A HISTORY OF DECISION-MAKING TOOLS FOR PRODUCTION SCHEDULING

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Abstract: Production scheduling is an important decision-making process that has embraced technology as computers and information systems became cheaper and easier to use. The history of production scheduling is not one of replacing human decision-makers with algorithms, however. This paper provides a historical perspective on the decision support tools that have been developed to improve production scheduling.

Key words: production scheduling, history, Gantt chart, scheduling systems

1. INTRODUCTION

Manufacturing facilities are complex, dynamic, stochastic systems. From the beginning of organized manufacturing, workers, supervisors, engineers, and managers have developed many clever and practical methods for controlling production activities.

Although dispatching rules, kanban cards, and other decentralized production control policies are in use, many manufacturing facilities generate and update production schedules, which are plans that state when certain controllable activities (e.g., processing of jobs by resources) should take place. Dispatching rules are usually quick but myopic because they typically they do not use global information. Production schedules can enable better coordination to increase productivity and minimize operating costs. A production schedule can identify resource conflicts, control the release of jobs to the job shop, ensure that required raw materials are ordered in time, determine whether delivery promises can be met, and identify time periods available for preventive maintenance.

The two key problems in production scheduling are, according to Wight (1984), "priorities" and "capacity." In other words, "What should be done first?" and "Who should do it?" Wight defines s*cheduling* as "establishing the timing for performing a task" and observes that, in manufacturing firms, there are multiple types of scheduling, including the detailed scheduling of a shop order that shows when each operation must start and complete. Cox *et al.* (1992) define *detailed scheduling* as "the actual assignment of starting and/or completion dates to operations or groups of operations to show when these must be done if the manufacturing order is to be completed on time." They note that this is also known as *operations scheduling*, *order scheduling*, and *shop scheduling*. This paper is concerned with this type of scheduling.

Production scheduling is a complex decision-making process. Research scientists, software companies, and manufacturing consultants have developed and implemented advanced scheduling systems to reduce the effort of production scheduling and generate better schedules. These scheduling systems include computer algorithms that exploit results from scheduling theory and advanced optimization techniques.

Production scheduling involves a system of information gathering, decision-making, and schedule dissemination. Moreover, because the manufacturing system is dynamic and unexpected events occur, rescheduling is necessary because the production schedule is a plan that must be updated when the state of the manufacturing system makes the current production schedule infeasible. There are many types of disturbances that can upset the plan, including machine failures, processing time delays, rush orders, quality problems, and unavailable material. See Vieira *et al.* (2003) for a more in-depth discussion of rescheduling.

Formal production scheduling systems will typically define a rescheduling period based on management measurement periods (one week or one day or one shift). But rescheduling also occurs (perhaps informally) during this period as unexpected events occur. As described by Wight and others, an informal scheduling process becomes necessary because the formal system cannot reschedule quickly enough to keep up with all of the different unexpected events that occur. The expediters (who check inventory, call suppliers, and stage material) work in the informal system. Task start times are delayed, jobs are reassigned to different resources, and other adjustments take place. Intuitively, one can see that while small disruptions may be ignored in an informal way, larger disruptions may require significant changes to the production schedule to maintain good system performance. Huge disruptions will require many changes.

This paper discusses the history of tools used to support decision-making in real-world production scheduling. This story goes from the first charts developed by Henry Gantt to advanced scheduling systems that rely on sophisticated software. The goal of the paper is to help production schedulers, engineers, and researchers understand the true nature of production scheduling in dynamic manufacturing systems and to encourage them to consider how production scheduling systems can be improved even more. This paper includes material from a wide variety of articles and books on production scheduling to demonstrate the timeless importance of production scheduling and the range of approaches taken to improve it.

This paper does not address the sequencing of parts processed in high-volume, repetitive manufacturing systems. In such settings, one can look to JIT and lean manufacturing principles for how to control production. These approaches generally do not need the same type of production schedules discussed here. Although project scheduling will be discussed, the paper is primarily concerned with the scheduling of manufacturing facilities, not general project management. Note finally that this paper is not a review of the scheduling literature, which would take an entire volume.

The remainder of this paper is organized as follows: Section 2 discusses production scheduling prior to the advent of scientific management. Section 3 describes the first formal methods for production scheduling, many of which are still used today. Section 4 describes the rise of computer algorithms used for scheduling. Section 5 concludes the paper.

2. EARLY PRODUCTION SCHEDULING

Although humans have been creating items for countless years, manufacturing facilities first appeared during the First Industrial Revolution, when centralized power sources made new organizational structures viable. Hounshell (1984) provides a detailed look at the development of manufacturing technology in the United States of America. Wilson (2000a) provides an overview of manufacturing management and notes how modern manufacturing organizations developed from the mills and workshops and projects of the past. Unfortunately, neither of these excellent sources discusses the scheduling function in detail. Hopp and Spearman (1996) also provide a general overview of manufacturing in America since the First Industrial Revolution. McKay (2003) provides a historical overview of the key concepts behind the practices that manufacturing firms have adopted in modern times, highlighting, for instance, how the ideas of just-in-time (though not the term) were well-known in the early twentieth century.

The first factories were quite simple, and production scheduling started simply also. Schedules, when used at all, listed only when work on an order should begin or when the order is due. They didn't provide any information about how long the total order should take or about the time required for individual operations (Roscoe and Freark, 1971). This type of schedule was widely used before useful formal methods became available (and can still be found in some small or poorly run shops). Binsse (1887) described a method for keeping track of time using a form almost like a Gantt chart.

Informal methods, especially expediting, have not disappeared. Wight (1984) stated that "production and inventory management in many companies today is really just order launching and expediting." This author's observation is that the situation has not changed much in the last 20 years.

3. THE INTRODUCTION OF FORMAL METHODS

Frederick Taylor's separation of planning from execution justified the use of formal scheduling methods, which became critical as manufacturing organizations grew in complexity. Wilson (2000b) gives an interesting overview of the production planning office proposed by Taylor around the time of World War I. Many individuals were required to create plans, manage inventory, and monitor operations. (Computers would take over many of these functions decades later.) The "production clerk" created a master production schedule based on firm orders and capacity. The "order of work clerk" issued shop orders and released material to the shop.

The man uniquely identified with production scheduling is, of course, Henry L. Gantt, who created innovative charts for production control. According to Cox *et al*. (1992): a *Gantt chart* is "the earliest and best known type of control chart especially designed to show graphically the relationship between planned performance and actual performance." However, it is important to note that Gantt created many different types of charts. Moreover, Gantt designed his charts so that foremen or other supervisors could quickly know whether production was on schedule, ahead of schedule, or behind schedule. Modern project management software includes this critical function even now.

Gantt (1903) describes two types of "balances": the "man's record," which shows what each worker should do and did do, and the "daily balance of work," which shows the amount of work to be done and the amount that is done. Gantt gives an example with orders that will require many days to complete. The daily balance has rows for each day and columns for each part or each operation. At the top of each column is the amount needed. The amount entered in the appropriate cell is the number of parts done each day and the cumulative total for that part. Heavy horizontal lines indicate the starting date and the date that the order should be done. According to Gantt, the graphical daily balance is "a method of scheduling and recording work." In this article, Gantt also describes the use of production cards for assigning work to each operator and recording how much was done each day.

In *Work, Wages, and Profits* (originally published in 1916), Gantt explicitly discusses scheduling, especially in the job shop environment. He proposes giving to the foreman each day an "order of work" that is an ordered list of jobs to be done that day. Moreover, he discusses the need to coordinate activities to avoid "interferences." However, he also warns that the most elegant schedules created by planning offices are useless if they are ignored, a situation that he observed.

In *Organizing for Work* (originally published in 1919), Gantt gives two principles for his charts: one, measure activities by the amount of time needed to complete them; two, the space on the chart can be used the represent the amount of the activity that should have been done in that time. Gantt shows a progress chart that indicates for each month of the year, using a thin horizontal line, the number of items produced during that month. In addition, a thick horizontal line indicates the number of items produced during the year. Each row in the chart corresponds to an order for parts from a specific contractor, and each row indicates the starting month and ending month of the deliveries. It is the closest thing to the Gantt charts typically used today in scheduling systems, though it is at a higher level than machine scheduling.

Gantt's machine record chart and man record chart are quite similar, though they show both the actual working time for each day and the cumulative working time for a week. Each row of the chart corresponds to an individual machine or operator. These charts do not indicate which tasks were to be done, however.

Clark (1942) provides an excellent overview of the different types of Gantt charts, including the machine record chart and the man record chart, both of which record past performance. Of most interest to those studying production scheduling is the *layout chart*, which specifies “when jobs are to be begun, by whom, and how long they will take.” Thus, the layout chart is also used for scheduling (or planning). The key features of a layout chart are the set of horizontal lines, one line for each unique resource (e.g., a stenographer or a machine tool), and, going across the chart, vertical lines marking the beginning of each time period. A large “V” at the appropriate point above the chart marks the time when the chart was made. Along each resource’s horizontal line are thin lines that show the tasks that the resource is supposed to do, along with each task’s scheduled start time and end time. For each task, a thick line shows the amount of work done to date. A box with crossing diagonal lines shows work done on tasks past their scheduled end time. Clark claims that a paper chart, drawn by hand, is better than a board, as the paper chart “does not require any wall space, but can be used on a desk or table, kept in a drawer, and carried around easily.” However, it is important to note that a chart carried and viewed by only one person is not a useful tool for communication.

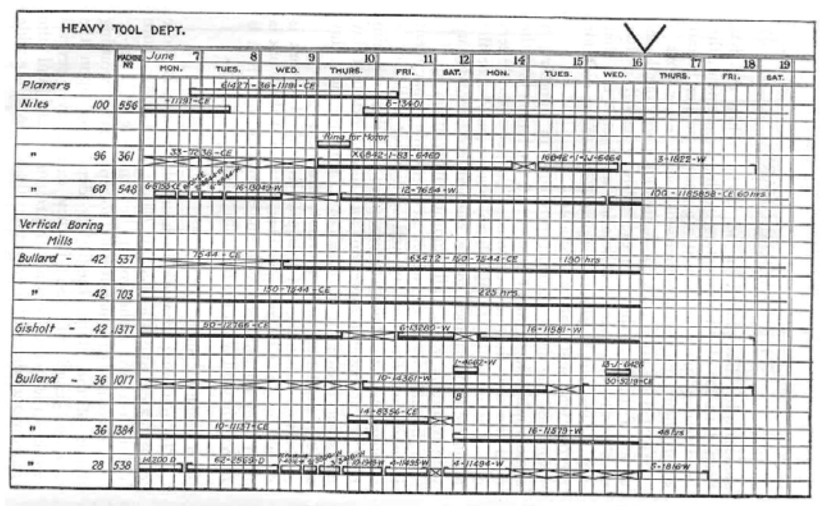

Figure 1. A Gantt Layout Chart (from Clark, 1942).

In conclusion, it can be said that Gantt was a pioneer in developing graphical ways to visualize schedules and shop status. He used time (not just quantity) as a way to measure tasks. He used horizontal bars to represent the number of parts produced (in progress charts) and to record working time (in machine records). His progress (or layout) charts had a feature found in project management software today: the length of the bars (relative to the total time allocated to the task) showed the progress of tasks.

Many firms implemented Taylor’s suggestion to create a production planning office, and production planners modified Gantt’s charts over the years. Mitchell (1939) discusses the role of the production planning department, including routing, dispatching (issuing shop orders) and scheduling. Scheduling is defined as “the timing of all operations with a view to insuring their completion when required.” Mitchell emphasizes that, in some shops, the shop foremen may be responsible for determining which specific worker and machine does which task. In others, the scheduling personnel have already determined this. The foreman, of course, has more insight into the qualitative factors that affect production. Mitchell describes two types of Gantt charts as typical of the graphical devices used to help those involved in scheduling. The Gantt load chart shows (as horizontal lines) the schedule of each machine and the total load on the machine to date. Mitchell's illustration of this doesn't indicate which shop orders are to be produced. The Gantt progress chart shows (as horizontal lines) the progress of different shop orders and their due dates.

Muther (1944) describes scheduling in job shops, saying that foremen decide which work to do and then assign it to operators. Muther discusses the system used to schedule automobile manufacturing, including the dispatching of orders to purchasing, the body plant, the assembly lines, and the shipping department. However, since most production is done on assembly lines, detailed production schedules are not used. Muther also shows a schedule chart used to plan and track tasks for a specific job. Various horizontal bars show the start and end of subassembly tasks, and vertical bars show when subassemblies should be brought together.

MacNiece (1951) begins his discussion of scheduling with loading, which assigns an operation to a specific day or week when the machine (or machine group) will perform it. This loading is finite since it takes into account the number of machines, shifts per day, working hours per shift, days per week as well as the time needed to complete the order. MacNiece also gives a beautiful example of using a Gantt (layout) chart to solve a scheduling problem. The problem is to determine if an order for an assembly can be completed in 20 weeks. The Gantt chart has a row for each machine group and bars representing already planned work to which he adds the operations needed to complete the order. He argues that using a Gantt chart is a much quicker way to answer the question.

Roscoe and Freark (1971) also provide an example of a Gantt chart. It is a graphical schedule that lists the operations needed to complete an order. Each row corresponds to a different operation and lists the machine that will perform the operation and the rate at which the machine can produce parts (parts per hour), from which one can calculate the time required for that operation. Each column in the chart corresponds to a day, and each operation has a horizontal line from the day and time it should start to the day and time it should complete. The chart is used for measuring progress, so a thicker line parallel to the first line shows the progress on that operation to date. The authors state that a "Gantt chart is essentially a series of parallel horizontal graphs which show schedules (or quotas) and accomplishment plotted against time."

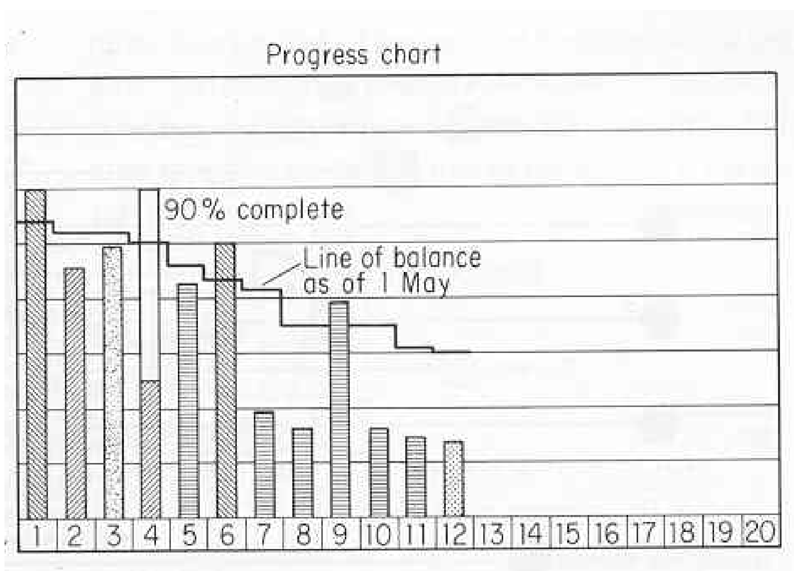

Figure 2. A Line of Balance (from O'Brien, 1969).

The *line of balance* can be used for determining how far ahead (or behind) a shop might be at producing a number of identical assemblies required over time. Given the demand for end items and a bill-of-materials with lead times for making components and completing subassemblies, one can calculate the cumulative number of components, subassemblies, and end items that should be complete at a point in time to meet the demand. This line of balance is used on a progress chart that compares these numbers to the number of components, subassemblies, and end items actually done by that point in time (see Figure 2). The underlying logic is similar to that used by MRP systems, though this author is unaware of any scheduling system that use a line of balance chart today. More examples can be found in O'Brien (1969) and *Production Scheduling* (1973).

Control boards are another important type of scheduling tool. Cox *et al*. (1992) state that a *control board* is "a visual means of showing machine loading or project planning." This is also called a *dispatching board*, a *planning board*, or a *schedule board*. MacNiece attributes planning boards to Taylor. The board described has one row of spaces for each machine. Each space represents one shift and contains one or more cards corresponding to the order(s) that should be produced in that shift, given capacity constraints. A large order requires multiple cards that are placed in consecutive spaces.

The Planalog control board was a sophisticated version developed in the 1960s. A Planalog is a board (up to six feet wide) that hangs on a wall (see Figure 3). The board has numerous rows into which one can insert gauges of different lengths (from 0.25 to 5 inches long). Each gauge represents a different task (while rows do not necessarily represent resources). The length of each gauge represents the task's expected (or actual) duration. The Planalog includes innovative "fences." Each fence is a vertical barrier that spans multiple rows to show and enforce the precedence constraints between tasks. Moving a fence due to the delay of one task pushes all subsequent dependent tasks simultaneously.

4. THE RISE OF COMPUTER ALGORITHMS

Unlike production scheduling in a busy factory, planning a large construction or systems development project is a problem that one can formulate and try to optimize. Thus, it is not surprising that large project scheduling was the first type of scheduling to use computer algorithms successfully.

O'Brien (1969) gives a good overview of the beginnings of the critical path method (CPM) and the Performance Evaluation and Review Technique (PERT). Formal development of CPM began in 1956 at Du Pont, whose research group used a Remington Rand UNIVAC to generate a project schedule automatically from data about project activities. In 1958, the development of PERT started in the office managing the development of the Polaris missile (the U.S. Navy's first submarine-launched ballistic missile). The program managers wanted to use computers to plan and monitor the Polaris program. By the end of 1958, the Naval Ordnance Research Calculator, the most powerful computer in existence at the time, was programmed to implement the PERT calculations. Both CPM and PERT are now common tools for project management.

Computer-based production scheduling emerged later. Wight (1984) lists three key factors that led to the successful use of computers in manufacturing:

1. IBM developed the Production Information and Control System starting in 1965.
2. The implementation of this and similar systems led to practical knowledge about using computers.
3. Researchers systematically compared these experiences and developed new ideas on production management.

O'Brien (1969) describes these early computer-based production scheduling systems, which automated the data collection and processing functions in existence since Taylor's day.

Wight (1984) also describes the success of material requirements planning (MRP), an approach that perfectly suited the computers in use at the time of its development. MRP, in turn, led to the rise of manufacturing resources planning (MRP II) and now enterprise resource planning (ERP) systems.

Rondeau and Litteral (2001) have described the history of MRP and ERP systems. For more about modern systems, see, for instance, Vollmann, Berry, and Whybark (1997).

Interactive, computer-based scheduling eventually emerged from various research projects to commercial systems. Godin (1978) describes many prototype systems. Duersch and Wheeler (1981) describe an early interactive computer-based scheduling program. The program, designed for assembly line production planning, could output graphs of monthly production and inventory levels on a computer terminal to help the scheduling personnel make their decisions. The software used standard strategies to generate candidate schedules that the scheduling personnel modified as needed. The software's key benefit was to reduce the time needed to develop a schedule. Adelsberger and Kanet (1991) use the term *leitstand* to describe an interactive production scheduling decision support system with a graphical display, a database, a schedule generation routine, a schedule editor, and a schedule evaluation routine. By that time, commercial leitstands were available, especially in Germany. The emphasis on both creating a schedule and monitoring its progress (planning and control) follows the principles of Henry Gantt. Similar types of systems are now part of modern manufacturing planning and control systems and enterprise resource planning systems.

Modern computer-based scheduling systems offer numerous features for creating, evaluating, and manipulating production schedules. Seyed (1995) provides a discussion on how to choose a system based on these features. Yen and Pinedo (1994) list the three primary components of a scheduling system: the database, the scheduling engine, and the user interface. The scheduling system may share a database with other manufacturing planning and control systems such as MRP or may have its own database, which may be automatically updated from other systems such as the manufacturing execution system. The user interface typically offers numerous ways to view schedules, including Gantt charts, dispatch lists, charts of resource utilization, and load profiles. The scheduling engine generates schedules and may use heuristics, a rule-based approach, optimization, or simulation. This framework is generally valid, but there exists a wide variety of scheduling software. Organizations such as APICS provide updated information about scheduling software and the vendors who sell them. McKay and Wiers (2004) provide practical guidelines on selecting and implementing scheduling software, and the challenge of implementing effective scheduling systems remains, as it did in Gantt's day (see, for instance, Yen and Pinedo, 1994, or Ortiz, 1996).

In some cases, manufacturing firms have created innovative scheduling systems to meet their particular needs. Each of these systems formulates the problem in a unique way that reflects each firm's specific scheduling objectives, and the system collects, processes, and generates information as part of a larger system of decision-making. Moreover, many years of research on optimization methods have created a large set of powerful algorithms that can be applied to generate schedules, from mathematical programming to searches that use concepts from artificial intelligence. Because a comprehensive review is not possible in this paper, a few examples will be mentioned.

Katok and Ott (2000) use mathematical programming to create a weekly schedule for an aluminum can manufacturing facility. Kuchta et al. (2004) use a mathematical programming approach to develop production schedules for mining at one of the world's largest underground mines. Numao (1994) describes production scheduling in a steel-making plant. Dawande et al. (2004) use a heuristic based on matching and bin packing to solve a slab design problem for a large steel plant.

Not all firms have embraced computer-based scheduling systems. Based on their survey of hundreds of manufacturing facilities, LaForge and Craighead (1998) conclude that computer-based scheduling can be successful if it uses finite scheduling techniques and if it is integrated with the other manufacturing planning systems. Computer-based scheduling can help manufacturers improve on-time delivery, respond quickly to customer orders, and create realistic schedules. Finite scheduling means using actual shop floor conditions, including capacity constraints and the requirements of orders that have already been released. However, only 25% of the firms responding to their survey used finite scheduling for part or all of their operations. Only 48% of the firms said that the computer-based scheduling system received routine automatically from other systems. 30% said that a "good deal" of the data are entered manually, and 21% said that all data are entered manually. Interestingly, 43% of the firms said that they regenerated their schedules once each day, 14% said 2 or 3 times each week, and 34% said once each week.

5. SUMMARY AND CONCLUSIONS

The large changes in production scheduling are due to two key events. The first is Henry Gantt's creation of useful ways to understand the complex relationships between men, machines, orders, and time. The second is the overwhelming power of information technology to collect, visualize, process, and share data quickly and easily, which has enhanced all types of decision-making processes.

The bad news is that many manufacturing firms have not taken advantage of these developments. They produce goods and ship them to their customers, but the production scheduling system is a broken collection of independent plans that are frequently ignored, periodic meetings where unreliable information is shared, expediters who run from one crisis to another, and ad-hoc decisions made by persons who cannot see the entire system. Production scheduling systems rely on human decision-makers, and many of them need help.

This overview of production scheduling tools should be useful to those just beginning their study of manufacturing planning and control. This paper is the only known overview, and it collects descriptions of production scheduling from over 100 years. The author hopes that practitioners and researchers will use this overview to consider what has been truly useful to improve production scheduling practice in the real-world.

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Figure 3. Planalog control board.