이산적 시뮬레이션 모델을 이용한 커피 생산 스케쥴

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ABSTRACT

This article describes the application of discrete event simulation in a process industry (coffee manufacturing) as a daily production-scheduling tool. A large number of end products (around 300), sporadic demand, and limited shelf life of coffee (90 days) make it difficult to generate feasible production schedules manually. To solve this problem, an integrated system was developed incorporating discrete event simulation methodology into scheduling process.

The integrated system is comprised of two components: a scheduling program and a simulation model. The scheduling program is used to generate daily schedules for roasting, grinding, and packing coffee. The simulation model uses the generated schedules to simulate the production of coffee and regenerates a modified production schedule. In this paper, each of the components will be described in detail, evaluated in terms of performance factors, and validated with a set of real production data.

Although this article focuses on a specific system, we will share our experiences and intuitions gained and encourage other process industries to develop simulation-based scheduling tools.

INTRODUCTION

Most applications of discrete event simulation focus on manufacturing industries and are used as system design/evaluation tools. This article describes the application of discrete event simulation in a process industry (coffee manufacturing) as a day-to-day production-scheduling tool.

The coffee production process falls under the general category of a flow-shop. There are four main processes with limited capacity, and all jobs (type of coffee) follow the same routing. Apart from the production resources, the in-process coffee needs to spend an extended period of time in storage bins (also with limited capacity) while they degas. Degassing is the term used to describe the waiting period when coffee releases carbon dioxide gas. It takes at least 24 hours to make a batch of coffee. Coffee should not be over produced because there is a limited shelf life.

There are a large number of end products (around 300) and most of them experience sporadic demand. This requires the production system to be very agile and to react to demand fluctuations in a short period of time. The demand is also highly seasonal. The demand for coffee is very high during a four-month period in the winter and is followed by an extended period of low demand. Due to limited shelf life (90 days), coffee cannot be produced too far in advance; and under ideal conditions, coffee is produced on demand. Meeting demand on time is imperative as the product (in general) is rather homogeneous and a dissatisfied customer can easily switch to a competing brand.

These factors need to be considered while generating the production schedule. This makes manual scheduling very difficult and tedious. Mathematical models cannot capture interactions between products and resources while producing solutions in a reasonable amount of time. Hence, a hybrid strategy was adopted to generate schedules. Simple rules will be used to sequence and schedule jobs at each process. At this stage, all the product and resource interactions will be ignored. A schedule will then be evaluated /modified using a discrete event simulation model of the actual system. A user interface that ties the scheduler and simulator, with real time inventory and orders database, was developed to give the user a seamless integrated tool.

Although this article focuses on a specific system, we will share our experiences and intuitions gained while encouraging other process industries to develop simulation-based scheduling tools.

CHARACTERISTICS OF COFFEE PRODUCTION

As mentioned earlier, coffee production involves four main production processes connected by a myriad of bins and tubes for storage and moving coffee. These processes are 1) Cleaning; 2) Blending / Roasting; 3) Grinding; and 4) Packing. A schematic representation of the system is given in Figure 1.

Unprocessed coffee beans, called green beans, are cleaned and stored in bins. There are approximately 15 types of green beans. Different combinations of these 15 beans are combined in specific ratios to form blends that are roasted in ovens to different degrees of darkness, resulting in 50 different blends/roasts. The blend combined with the darkness of the roast gives each coffee it's unique flavor and taste. The roasted coffee beans are stored in bins where they are degassed and cooled. Each blend/roast of coffee has a different minimum degas time. The roasted and degassed coffee beans remain in the bins until they are ground into various degrees of fineness and again stored in bins to degas and cool. At this stage, there are as many as 150 different types of ground coffees. After degassing, these ground coffees are packed by machines into bags of different sizes and brand names. These bags are packed into cases and stored as finished goods. As previously described, the Stock Keeping Units (SKUs) increase as they flow down the system (Figure 2). Srikanth and Umble [5] refer to such plants as V-plants.

PROBLEM STATEMENT

Many difficulties arise due to the nature of this system and should be taken into account when generating schedules.

Extremely long manufacturing lead times: It takes a single batch of coffee 24 to 36 hours to flow through the system without any other products competing for scarce resources. This long flow time makes it very important to have the right product available to be processed at each stage in the production process.

Limited capacity: As is the case with most systems, there are many capacity constrained resources(CCRs). Due to the extended degassing periods, the storage bins, located between the processes, become the main bottlenecks within the system. Thus, utilizing capacity becomes a critical issue[2].

Large number of SKUs: With limited capacity, handling large numbers of SKUs is difficult. For example, after grinding, 150 SKUs are stored in 20 bins and degassed for 6 to 20 hours before being packed. Thus, if all 20 bins are being degassed at the same time, no machines can pack the coffee. During this time, the grinders cannot be operated because there are no bins available for the ground coffee.

Nature of demand: Demand for coffee is seasonal, sporadic, and continuously on the increase. Quite often, new blends are launched which increases the number of different SKUs that need to be handled. Since demand is sporadic, plans and schedules need to be very flexible and adapt to constant change. The high demand seasonality requires the scheduling strategy to change according to the season. For example, use large batches in summer and smaller batches in winter, as smaller batches can be processed faster thereby not holding up subsequent products.

Homogenous products: Except for specialized blends, all manufacturers can produce most products; therefore, a dissatisfied customer can take his business elsewhere. Meeting demands becomes very important and so does the reliability of schedules.

Cannot isolate CCRs: In traditional manufacturing processes, the CCR determines the overall system throughput (Drum-Buffer-Rope analogy Goldratt[3]) and the schedule should focus on maximizing the utilization of the CCR. However, in the case of coffee production, the CCR is not fixed, and could change based on the schedule. The storage bins are generally the CCRs and the production resources are usually under utilized (30% to 40% utilization levels). However, if poorly scheduled, it is possible that all of the stored roasted coffee could finish degassing at the same time. Now the grinders are the CCRs holding up production. Thus, a resource with an average utilization level of 40% becomes a CCR! When roasted coffee bins become available the roasters can not function fast enough to fill up the bins making the roasters the next CCR.

Need for rescheduling: Any unforeseen events during the day, such as breakdowns, arrival of a large new order, etc., would require rescheduling. This makes the need for a computerized tool essential.

Given such a scenario, we were to determine a better way to utilize capacity and improve throughput. Despite the presence of CCRs, increasing capacity did not make economic sense because the existing capacity was quite adequate to meet the summer months' demand. Further, CCRs cannot be uniquely identified and, as illustrated earlier, change constantly. It is concluded that the best approach will be to increase throughput by better scheduling.

Due to the nature of most job-shop type problems, mathematical models were complicated to formulate and difficult to solve. Hence, we decided to follow simple rules to determine the production quantities and sequence ignoring all the interactions between products and resources. To induce more reality and generate implementable schedules, a simulation model was developed. This simulation model will depict the actual system to the best possible extent. The generated schedule was fed to the simulation model that attempts to process the jobs in the specified sequence. The simulation model also makes changes to the schedule intelligently (quantity as well as sequence) depending on the scenario during that day. A complete trace of the simulation run is captured and the sequence in which the scheduled jobs are processed in the simulation model is used as the actual production schedule for the day. The simulation model has some built-in intelligence to over-rule the schedule if any problems are encountered. Otherwise, a copy of the trace and the performance statistic output enable the scheduler to alter the schedule further and to enhance throughput. In the following section, the scheduling tool and the simulation model are briefly described. This is followed by an analysis where specific examples are discussed.

DESCRIPTION OF THE TOOL

The Scheduler

The main drivers of the schedule are the work-in-process inventory levels obtained through the plant information system and open orders data obtained from the Sales Department. The Sales Department also provides the forecast for coffee with heavy demand. The schedules are generated according to a pull system starting with packing. This is illustrated in Figures 3 and 4. The following simple scheduling rules are applied to generate schedules.

Packing Schedule: Since minimizing the number of late jobs is the main objective, the earliest due date (EDD) rule is used to sequence jobs. Jobs that can be packed immediately are scheduled first. This depletes the stock of ground coffee. The batch size of the jobs is determined. For the low demand products, the batch size equals the firm order quantity. These products are never overproduced. The heavy movers are always over produced to meet known firm orders for the next three days as well as forecast demand for the same period. This batch size is increased to include one week's demand during the low demand summer months. All batch sizes, however, are limited to the size of the bin from where the coffee is to be packed. The packing schedule, once completed, will account for all the available ground coffee.

Grinding Schedule: After the packing schedule for the ground coffee is complete, the bins which are expected to become empty the earliest are identified based on the average packing rates of the machines connected to the bins. Degassed roasted coffee required to produce the product with the earliest due date (whose demand has not yet been satisfied) is scheduled to be ground into the earliest available bin. Thus, the grinding schedule will empty all the roasted coffee bins. Grinding jobs will be sequenced according to the EDD rule and assigned to storage bins according to availability. A packing schedule is then generated for the ground coffee. The packing schedule of the ground coffee is sequenced in the order in which it is expected to become available. The simulation model might alter this sequence.

Roasting Schedule: All end products with demands that cannot be met using ground or roasted coffee that is available at the beginning of the day are now scheduled for roasting. At this stage, all jobs with similar blend/roast are grouped together. The batch size is usually the size of the bin, unless it is a specialty job that requires a very small amount of coffee. The degassing time is the same if the bin is completely full or half-full, and hence roasting jobs are usually in terms of bin size. Roasting jobs are not assigned to specific bins because it is very difficult to determine when a bin will become available. This is a major problem faced by the scheduler. The scheduling model only specifies a preferred sequence for the roasting jobs. The simulation model will decide where to store the roasted beans on a real-time basis. The roasting jobs are then scheduled for grinding and packing. These are only preferred sequences that are finalized later by the simulation model.

Cleaning Schedule: The scheduler generates the gross cleaning requirements. The simulation model decides the cleaning sequence of the green beans.

The best way to improve throughput is to have all storage bins full of the right, completely degassed, coffee. Then the machines can start processing jobs at the beginning of the day. There is not enough time during the week to ensure full degassed storage bins at the beginning of the next day. However, the weekend provides an opportunity to do so. Thus, a different schedule is generated for the weekend. This schedule requires the cleaner, roaster, and grinder to fill the bins on Saturday. Small jobs that will not require full bins of coffee are not scheduled for the weekend unless absolutely necessary, ensuring that the scheduled jobs fill the bins. Sunday is available for degassing and therefore, each week begins with full bins of coffee. Thus, two simulation models were developed.

Simulation Model

A simulation model was developed to evaluate the schedule created by the scheduler and to determine a new valid and feasible production schedule by taking factors, such as demand, the inventory level of storage bins, and operational status of the machines, into consideration. The simulation model is made up of with four modules; cleaning, roasting, grinding, and packing. Each of the modules was developed to mimic the actual system to the greatest possible extent. The cleaning module generates schedules for dumping the green beans into one of the storage bins in a way that best supports the roasting schedule. It tries to find a cleaning and dumping sequence that ensures that the roaster is never starved due to the non-availability of appropriately cleaned green beans. The roasting module reads the roasting schedules generated by the scheduler and simulates it with the parameters of the actual system. It then generates a new roasting schedule that can minimize the prep time due to the changeover and maximize the uptime of the roasters. The grinding module works the same way as the roasting module. It reads grinding schedules created by the scheduler and simulates it based on the operational status of the grinders and the accessibility of the conveyors leading to the packing area. Then it generates a new grinding schedule so that the prep time and the waiting time for the conveyor may be minimized. The packing module also reads packing schedules and regenerates a packing schedule for each of the packing machines based on availability to increase the throughput.

As explained earlier, two simulation models were developed, one for weekdays and the other for weekends. Both models were identical as far as the resources and the resource connectivities were concerned. The overall operating guidelines, such as machine hours, were different for the two models.

The simulation models were validated by comparing simulation output over a two-week period with the actual system output during the same two weeks. Trace reports were also generated and manually verified. The same trace reports were also used as input for the user to evaluate schedules.

The Integrated Tool

The integrated tool was developed using Microsoft Visual Basic[1]. This tool provides the user with an interface that ties in the data input sources, the scheduler, and the simulation program. The main data inputs are firm-orders, forecasts, finished goods inventory, and WIP inventory. Figure 5 shows the overall architecture of the integrated tool.

The Sales Department provides the firm-orders and forecasts as database tables. The warehouse provides the finished goods inventory levels. WIP information is available through the plant information system. The interface passes the data to the scheduling model, also developed in Visual Basic, which generates Packing, Grinding, Roasting, and Cleaning schedules. These schedules and the WIP inventory levels are then passed on to the simulation model that was developed using SIMAN[4]. The simulation model processes all information and generates trace reports and performance statistics. It also generates modified schedule files. The trace reports and performance statistics are read by the integrated tool. This is presented to the user that gives him the opportunity to evaluate and approve the schedules. The user might decide to make some alteration and run the modified schedule through the simulation model again. An approved schedule will tell each operator the timetable and the quantity of each job.

Thus, the tool develops a generic schedule that is modified and processed by the simulation model. Based on the simulation results, the schedule is tweaked, evaluated, and approved by the user before being implemented. This helps the user take a productive approach to scheduling and also generates schedules that are implementable and reliable.

ANALYSIS

Two examples of how this tool was used are given in this section. In the first case, we evaluate the performance of the tool. To do so, we compare the simulation output to the actual system performance during a test period. The second example illustrates the use of the simulation model as a scheduling tool. This example shows how on a given day the schedule generated is modified by the simulation program to improve throughput and system efficiency.

Performance Evaluation

The same inputs used by the plant's production scheduler were fed into the simulation model. The initial conditions were the same as the actual system. Starting with the second day, all inventory data were based on what the simulation model produced the previous day except for firm-orders and shipment during the day.

Such an experiment was done over a two-week

(10 days) period. The performance of the system according to the simulation output was compared to the actual performance during the same period. Since the simulation model was as close to the actual system as possible, any difference in throughput was attributed to the way the jobs are scheduled. It is evident that the simulated system's performance was better than the actual system based on the summary statistics shown in Table 1.

Table 1: Comparison of System Performance

Factors	Original System Model	Integrated Model
Cleaner Utilization	82.3 %	98.4 %
Blender Utilization	78.0 %	99 %
Roaster Utilization	73.5 %	95.3 %
Grinder Utilization	25.1 %	29.2 %
Packer Utilization	67.7 %	71.1 %
Bin Utilization	76.9 %	86.1 %
Quantity Roasted	85,850 lbs.	116,450 lbs.
Quantity Ground	57,557 lbs.	79,371 lbs.
Quantity Packed	75,332 lbs.	98,676 lbs.

Coffee is packed after roasting as well as grinding. Hence, the quantity packed is greater than the quantity ground

Table 1 shows that all utilization rates of the production facilities have been increased. Specifically, the utilization levels of the cleaner and the roaster increased substantially and the utilization levels of the grinder and the packer also showed some improvement. The bottleneck of the production system was at the cleaning and roasting operations making grinding and packing non-bottleneck operations.

An Approved Schedule

Table 2 shows the parts of a daily schedule (packing/grinding/roasting). The initial schedule generated by the scheduling model and the modified scheduled obtained from the simulation model are shown together for comparison. Table 2 shows the difference of the job sequence processed in the roasters. The job, generic code 27-50-00, was initially scheduled to process first, but it was modified to be processed in the middle of a day's production. This way it can save the changeover time and speed up the roasting process.

Table 2: Original Schedule vs. Modified Schedule for Roasting Process

Generic Code	Job Sequence	
	Original	Modified
27-50-00	1	196
07-40-90	2	1
07-40-90	3	2
04-40-00	4	120
04-40-00	5	121
12-30-00	6	4
07-40-90	7	6
07-40-90	8	7
12-30-00	9	5
12-30-00	10	6

Table 3 compares a hand-made grinding schedule with one generated by the integrated model. The coffee 06-20-80 was scheduled to be processed first as a batch, but it was divided by two separated batches and scheduled to be processed at a later sequence by the integrated model. The coffee 03-20-80 was scheduled at the sequence of six, but it was cancelled (denoted by a).

Table 3: Original Schedule vs. Modified Schedule for Grinding Process

Generic Code	Original Schedule			Modified Schedule		
	Qty.	Bin	Seq.	Qty.	Bin.	Seq.
06-20-80	7000	53	1	3608	53	13
				3392	53	15
12-30-30	7664	61	2	7664	61	3
18-20-80	1250	40	3	1250	40	4
06-40-80	6382	56	4	6382	56	6
01-30-80	1250	41	5	1250	41	1
03-20-80	1250	42	6		42	
06-40-30	4526	61	7	4526	61	5

Table 4 also compares the packing schedule generated by the scheduler with the packing schedule generated by the integrated system. The sequence of processing the packing has been totally changed to a new sequence and some of the jobs scheduled originally were cancelled. The packing process, as the final process, forces the scheduler to consider blends, weight, packing machines, and bins. There exist hundreds of different combinations, which the schedule cannot take fully into consideration. The integrated model can help the scheduling process by simulating all the combinations.

Table 4: Original Schedule vs. Modified Schedule for Packing Process

Generic Code	Original Schedule			Modified Schedule		
	Qty.	Mc.	Seq.	Qty.	Mc.	Seq.
01-30-80	565	1	1			
18-40-80	1775	1	2	1775	1	13
18-40-80	118	1	2	118	1	25
18-40-80	1208	1	3	1208	1	26
18-40-80	1710	1	4	1710	1	31
18-40-80	202	1	5	202	1	40
18-40-80	2183	1	6			
03-20-80	2914	2	7			
03-20-80	672	2	8			

CONCLUSION

This article illustrates a unique application of a discrete event simulation model as a daily scheduling tool. We show how a complex system and a complicated scheduling environment can benefit from a clever hybrid approach. Simple scheduling rules are applied in a myopic way to schedule jobs at individual stages in the production process. A simulation model that helps evaluate/modify the schedule until a satisfactory schedule is determined captures the overall effect of the schedule. Such a schedule is reliable and implementable and helps improve the throughput of the system.

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