n/a). To us, it indicates that this is a hard scheduling problem, with a strong likelihood of there being no solution. In practice of course the schedulers may find solutions to these scenarios with greater analysis and effort. They may relax constraints for example, but it is sufficient to know at this stage, that it will possibly be hard to schedule and may mean relaxing some conditions.

6. CONCLUSIONS AND FUTURE WORK

In this paper, we attempt to develop an understanding of the relationship between manufacturing process design and quality of schedules, on a small set of real-world test examples. To do so, we propose and implement a prototype architecture that allows selecting and configuring various types of casting/moulding processes. Two scenarios were considered which required evaluating alternative designs and obtained the scheduling consequences of these. In one scenario, the change did not have significant scheduling implications, but for the other, there could be quite a difference in quality of schedule.

The system has been run against other scenarios such as increased demand and end of product life. In these and the reported cases, the company have verified the schedules against historical outcomes and found them consistent. The system has though allowed the planners to examine, in detail, other options, which had not been considered at the time. In this way, confidence has grown, to the extent that we are now involved in helping design the processes in their packaging plant.

It is clear that in future work to help propose better designs is needed; where the resulting schedules have been poor or not obtained. Through experience of scheduling algorithms, an expert may be able to analyse the results to determine possible changes to the design in order to improve the current schedule. We envisage proactively suggesting designs based both on scheduling rules and on examples of previous designs and their resulting schedules.

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