OVERCOMING THE BARRIERS TO BATCH PROCESS SCHEDULING

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Abstract

While sophisticated systems for both process control and production planning enjoy a wide industrial acceptance, tools for batch process scheduling represent a serious gap in the fully automated batch plant. Despite over fifteen years of academic research in batch scheduling algorithms and Moore's law increases in computing power, spreadsheets and calculators remain the state-of-the-art means for scheduling in most batch plants. The potential benefit of closing this technology gap is in the billions of dollars. Factors contributing to the lack of acceptance of scheduling tools include the industry's perception that advanced scheduling systems are expensive and risky and the shortage of individuals trained to implement or maintain scheduling systems. The vision for an integrated batch scheduling system presented here features an accurate model of the manufacturing process; a constraint-guided heuristic approach to the scheduling problem; and the ability to interact with both the production planning and process control systems. A simple illustrative example is provided.

Keywords

Batch processing, scheduling, planning

Introduction

Each year in the United States about 17,000 batch or multi-product processing facilities produce over 550 billion dollars worth of shipped materials[1]. At each of these facilities, which include chemical, food and beverage, and pharmaceutical plants, there is almost certainly an individual assigned to short term scheduling. The scheduler's job, in general terms, is to determine how to use the plant's equipment to make the required products. This can be a challenging task in large multipurpose batch facilities, so the scheduler's goal is usually to develop a workable plan as quickly as possible. Automated scheduling systems could help the scheduler find more efficient schedules, reducing production costs and providing additional effective capacity without capital expenditures. Despite these apparent advantages, automated scheduling systems have made only limited inroads in the batch processing industry.

Terminology

Batch process scheduling is the translation of a set of product demands and deadlines into operating instructions for a batch processing facility. This activity includes the determination of the number of batches of each product along with their timing, and equipment and other resource assignments.

The general instructions for making a single batch of a product constitute a recipe. Petrides and Koulouris (2001) provide the recipe structure shown in figure 1.

[1] Figures are estimated from data in the 1997 U.S. Economic Census.

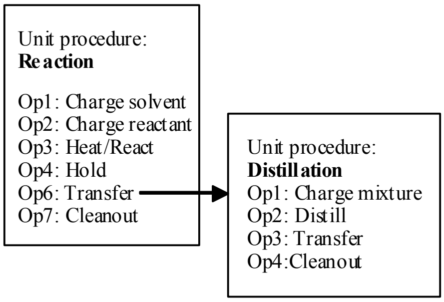

Figure 1. Recipe Structure

A unit procedure is a primary process step and is assigned a single piece of primary equipment. Operations are individual tasks within a unit procedure. All resources other than primary equipment, i.e. secondary equipment, labor, materials and utilities, are associated with operations. There may be timing relationships among operations. In Figure 1, operation 6 in the reaction procedure is concurrent with operation 1 in the distillation procedure.

Constraints on scheduling include limits on the availability of equipment, labor, materials, utilities, and inventory capacity.

A typical objective in scheduling is to minimize the total time required (makespan). If all of the products can not be made on time, the goal may be to minimize the average delay.

Schedule implementation is the process of communicating the schedule to the process operators who will execute it.

Scheduling Technology

There are a number of commercially available software systems for batch process scheduling. The technology can be divided into two broad categories: heuristic scheduling and systematic scheduling.

Heuristic or knowledge-based (KB) scheduling techniques, which have been summarized by Sauer (1999), generally involve a search guided by problem specific rules about how to prioritize timing and resource selection. The goal of this type of technique is to arrive quickly at a reasonably good schedule. Often this technique is interactive, allowing the human scheduler to influence the schedule and the constraints.

Systematic techniques include mathematical programming, constraint programming, and evolutionary techniques, e.g., genetic algorithms.

Mathematical programming (MP) involves building a mathematical representation of the scheduling problem with constraints that capture operation sequence in the recipes as well as the limitations on resources. An appropriate solver program is then used to optimize an objective function, e.g. makespan. Pinto and Grossman (1998) suggest that the selection of the mathematical formulation depends on the specific nature of the scheduling problem at hand.

Wang et al. (2000) suggest genetic algorithms (GA) as a means of simplifying problem formulation. Developing an effective GA does, however, require careful selection of a "chromosome," i.e. a set of variable that represents a complete schedule along with appropriate mutation and crossover functions. This approach also requires a feasible starting schedule upon which to improve.

Constraint programming (CP) as described by Lustig and Puget (2001), is comparable to math programming. The constraint solver first finds a feasible schedule, or else proves that none exists. The solver then searches for an optimal schedule. This technique has also been combined with MP approaches.

The KB techniques are intuitive, but a solution is not guaranteed. The MP and CP techniques provide guaranteed results but require a greater level of expertise to implement. Pinto and Grossman (1998), note that systematic techniques may not be able to handle large or complicated industrial problems. Table 1 describes some common commercial scheduling systems; many of these are custom solutions as opposed to "shrink wrapped" software. This list is not intended to be exhaustive. The descriptions are based on available product literature and do not represent a review or recommendation.

Table 1. Some Commercial Scheduling Systems

System	Technology	Provider
Aspen Plant Scheduler	KB, MP	Aspen Tech. Cambridge MA
I2 SCM-FPS	GA, MP	I2, Dallas TX
ILOG Scheduler	CP, MP	ILOG, Paris, France
Model Enterprise	MP	Process Systems Enterprise, London UK
RSBizWare Scheduler	KB	Rockwell Software, Milwaukee, WI
SAP/APS	CP, MP	SAP, Waldorf , Germany
Schedule Pro (Available2003)	KB	Intelligen, Scotch Plains, NJ

Barriers to Planning and Scheduling

As with any technology, the introduction of a plant system must be evaluated on its business benefit. The economics must be attractive, and the likelihood of success must be high. The necessary infrastructure must be in place, and the system must be reasonably usable. Finally, for some industries, there is a need to validate the system to ensure that it will not adversely affect the process.

High Risk, Low Reward

For even a moderately sized plant, software and consulting costs for an automated scheduling system could be on the order of $0.5 million to $1.00 million. Furthermore, process and product changes may require that the scheduling system be reworked after 3-4 years. For a company to achieve a reasonable internal rate of return (IRR), say 18%, the system would need to have an annual benefit of nearly $250,000. Where there is some risk that the benefit won't really be achieved, the IRR requirement may be much higher, posing a real economic barrier to automated scheduling.

Data Availability and Reliability

There are two primary types of data required by any scheduling system: (1) recipe data which describes the process and (2) resource data which describes when equipment, labor, materials, and utilities are available. The latter can often be found in existing plant systems, e.g. ERP or MRP systems. The former can be found in recipe management systems.

Recipe data, however, is usually process oriented, e.g. "charge 20 kg material to the reactor," while a scheduling system, of any type, requires timing information: "charge 20 to the reactor for a duration of 30 minutes." Timing information for batch operations may change with equipment changes or with environmental changes, e.g. cooling water temperature.

Usability

Usability is a concern for any manufacturing system. Systems that require carefully typed data, such as product codes, can lead to errors and frustration. The system should also deliver results quickly—even for relatively large problems.

Validation Concerns

Manufacturers that make products for medical use or for human consumption are subject to FDA process validation requirements. Process validation provides documented evidence that the process can reproducibly produce the product within predetermined specifications (Kirrstetter, 2002). Scheduling systems for running plant activities must be suitably documented, and change-control procedures need to be in place. In addition, an electronic version of the plant production schedule may be subject to FDA rules concerning electronic records (FDA 1997).

Toward Overcoming Barriers to Process Scheduling Systems

Figure 2 shows the proposed architecture for a lower cost, lower risk alternative for production scheduling.

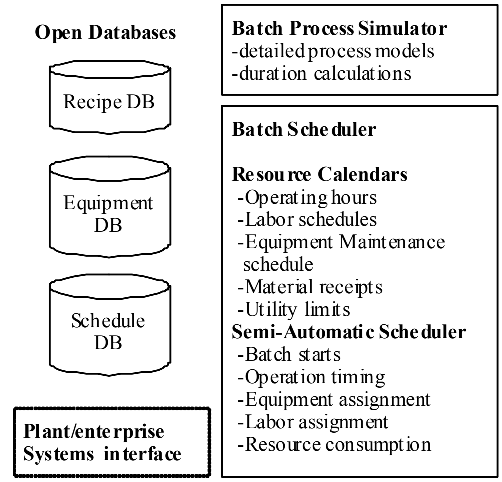

Figure 2. Overall Architecture.

Batch-Simulation for Recipe Maintenance

The representation of a recipe is the hierarchical description of the process shown in Figure 1. The recipe is a description of the process for making 1 batch of the main product. It specifies the type and amount of equipment and resources required, the relationships among operation start times, and the conditions for each operation.

The primary means of entering a recipe is through a batch simulation program. The batch simulation program provides a convenient means of entering recipes. It calculates the durations of each operation along with the resource requirements that are not directly specified. Recipes are maintained in an open database format.

The scheduling program provides a secondary means of recipe entry when the batch process simulator is not required or is not available.

User-Driven Heuristic Scheduling

An interactive KB scheduling system performs the actual scheduling. The system's interface provides for the entry of resources including equipment, raw materials, labor, utilities, and storage capacity. Each type of resource is associated with a cost and an availability schedule, which describes when and how much of reach resource is available at a given time.

The user interacts with the system by entering or importing recipes and resource data. The system allows for increasingly automated modes of operation. At the most basic level, the user selects batches of various recipes and assigns start times and resources, while the system provides feedback about resource conflicts. In the most automated mode, the system calculates the schedule based on product demand and due dates.

A Simple Example

The following example illustrates how an interactive tool can simplify a mundane scheduling task. A batch process has 4 unit procedures: reaction, crystallization, filtration, drying. Each operation requires one operator except drying which can, except for loading/unloading, can be unattended. To plan 6 batches with crew size of 2, the user sets up the recipe in the batch simulator to calculate the process durations and saves the results in the recipe database. The user then runs the scheduling program and specifies the number of batches and the operator limit. The system can display the resulting schedule in a variety of ways. Figure 3 shows that labor is a bottleneck and that the makespan is about 6 days. The user may explore the effect of adding operators to relieve the bottleneck. In this case, the addition of one operator reduces the makespan to 3 days.

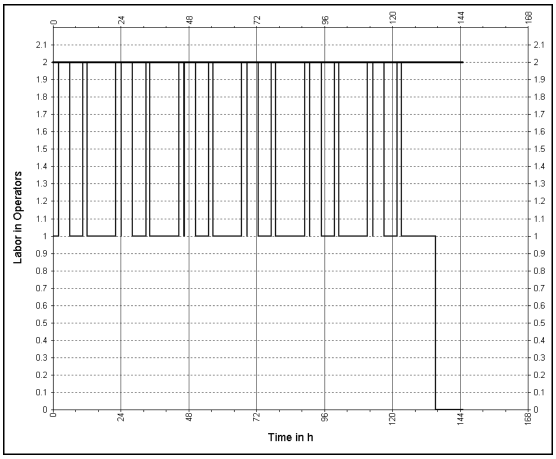

Figure 3. Labor Resource Profile

Connectivity

Connection to existing plant systems is possible through an open database interface. Plant system might, for example, update the resource availability calendars.

Validation and Change-Control

The scheduling system provides for some basic controls to ensure that it will not be a source of process deviations. The system provides for restricting resource assignment only to qualified equipment. The user may build and evaluate alternative schedules, but only a single version is published.

The scheduling tool can potentially be synchronized with recipe management systems (RMS). While differences in recipe structure may preclude the scheduling tool from directly sharing recipes with an RMS, an update to a recipe in the RMS should invalidate the corresponding recipe in the scheduling tool.

Finally, the scheduling tool can provide for compliance with electronic record regulations. Specifically, the user can be appropriately authenticated to publish a schedule and changes to the schedule or to recipes may be logged.

Alternative Scheduling Algorithms

While the heuristic approach provides a low-cost scheduling capability for a wide range of industrial sized problems, it may not be the way of the future. Improved combinatorial techniques are likely to emerge. As suggested by Pekny and Reklaitis (1998), the system is designed with an open interface, allowing it to use external software.

Conclusions

The primary barrier to the use of scheduling tools is their high cost and perceived risk. Much of the cost is due to the skill required to formulate the scheduling problem and apply and appropriate solution algorithms. A user-driven heuristic scheduling tool may provide a low-cost entry point for process scheduling while potentially facilitating the later application of more advanced approaches.

References

Kirrstetter, R. (2002). Requirements for Process Validation of Biotech Active Pharmaceutical Ingredients. *Pharmaceutical Engineering*, Vol. 22 no. 3, 36.

Lustig, I.J., J. Puget (2001) Program Does Not Equal Program: Constraint Programming and Its Relationship to Mathematical Programming, *Interfaces* Vol. 31 no. 6 pp.29-53.

Pekny, J. F., Reklaitis, G.V. (1998) Towards the Convergence of Theory and Practice: a Technology Guide for Scheduling/Planning Methodology, *Proceedings of the Third International Conference on Foundations of Computer-aided Process Operations,* Utah, U.S.A.

Petrides, D., A. Koulouris (2001) Batch Process Simulation – Historical Overview and Future Outlook, *AIChE Batch Processing Topical Proceedings*, Reno, NV, pp 293-305.

Pinto, J., I. E. Grossman (1998) Assignment and Sequencing Models for the Scheduling of Process Systems, *Annals of Operations Research*, Vol. 81, pp 433-466.

Sauer, J. (1999) Knowledge Based Scheduling Techniques in Industry, *Knowledge Based Intelligent Techniques in Industry*, L. C. Jain, R.P. Johnson, Y. Takefuji, L.A. Zadeh eds., CRC Press.

U. S. Department of Commerce, *1997 Economic Census, Manufacturing Series.*

U.S. Department of Health and Human Services: Food and Drug Administration (1997). 21 CFR Part 11, Electronic Records; Electronic Signatures; Final Rule, *Federal Register* Vol. 62 no.54, 1342.

Wang, K., T. Lohl, M. Stobbe, S. Engell (2000) A Genetic Algorithm for Online-Scheduling of a Multiproduct Polymer Plant, *Computers & Chemical Engineering,* Vol. 24, pp 393-400.