Scientific Management of High-Variety, Complex Production in Job Shops

By
Prasad Velaga, PhD
Optisol (http://www.optisol.biz)
College Station, Texas, USA
Email: prasad@optisol.biz

Abstract

Many small and mid-sized job shops regularly face a lot of difficulty in managing their high-variety, complex production for various reasons. In spite of worldwide promotion of several manufacturing methodologies like lean manufacturing, a vast majority of job shops still do not seem to be confident that those methodologies can adequately support efficient management of high-variety, complex production without demanding a lot of system simplification. This article suggests a complementary, scientific, quantitative approach to fill in the gap for efficient management of complex job shop production.

Introduction

It is not easy to find a universally accepted definition of job shop. However, many existing definitions of job shop cover some important characteristics of job shops. Most manufacturing units described as job shops are relatively small in size and revenue and accept a variety of custom orders for small quantities. A job shop is more general than a production line that can make a variety of products one after another sequentially. Job shops can be found among industries described as:

- Custom manufacturing units
- Make-to-order (MTO) production units
- Engineer-to-order (ETO) production units
- High-variety production units
- High-mix, low-volume production units
- Order-driven production units

Specifically, job shops include many types of units like machine shops, fabrication shops, forge shops, mold shops, tool & die shops, custom wood working units, furniture makers, repair shops, laboratories, certain service units, etc. Management of multiple, concurrent projects which share many common resources of limited capacity is often quite similar to production management in job shops like fabrication units. The volume of custom production has been increasing over years along with the level of automation in industries. Since mass production is getting outsourced, the percentage of high-variety production units is increasing in western countries and the methodology for improving the management of high-variety production in job shops is becoming more relevant.

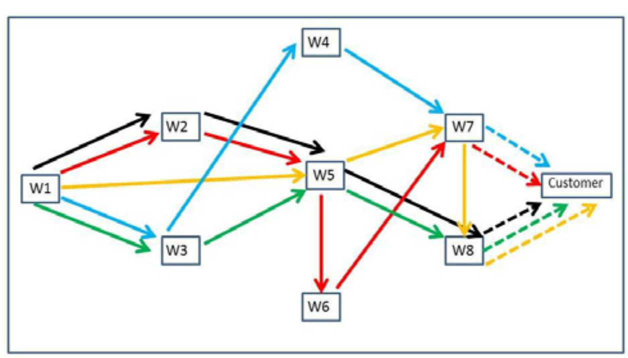
Many small and mid-sized job shops mostly deal with a variety of numerous, low-quantity orders without any predictability of the process requirements and arrival times of orders. This phenomenon involving unpredictable demand and unpredictable changes in product mix on shop floor usually forces job shops to make products only against orders actually placed by customers. The variation in product mix can make rapid fluctuations in the requirements of materials and resources and small shops cannot afford to maintain inventories of a variety of raw materials for supporting make-to-order production. For various reasons, job shops tend to use multi-functional machines and multi-skilled workers of limited capacity to process customer orders.

Even if job shops can perform each production operation perfectly, eliminate defects and non-value material handling and minimize all setup operations, all other factors mentioned above can still make production management a true challenge for many job shops. In spite of this major challenge, there is not much focus on the development of better solutions for management of high-variety production probably because job shops which are small in size and revenue did not attract the attention of management gurus. Many manufacturing experts suggest system simplification to eliminate the complexity of high-variety production. System simplification is not however always simple, easy or economical in practice, particularly for small job shops. Without system simplification, management of high-variety, complex production is quite difficult. System simplification suggested by lean manufacturing and the theory of constraints (TOC) is still not widely implemented in high-variety, complex production systems. Even other methodologies like Quick Response Manufacturing, Factory Physics, Mixed-Model Value Streams, etc. are not still widely accepted by job shops for efficient production management. All these methodologies seem to lack something that is essential to efficient production management in many small and mid-sized job shops.

One of the objectives of job shops is to first maximize the overall shop performance by optimally using the available resource capacities and then identify cost-effective simplifications as well as opportunities for improvements that can yield the highest marginal gains in KPIs. A scientific approach can help achieve this objective.

A Generic Description of Job Shops

A generic job shop with high-variety production is fairly complex. It is not necessarily a production line that makes a large variety of products sequentially one after another. It is more complex than a mixed model production system. Similarly, it is more complex than a high-variety production system consisting of one resource constraint and all



Five Different Routings Through Eight Work Centers other resources with sufficient capacity. Some of the prominent features of job shops are:

- A variety of small quantity orders (jobs) are received from customers with unpredictable process requirements at unpredictable times
- Jobs may have different quantities, material requirements, routings, priorities, target lead times and margins
- An order may involve producing a set of similar components or producing different types of components and making subassemblies and a final assembly from thosecomponents
- Several jobs may simultaneously move through the system along the respective routings while competing for shared resources
- Processing of a job may include some external operations
- Production operations for a job may be sequential or they may have certain precedence relations
- The set of operations and precedence relations may vary with job

- Setup times and cycle times of any operation may vary with job
- Setup times for operations may also depend on job sequence
- An operation may require a single resource or it may simultaneously require multiple resources like machines, workers, etc.
- Resources may be multi-functional machines and multi-skilled workers
- Resources may have individual calendars (working hours) and calendar exceptions
- A long operation may or may not be shared by several alternative resources for reducing its duration.
- Material of a job may move through the system as a single batch or as small transfer batches.

Issues Faced by Job Shops

Job shop managers regularly face a lot of issues and challenges. The difficult issues faced by many of them include:

- Dealing with customer-imposed lead times and late changes in orders
- Finding rational lead times for new jobs based on material lead times, the existing workload and resource capacities
- Finding right start times for jobs for controlling production lead times and WIP without compromising the promised delivery dates
- Estimating completion times of jobs
- Foreseeing the imminent bottlenecks(due to changes in product mix) and mitigating them in advance
- Revising production plan subject to material delays for some jobs
- Revising production plan subject to changes in job priorities
- Capacity planning for meeting due dates of jobs which are likely to become late
- Handling rush orders (hot jobs) for high margins with minimal effect on lead times of the existing jobs
- Estimating overtime requirements to handle rush orders without any adverse impact on other orders

- Overcoming interruptions caused by machine breakdowns and worker absence to avoid late deliveries
- Overcoming the adverse impact of rework / rejections
- Managing overtime optimally to improve on-time delivery or accept rush orders.

Many of the above issues and challenges are absent or less severe in repetitive production systems. They distinguish high-variety production of job shops from repetitive production.

Management of Job Shop Complexity

Some people in job shops are not confident of controlling and managing their production efficiently in a proactive manner because they feel that their production system is subjected to too many variables which cannot be duly taken into account. Many of these variables come from the large known variation in the requirements of jobs for materials, processes and resources, changes in job priorities, interruptions due to machine breakdowns, worker absence, uneven availability of skills and machines over shifts, material delays, rework / rejection, etc. It is not easy to take into account all such variables for managing complex, high-variety production. Moreover, many job shops have to make a product mostly in response to an order received from a customer. Job shops regularly face difficulty with production management mainly because of:

1. High variation in quantities and process requirements of orders
2. Unpredictable requirements of future orders for materials, processes and resources
3. Unpredictable ordering times
4. Frequent changes in job priorities or due dates
5. Continuously varying product mix
6. Simultaneous processing of multiple, diverse jobs using shared resources
7. Finite capacity of resources.

System Simplification

A rational approach to reducing the difficulty of managing job shop production is to simplify the system sufficiently. It is better to pursue simplification as much as possible although there may be some practical limits to it. Simplification may not always come for free. The following are two practical methods for simplifying job shop production system:

I. Process flow analysis, part family identification, design of cells for different part families and cellular manufacturing
II. Increase resource capacities sufficiently.

The first method can certainly reduce the above described complexity if resources can be dedicated to various cells as required. It can be quite useful to parts manufacturing units. However, in project-oriented job shop production like fabrication, this method may have certain limitation. Job shop production management can be greatly simplified if resource capacities can be increased as required. The simplification by capacity enhancement is not economically viable for some small job shops because maintaining a lot of unused resource capacity can increase the overall production cost. Some of the existing approaches to simplification are not effective in this regard. For example,

a) Lean manufacturing approach involving takt time, line balancing, heijunka, VSM for each product and good practices is not adequate for simultaneous processing of multiple, diverse jobs
b) Capacity planning suggested by the theory of constraints (TOC) in the form of a single constraint with full subordination for the purpose of system simplification is not accepted by a vast majority of job shops probably because those shops do not find it cost effective.

Although simplification of complex, high-variety production is very desirable, it should not compromise production flexibility of the shop.

A Comprehensive, Scientific, Model-Based Approach

For high-variety, complex production systems with moving bottlenecks, if simplification cannot be achieved adequately in economic and affordable fashion, it is possible to make further progress in production management by adopting a comprehensive (plant-level), scientific, model-based, approach. This approach will duly take into account many variables which industry people cannot consider in their decision making in a different approach. It involves:

1. **Synchronization of production operations of jobs (subject to all relevant constraints)**
2. **Quick resynchronization in response to significant changes in the system**
3. **Reliable prediction of work progress, job completion times and bottleneck formations over time**
4. **What-if analysis**
5. **Proactive capacity planning**.

Operations synchronization provides an excellent guideline for organizing workload over time in a systematic manner. It makes production management easier. Synchronization also provides optimal job start times to minimize WIP and production lead times of jobs.

We can achieve the best synchronization by having a lot of resources but this option is not cost effective. If resources are not always available as much as needed for processing multiple, concurrent jobs of different routings, the best synchronization cannot be achieved by making decisions based on only the existing situation at any time point. Whenever job shop managers make decisions related to the flow (progress) of work, it is mostly done on the basis of the existing situation. They use their experience, knowledge, commonsense and intuition in decision making but not the prediction of how the work is going to progress and how the bottlenecks are going to form over time. In other words, they do real-time decision making in the best possible way. The real-time control systems do not take into account the future consequences of current decisions and therefore, they cannot offer the best synchronization.

Kanban, the real-time control mechanism in reactive mode is not proven to provide the best synchronization in high-variety, complex production. CONWIP, another method for production control is not rigorous enough to deal with simultaneous processing of multiple jobs with different routings and quantities. There is no convincing proof that even POLCA, a real-time production control method of quick response manufacturing (QRM) offers the best synchronization. In TOC, scheduling on the single constraint, timely release of material for jobs and buffer management are supposed to offer good synchronization but ensuring a single constraint with the necessary subordination appears to be a major economic challenge in many small job shops.

Prediction of work progress, job completion times and bottleneck formations reduces apprehension about how jobs will progress on shop floor, whether jobs can meet their due dates and when and how bottlenecks are going to form. The predictive capability supports proactive decision making. For high-variety complex production, proactive management based on both real-time situation and workflow prediction is more effective than management based on only real-time situation.

The predictive capability facilitates what-if analysis of workflow with respect to any contemplated changes in a high-variety production system. What-if analysis helps managers to evaluate and compare the effectiveness of various possible decisions on production and select the best decision. Without prediction and what-if analysis functionality, people in complex production make decisions based on real-time situation, experience, knowledge, commonsense, guess work and hope. Such decisions may turn out to be quite disadvantageous sometimes.

Capacity planning is essential for managing high-variety, complex production systems in which demand for resources keeps varying over time due to the changing product mix. It is needed for many objectives like (a) accommodating rush orders, (b) implementing changes in order priorities, (c) advancing due dates of some orders, (d) mitigating the moving bottlenecks, (e) reducing the lead times of jobs that are likely to be late, etc. Capacity planning is relevant to any system in which resources may not always have as much capacity as needed.

The above functionality can be achieved by using an appropriate, scientific model and right data for a target production system. This approach complements 5S, good work culture, visual management, improvements in setup time, cycle time and quality of individual operations and improvements in material movement times on shop floor. It takes into account the stationary and moving bottlenecks in the system.

Operations-Level Production Scheduling in Support of Scientific, Model-Based Approach

The above described scientific approach to management of high variety, complex production can be easily adopted with the help of a rigorous, scientific method for detailed (operations level) production scheduling. To achieve the best operations synchronization in such systems, we can optimally schedule in advance all production operations subject to all relevant constraints and then implement the schedule with necessary perturbations in real time. An optimal production schedule that satisfies all constraints provides the required synchronization.

A detailed production schedule specifies, for each operation of each job, a time interval with feasible resource assignment. But, due to some uncontrollable natural variation in the system, we will not be able to perform each operation exactly during its scheduled time slot. In the presence of uncontrollable natural variation, the actual progress on shop floor increasingly deviates from the detailed production schedule as time progresses, making the implementation of a detailed schedule difficult. To overcome this difficulty, the detailed schedule can be converted into daily dispatch lists (operation sequences) for resources.

It is much easier to implement, as a substitute for the detailed schedule, the resource dispatch lists which are less sensitive to uncontrollable variation on shop floor. Implementation of dispatch lists does not need the scheduled start and finish times of operations. Minor exceptions to a dispatch list can be made in real time whenever necessary. The cumulative deviation of work progress on shop floor from the schedule may keep increasing and make even dispatch lists infeasible at some time point. Therefore, the schedule must be periodically revised along with dispatch lists on the basis of the existing workload for controlling the deviation between the actual work progress and the schedule. In the presence of uncontrollable natural variation, an operations level production schedule (generated by even a powerful algorithm) serves as a budget of resource available times for managing production over time. A good production schedule can offer an excellent guideline for managing complex high-variety production.

A feasible, detailed production schedule provides a prediction of work flow, job completion times and bottleneck formations over time. Inserting time buffers for jobs at bottlenecks in a judicious manner (conceptually somewhat similar to drum-buffer-rope method of TOC) without any adverse effect on shop performance, we can create a production schedule which determines job completion times that are dependable even in the presence of uncontrollable natural variation. One can perform fast and extensive what-if analysis of schedules when the scheduling method is implemented by a software tool on computer. Any scheduling mechanism that provides workflow prediction and facilitates extensive what-if analysis also supports capacity planning.

It is also possible adopt the above described scientific approach to job shop management with the help of discrete even simulation. But, for factory people without simulation experience, it is much easier to run scheduling software as part of the approach.

Scheduling Solutions for High-Variety, Complex Production

Job shops currently use many methods for scheduling their high-variety production. The methods include whiteboards, MRP scheduling, Excel applications, project management software like MS Project, Drum-Buffer-Rope method of TOC and finite capacity scheduling (FCS) software. An advanced planning and scheduling (APS) software is also an FCS tool that takes into account all resource constraints. In this article, FCS refers to both FCS and APS. There are some drawbacks with the above scheduling methods except FCS software to support the scientific, model-based approach that is described earlier.

Whiteboard scheduling is too simple to support synchronization and quick resynchronization. MRP scheduling is not helpful to high-variety systems because it works with unrealistic, simple production models based on the assumption of infinite capacity. Many job shops are unhappy with the scheduling function of their MRP systems. Dissatisfaction with MRP scheduling led to creation of in-house, commonsense-based Excel applications in many job shops. However, many in-house Excel applications for scheduling high-variety production are not rigorous enough to generate a rational operations-level schedule that satisfies all constraints including resource capacities. Project management software is generally known to be weak for automatically creating a schedule without resource overloading. The required manual resource leveling in that software is laborious and time consuming in production environment. Those tools are not developed for scheduling production operations. It is very uncommon for any of the above methods except FCS software to automatically generate a rational, detailed production schedule at plant level subject to all important constraints. This is because they are not usually based on rigorous scheduling models and logic.

Most FCS tools are based on a rigorous, scientific scheduling paradigm and use powerful algorithms to generate an optimal operations-level production schedule subject to all relevant constraints. For efficiently managing high-variety, complex production, they offer workflow prediction and the best operations synchronization and support what-if analysis and accurate capacity planning. The best synchronization corresponds to optimal job start times. For example, look at Figures 1 and 2 shown below. Figure 1 displays a schedule (over several weeks) of about

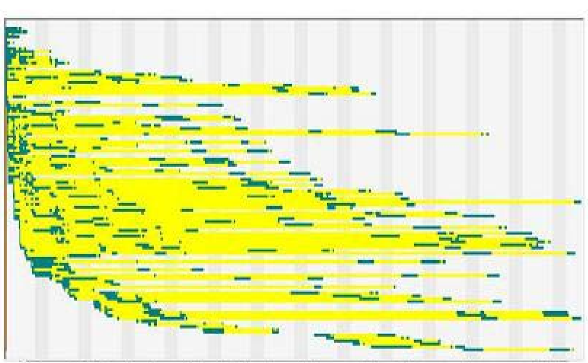


Figure 1: Production Schedule when jobs are loaded as early as possible

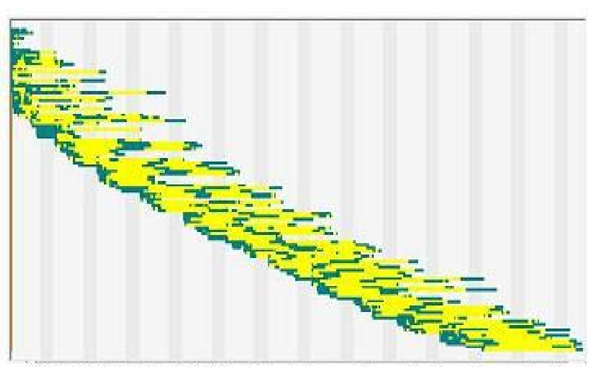


Figure 2: Production Schedule when jobs are released to shop floor optimally

1900 operations of 114 jobs in a job shop. Each thin horizontal line in the chart represents the schedule of one of 114 jobs. The green segment in the line represents the time during which at least one operation is scheduled for the job and yellow segment mostly represents waiting time of the job for an operation that needs a bottleneck resource. In this schedule, all operations of every job are scheduled as early as possible subject to resource availability and operation precedence relations without much synchronization.

Figure 2 displays a schedule of the same workload that provides operation synchronization while inserting some waiting time for jobs before bottlenecks in order to absorb uncontrollable natural variation. The lower envelope in Figure 2 gives optimal job start times. They are optimal in the sense that an earlier start of a job may increase job lead time without advancing the job completion time and a late start may delay the completion of the job and some of the subsequent jobs.

Other methods of production management cannot determine such optimal job start times in complex, high-variety production without system simplification.

Basic Functionality of FCS Tools

Although FCS tools have been available for production scheduling for at least 4 decades, they were not well adopted by job shops in the past due to several reasons. Powerful and sophisticated versions of FCS tools based on scientific scheduling methods are currently available. They take into account what job shop people consider as numerous variables which contribute to the difficulty of production management. These tools provide:

- Prediction of workflow and bottleneck formations over time
- Prediction of job completion times
- Prediction of busy and idle times of resources over time
- Estimates of percentage utilization of resources for any selected time interval

- Graphic displays of job schedules and resource schedules
- Support for fast and extensive what-if analysis
- Support for proactive capacity planning.

This functionality provides excellent decision support for managing high-variety production. The predictive capability of FCS tools enables managers to make better decisions in real time on the basis of not only the existing situation but also the potential consequences of various possible decisions. Such capability is unavailable in almost all other methods for high-variety production. The ability to perform what-if analysis and proactive capacity planning quickly and accurately gives a major advantage to managers of high-variety production. Short term operations-level schedules provide good guidance for efficient control and management of high-variety production as mentioned below.

Benefits of FCS Tools

FCS tools offer many short term benefits in support of efficient management of job shop production. The benefits include the following:

- A rational due date will be fixed for each new order by balancing customer aspiration and the stress of production people in meeting the committed due date
- An optimal start time will be determined for each new job for minimal production lead time without any adverse effect on the job completion time (Earlier start may cause longer lead time due to waiting in the priority line at bottlenecks while late start may cause late completion time for the job)
- The impact of accepting a rush order on completion times of the existing jobs can be easily quantified (The quantification helps in making cost-benefit analysis of accepting rush orders)
- The impact of changing job priorities (or due dates) on job completion times can be easily quantified
- The existing workload can be rescheduled almost instantaneously in response to major changes or

interruptions in production due to factors like unexpected changes in job priorities, machine breakdowns, worker absence, material delays, rework, etc.

Long-term production scheduling by FCS tools supports long-term capacity planning and resource planning.

Why Did FCS Tools Fail To Receive Proper Recognition In Job Shops?

Many FCS tools developed decades ago are basically not suitable for detailed, operations-level scheduling in job shops with high-variety, complex production. They used to take several hours on main frame computers to generate a rational, resource-constrained schedule. Electronic shop floor data collection systems were not available for updating job status information in support of FCS implementation. Therefore, FCS software could not support quick schedule revisions and what-if analysis. Poor utilization of FCS software was also caused by lack of training, improper usage, cumbersome implementation (fixing several parameters of the software), user resistance, lack of faith in the output, etc. Attempts to implement the exact scheduled start and finish times of operations under the influence of uncontrollable variation can cause a lot of frustration with FCS software.

Following the arrival of Microsoft Excel, planners and schedulers in job shops started developing simple, in-house scheduling solutions for themselves using shop floor knowledge, experience and commonsense. This development was driven, to a large extent, by the frustration with scheduling modules of ERP / MRP systems for job shops. In many cases, job shop managers are unhappy even with the performance of these simple, commonsense scheduling solutions in Excel. Most in-house Excel applications for scheduling do not seem to be based on a rigorous, scientific scheduling model. Those Excel applications are usually not rigorous enough to support operations synchronization across the plant.

Some powerful versions of FCS tools started entering the market from mid 1990s. These tools are scientific, rigorous, versatile and fast and also they have excellent, interactive graphic user interface for displaying job schedules and resource schedules. Being fast, they support extensive what-if analysis of schedules and proactive capacity planning in dynamic production environment. Fortunately, these FCS tools found good support from the increasingly sophisticated ERP systems and electronic shop floor data collection systems for getting the required input data. However, even these modern FCS tools are not yet widely adopted across the job shop world due to various issues including:

- Price
- Functionality
- Suitability
- User friendliness
- Availability of up-to-date input data at the time of scheduling
- Resistance to a new scheduling paradigm, a new way of schedule creation and a new format of schedule
- Manager’s desire to somehow make use of the weak scheduling module in the ERP / MRP system

- Scheduler's desire to continue with his /her current commonsense-based Excel application for scheduling.

Every software described as a tool for finite capacity scheduling of production is not necessarily efficient to support the scientific, model-based approach to production management described earlier. An FCS tool must be really strong to schedule production operations optimally subject to all constraints in order to support the approach. Right now, there are a limited number of FCS tools in the market with such strength.

Summary

High-variety production is complex in many job shops due to several factors like unpredictable process requirements of customer orders, need to make products only against received orders, customer-imposed lead times, acceptance of rush orders, abrupt changes in order priorities, machine breakdowns, worker absence, material delays, rework / rejections, continuous change in product mix, simultaneous processing of several diverse jobs using many common resources of limited capacity, etc. More importantly, job shops are usually on the receiving end of negotiations with diverse customers.

Irrespective of the plant size and revenue level, many job shops find it difficult to control and manage their high-variety, complex production. *It is not always easy or economical to simplify a job shop production system in order to make production management easy.* Positive factors like kanban-based production control, good practices, work culture, 5S, kaizen, etc. are not always adequate to deal with production complexity in job shops. To handle some job shops efficiently, we need more than 5S, takt times, Gemba walks, visual management and line balancing. Some small and mid-sized job shops may real concerns to enhance resource capacities for achieving subordination as part of TOC implementation. When production systems cannot be simplified as desired, job shops need not be hopeless about efficient management of their complex, high-variety production. With or without system simplification, job shops can still handle production complexity efficiently by adopting the scientific, model-based approach described above. The modern, powerful

FCS software tools based on scientific scheduling models and rigorous logic enable job shops to achieve it. People on shop floor need not develop scientific scheduling models to adopt this approach. Versatile FCS tools come with a very generic scheduling paradigm to cover a wide spectrum of job shops.

A powerful FCS software tool helps determine a rational due date and a right start time for each new order based on the existing workload, resource requirements and resource capacities. It precisely shows the effect of accepting a rush order or expediting an existing order on order completion times. It also shows the effect of changing order priorities on order completion times. It foresees changes in bottlenecks as product mix changes over time and enables capacity planning by means of quick what-if analysis. This functionality itself will be of immense value to complex job shops even if the software is not to be used for scheduling production operations on a daily basis. FCS software can serve as a powerful decision support tool in managing complex, high-variety production. Information systems currently being used by industries can greatly support FCS implementation.

Schedlyzer (http://www.optisol.biz) is a job shop scheduling software that fits into the above description. It can also efficiently handle multi-functional machines, multi-skilled workers, multi-shift production (resources with different weekly calendars), multi-resource requirements of operations and generic precedence relations among operations of a job. Schedlyzer Lite is a low-priced version of Schedlyzer for small job shops with complex production. Figures 1 and 2 of this article contain screenshots from Schedlyzer Lite.