THE INSTITUTE FOR SYSTEMS RESEARCH

ISR TECHNICAL REPORT 2007-26

The Legacy of Taylor, Gantt, and Johnson: How to Improve Production Scheduling

Jeffrey W. Herrmann

THE LEGACY OF TAYLOR, GANTT, AND JOHNSON: HOW TO IMPROVE PRODUCTION SCHEDULING

JEFFREY W. HERRMANN

Department of Mechanical Engineering and Institute for Systems Research
University of Maryland, College Park, MD 20742, jwh2@umd.edu

The challenge of improving production scheduling has inspired many different approaches. This paper examines the key contributions of three individuals who improved production scheduling: Frederick Taylor, who defined the key planning functions and created a planning office; Henry Gantt, who provided useful charts to improve scheduling decision-making, and S.M. Johnson, who initiated the mathematical analysis of production scheduling problems. The paper presents an integrative strategy to improve production scheduling that synthesizes these complementary approaches. Finally, the paper discusses the soundness of this approach and its implications on OR research, education, and practice.

Subject classifications: Production/scheduling: sequencing. Professional: OR/MS philosophy.

---

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. Many manufacturing organizations generate and update production schedules, which are plans that state when certain controllable activities (e.g., processing of jobs by resources) should take place. Production schedules coordinate activities to increase productivity and minimize operating costs. A production schedule can identify resource conflicts, control the release of jobs to the 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 “priorities” and “capacity” (Wight, 1984). 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.

Unfortunately, many manufacturers have ineffective production scheduling systems. They produce goods and ship them to their customers, but they use 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 dealing with the swampy complexities of real-world scheduling (discussed in detail by McKay and Wiers, 2004).

Herrmann (2006a) provides a historical perspective on the decision support tools that have been developed to improve production scheduling, from Gantt charts to computer-based scheduling tools. Computer software has been useful in cases. For example, in the 1980s, IBM developed the Logistics Management System (LMS) an innovative scheduling system for semiconductor manufacturing facilities. Fordyce *et al*. (1992) provide an overview of the system, which was eventually used at six IBM facilities and by some customers (Fordyce, 2005).

However, information technology is not necessarily the answer. Based on their survey of hundreds of manufacturing facilities, LaForge and Craighead (1998) conclude that computer-based scheduling can help manufacturers improve on-time delivery, respond quickly to customer orders, and create realistic schedules, but success requires using finite scheduling techniques and integrating them with other manufacturing planning systems. Finite scheduling uses 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. Integration is also difficult. Only 48% of the firms said that the computer-based scheduling system received routine data 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.

Academic research on scheduling problems has produced countless papers on the topic. Pinedo (1995) lists a number of important surveys on production scheduling. Vieira *et al*. (2003) present a framework for rescheduling, and Leung (2004) covers both the fundamentals and the most recent advances in a wide variety of scheduling research topics. However, there are many difficulties in applying this work to real-world situations (Dudek *et al*., 1992).

Given the limitations of applying information technology or analyzing problems mathematically, we conclude that a holistic approach is needed to improve production scheduling.

The elements required to construct the needed approach can be found by examining the history of production scheduling. This paper examines the key contributions of three individuals who improved production scheduling: Frederick Taylor, who defined the key planning functions and created a planning office; Henry Gantt, who provided useful charts to improve scheduling decision-making, and S.M. Johnson, who initiated the mathematical analysis of production scheduling problems.

Each one took a different approach to improve production scheduling. This paper reviews their accomplishments and discusses the perspectives that they adopted. Each perspective looks at the task of production scheduling in a distinct way and thus proposes a different approach to improve it. Taylor changed the organization, Gantt created tools to improve decision-making, and Johnson solved optimization problems.

The paper then presents an integrative strategy to improve production scheduling that synthesizes these complementary approaches. This strategy, which is based on the work of the author and others, was originally presented in Herrmann (2006b), but the current paper examines the key historical antecedents and their relationship to this strategy. Finally, the paper discusses the soundness of this approach and its potential to increase our ability to improve production scheduling.

2. FREDERICK TAYLOR AND THE PLANNING OFFICE

Generally known for his fundamental contributions to scientific management in the late 1800s, Frederick Taylor's most important contribution to production scheduling was his creation of the planning office (described in Taylor, 1911). His separation of planning from execution justified the use of formal scheduling methods, which became critical as manufacturing organizations grew in complexity. It established the view that production scheduling is a distinct decision-making process in which individuals share information, make plans, and react to unexpected events.

In keeping with the idea of specialized work, there were many different jobs in Taylor's planning office, from route clerk to speed boss to inspector (Thompson, 1974). Wilson (2000) lists fifteen different positions. Here we briefly describe some of the positions that are most closely related to scheduling. The route clerk created and maintained routings that specified the operations required to complete an order and the components needed. The instruction card clerk wrote job instructions that specified the best way to perform the operations. The production clerk created and updated a master production schedule based on firm orders and capacity. The balance of stores clerk maintained sheets with the current inventory level, the amount on order, and the quantity needed for orders. This clerk also issued replenishment orders. The order of work clerk issued shop orders and released material to the shop. Recording clerks kept track of the status of each order by updating the route charts and also creating summary sheets (called progress sheets). The relative priority of different orders was determined by the superintendent of production.

An interesting feature of the planning office was the bulletin board. There was one in the planning office, and another on the shop floor (Thompson, 1974). The bulletin board had space for every workstation in the shop. The board showed, for each workstation, the operation that the workstation was currently performing, the orders currently waiting for processing there, and future orders that would eventually need processing there. (In modern software, this bulletin board has been replaced by the dispatch lists that show all of the work waiting for processing at a workstation.)

Many firms implemented versions of Taylor's production planning office. 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 widespread adoption of Taylor's approach reflects the importance of the organizational perspective of scheduling, a system-level view that scheduling is part of the complex flow of information and decision-making that forms the manufacturing planning and control system (McKay *et al.*, 1995; Herrmann, 2004). The rise of information technology did not eliminate the planning functions defined by Taylor; it simply automated them using ever more complex software that is typically divided into modules that perform the different functions more quickly and accurately than Taylor's clerks could (see Vollmann *et al*., 1997, for a detailed description of modern manufacturing planning and control systems).

3. HENRY GANTT AND HIS CHARTS

The man most commonly identified with production scheduling is Henry Gantt, who worked with Taylor at Midvale Steel Company, Simonds Rolling Machine Company, and Bethlehem Steel and then worked as a consultant (for more about Gantt's life, see Alford, 1934). In *Work,* *Wages, and Profits* (originally published in 1916), Gantt explicitly described scheduling, especially in the job shop environment. He discussed the need to coordinate activities to avoid "interferences" but warned that the most elegant schedules created by planning offices are useless if they are ignored.

To improve managerial decision-making, Gantt created innovative charts for visualizing planned and actual production. 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."

Gantt designed his charts so that foremen or other supervisors could quickly know whether production was on schedule, ahead of schedule, or behind schedule. His charts were improvements to the forms that Taylor developed for the planning office. Notably, he created charts for the personal use of supervisors in a format that they could carry with them at all times (unlike Taylor's bulletin board, which was only useful to those near those central locations). Wilson (2003) reviews the history of the Gantt chart and describes its impact on project management. Wilson emphasizes that, although they were part of Taylor's broader manufacturing planning system, Gantt charts were meant to help individual managers make better decisions.

It is important to note that Gantt created many different types of charts, based on the specific needs of managers at Brighton Mills, Frankford Arsenal, and other manufacturing organizations. He also created charts during World War I to improve the management of new ship construction and shipping operations.

His charts attempt to make schedules useful. In *Organizing for Work* (originally published in 1919), Gantt gave two principles for his charts: one, measure activities by the amount of time needed to complete them; two, use the space on the chart to represent the amount of the activity that should have been done in that time.

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."

Gantt's charts have had great influence. Gantt charts are ubiquitous in production scheduling and project management. 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.

Gantt's work on charts reflects the decision-making perspective, which is the view that scheduling is a decision that a human must make. Schedulers perform a variety of tasks and use both formal and informal information to accomplish these. Schedulers must address uncertainty, manage bottlenecks, and anticipate the problems that people cause (McKay and Wiers, 2004). Gantt's charts attempt to provide clearly the key data needed to make these decisions.

4. JOHNSON AND THE FLOW SHOP SCHEDULING PROBLEM

Asked by a colleague at the RAND Corporation for help with a "book-binding" problem (according to Dudek *et al*., 1992), S.M. Johnson analyzed the properties of an optimal solution and presented an elegant algorithm that constructs an optimal solution. The published paper (Johnson, 1954) not only analyzed the two-stage flow shop scheduling problem (a basic result in the theory of production scheduling) but also considered problems with three or more stages and identified a special case for the three-stage problem.

The paper inspired a great deal of work on other versions of the flow shop scheduling problem and set a standard for the analysis of production scheduling problems of all kinds from the very beginning. Jackson (1956) generalized Johnson's results for a two-machine job shop scheduling problem. Smith (1956) considered some single-machine scheduling problems with due dates. Both of these early, important works cited Johnson's paper and used the same type of analysis.

Johnson's paper epitomizes the problem-solving perspective, in which scheduling is an optimization problem that must be solved. A great deal of research effort has been spent developing methods to generate optimal production schedules, and countless papers discussing this topic have appeared in scholarly journals. Typically, such papers formulate scheduling as a combinatorial optimization problem independent from the manufacturing planning and control system in place. Schedule generation methods include most of the literature in the area of scheduling. Interested readers should see Pinedo and Chao (1999), Pinedo (1995), or similar introductory texts on production scheduling. Researchers will find references such as Leung (2004) and Brucker (2004) useful for more detailed information about problem formulation and solution techniques.

Although there exists a significant gap between scheduling theory and practice (as discussed by Dudek *et al*., 1992; Portougal and Robb, 2000; and others), researchers have used better problem-solving to improve real-world production scheduling in some settings (see, for instance, Zweben and Fox, 1994; Dawande *et al*., 2004; Bixby *et al.*, 2006; Newman *et al.*, 2006). It may be that the results of production scheduling theory are applicable in some, but not all, production environments (Portougal and Robb, 2000).

5. AN INTEGRATIVE STRATEGY

The contributions of Taylor, Gantt, and Johnson reflect three different perspectives on production scheduling. If each of these perspectives is a valid one, then we should exploit them in a coordinated way. This section presents an integrative strategy for improving production scheduling.

Based on the above discussion, it is clear that these three perspectives form a hierarchy, with the problem-solving perspective at the lowest level, the decision-making perspective in the middle, and the organizational perspective at the highest level. Figure 1 illustrates this relationship in a conceptual way. Moving among these three perspectives corresponds to shifting one's focus from the production planning organization to one person to one task. Thus, this hierarchy of perspectives does not correspond to a temporal or spatial decomposition of the manufacturing system. Instead, it is related to a task-based decomposition of the production scheduling activity.

The layered structure of Figure 1 is not meant to correspond to the different time frames of production planning; instead, the layers are different ways to view production scheduling. Moving from one layer to the layer below is like zooming in on a scheduling decision, in some sense. In the organization layer, information moves from person to person through information-gathering and decision-making tasks. For example, one person sets a due date, another reviews it and negotiates a new one, and a third uses it to make a schedule. In the decision-making layer, the scheduler uses this information to solve current problems and avoid future ones. For instance, he checks the due date to evaluate the progress of an order, tries to get the due date changed, uses it to persuade someone to work on the order, and enters it into a scheduling routine. In the problem-solving layer, scheduling algorithms perform calculations on the data to generate and evaluate schedules. For instance, due dates can be used to sequence jobs and to measure tardiness.

This hierarchy suggests the following integrative strategy for improving production scheduling. It is important to note that, throughout this process, the input and feedback of those doing and supervising production scheduling must be included.

1. Study the production scheduling system. Create a model of the persons in the production scheduling system, their tasks and decisions, and the information flow between them. Swimlanes, GRAI models, and other approaches can be used (Herrmann, 2004; Guinery and MacCarthy, 2005).
2. Analyze this model and determine if changes to the information flow, task assignments, or decision-making responsibilities are desirable and feasible. If changes are needed, go to Step 6.
3. Given that the patterns of information flow are satisfactory, consider the decision-making process that the scheduler uses. Determine if the scheduler is able to manage bottleneck resources effectively, understand the problems that occur (whether caused by others or by themselves), and take steps to handle future uncertainty (McKay and Wiers, 2004). If not, changes in these areas are suggested. If changes are needed, go to Step 6.
4. Consider dividing the workload between the human scheduler and a decision support tool. As suggested by McKay and Wiers (2006), the design of a scheduling decision support tool should be guided by the following concepts: (1) the ability of the scheduler to directly control the schedule (called “transparency”), (2) the amount of uncertainty in the manufacturing system, (3) the complexity of the scheduling decison, and (4) how well-defined the scheduling decision is.

An ill-defined scheduling decision is characterized by incompleteness, ambiguity, errors, inaccuracy, and possibly missing information (McKay and Wiers, 2006). If a new or improved decision support tool is needed, go to Step 6.

5. Finally, consider improving production scheduling problem-solving by developing a more appropriate problem formulation or installing more powerful algorithms that can find better solutions faster. Consult the enormous literature on scheduling problems for different approaches to these challenges.

6. Implement the changes that were selected.

7. Assess the impact of the implemented changes and repeat the above steps as necessary.

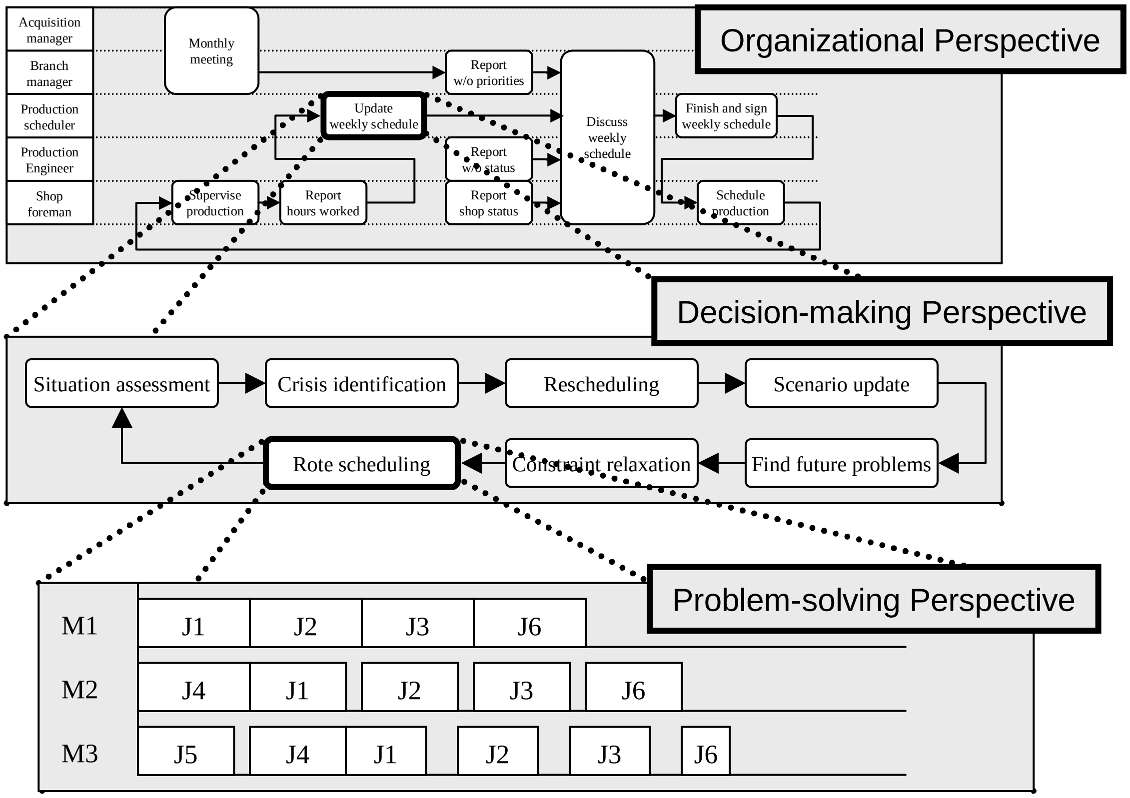

Figure 1. Perspectives on production scheduling.

6. DISCUSSION

The integrative strategy presented here includes a variety of techniques and requires creativity to identify the right tools and adapt them appropriately for a particular situation. It is not a simple algorithm that specifies precisely what to do. Although it is not possible to evaluate the approach quantitatively outside of a specific setting, we will make some observations to establish its usefulness for improving production scheduling and its ability to advance the field of operations research.

The historic work of Taylor, Gantt, and Johnson demonstrate the importance of three important perspectives: the organizational, the decision-making, and the problem-solving. This strategy explicitly incorporates all three. The progression within the strategy from one perspective to the next follows a well-established approach to system design, in which one considers the entire system before moving to its subsystems and then its components. Moreover, this progression corresponds to the historical development of these perspectives. Taylor changed the organization, then Gantt developed charts to improve decision-making, and finally Johnson studied the optimization problem.

In addition, this strategy uses multiple perspectives and involves the persons that have the problem in order to increase understanding of the real-world situation, which is an important objective (cf. Hall, 1985; Meredith, 2001). The strategy calls for implementing solutions, evaluating their performance, and repeating the process in a spirit of continuous (continual) improvement.

More generally, this strategy provides an interdisciplinary structure to attack the swampy complexities of real world messes, as the earliest work in operations research did (Miser, 1987). Because it addresses messy problems, requires the use of multiple techniques, and focuses on understanding the situation, this strategy contributes to management engineering, an underdeveloped area of operations research that falls between the straightforward application of existing techniques and the research activities that add to our body of knowledge (Corbett and Van Wassenhove, 1993).

7. CONCLUSIONS

From a hundred years of work on improving production scheduling, three important perspectives stand out: the organizational, the decision-making, and the problem-solving. Frederick Taylor, Henry Gantt, and S.M. Johnson made important original contributions to each perspective and greatly influenced those that followed.

Because no single perspective is sufficient alone, the integrative strategy presented in this paper builds on their legacies and attempts to put the three different perspectives in proper relationship to each other, which will enhance the value of all. Applying this strategy involves a set of approaches to improving production scheduling and a wide range of skills that go beyond useful talents in analyzing optimization problems and programming decision support tools. Thus, establishing an interdisciplinary team may be the best way to use this strategy. A final implication is that educational programs may need to design new interdisciplinary courses that cover the constituent topics to prepare engineers and consultants more appropriately to improve production scheduling and other decision-making activities that can benefit from a similar strategy.

It is the author's hope that this paper will help production schedulers, engineers, and researchers understand the history of production scheduling, will show them that this history provides useful suggestions that are relevant today, and will encourage them to develop more powerful approaches to improve production scheduling.

ACKNOWLEDGMENTS

The author is grateful for the support of collaborators who provided opportunities to help improve production scheduling systems, the assistance of students who performed the work, and the encouragement of colleagues, especially Kenneth Fordyce, who shared their valuable time and ideas.

REFERENCES

Alford, Leon P., *Henry Laurance Gantt: Leader in Industry*, ASME, New York, 1934.

Bixby, Robert, Rich Burda, and David Miller, “Short-interval detailed production scheduling in 300mm semiconductor manufacturing using mixed integer and constraint programming,” 17th Annual SEMI/IEEE Advanced Semiconductor Manufacturing Conference, pages 148-154, Boston, 2006.

Brucker, Peter, *Scheduling Algorithms,* Fourth Edition, Springer-Verlag, Berlin, 2004.

Dudek, R. A., S.S. Panwalkar, and M.L. Smith, “The lessons of flowshop scheduling research,” *Operations Research*, Vol. 40, No. 1 (Jan. - Feb., 1992), pp. 7-13.

Clark, Wallace, *The Gantt Chart, a Working Tool of Management*, second edition, Sir Isaac Pitman & Sons, Ltd., London, 1942.

Corbett, Charles J., and Luk N. Van Wassenhove, “The natural drift: what happened to operations research?” *Operations Research,* Volume 41, Number 4, pages 625-640, 1993.

Cox, James F., John H. Blackstone, Jr., and Michael S. Spencer, editors, *APICS Dictionary*, American Production and Inventory Control Society, Falls Church, Virginia, 1992.

Dawande, M., J. Kalagnanam, H.S. Lee, C. Reddy, S. Siegel, and M. Trumbo, “The slab-design problem in the steel industry,” *Interfaces,* Volume 34, Number 3, pages 215-225, 2004.

Dudek, R.A., S.S. Panwalkar, and M.L. Smith, "The lessons for flowshop scheduling research," *Operations Research*, Volume 40, Number 1, pages 7-13, 1992.

Fordyce, K., personal communication, 2005.

Fordyce, K., Dunki-Jacobs, R., Gerard, B., Sell, R., and Sullivan, G., "Logistics Management System: an advanced decision support system for the fourth tier dispatch or short-interval scheduling," *Production and Operations Management*, **1**(1):70-86, 1992.

Gantt, Henry L., *Work, Wages, and Profits*, second edition, Engineering Magazine Co., New York, 1916. Reprinted by Hive Publishing Company, Easton, Maryland, 1973.

Gantt, Henry L., *Organizing for Work*, Harcourt, Brace, and Howe, New York, 1919. Reprinted by Hive Publishing Company, Easton, Maryland, 1973.

Guinery, J.E., and B.L. MacCarthy, "The Prochart Toolkit for the re-design of production planning, scheduling and control processes," Proceedings of the 18th International conference on Production Research (ICPR18), Salerno Italy, July 2005.

Hall, Randolph W., "What's so scientific about MS/OR?" *Interfaces,* Volume 15, Number 2, pages 40-45, 1985.

Herrmann, Jeffrey W., "Information flow and decision-making in production scheduling," 2004 Industrial Engineering Research Conference, Houston, Texas, May 15-19, 2004.

Herrmann, Jeffrey W., "A history of production scheduling," in *Handbook of Production Scheduling*, Springer, New York, 2006a.

Herrmann, Jeffrey W., "Improving production scheduling: integrating organizational, decision-making, and problem-solving perspectives," Proceedings of the 2006 Industrial Engineering Research Conference, Orlando, Florida, May 20-24, 2006b.

Hopp, Wallace J., and Mark L. Spearman, *Factory Physics*, Irwin/McGraw-Hill, Boston, 1996.

Jackson, J.R., "An extension of Johnson's results on job lot scheduling," *Naval Research Logistics Quarterly*, Volume 3, pages 201-203, 1956.

Johnson, S.M., "Optimal two- and three-stage production schedules with setup times included," *Naval Research Logistics Quarterly*, Volume 1, pages 61-68, 1954.

LaForge, R. Lawrence, and Christopher W. Craighead, Manufacturing scheduling and supply chain integration: a survey of current practice, American Production and Inventory Control Society, Falls Church, Virginia, 1998.

Leung, Joseph Y-T., editor, *Handbook of Scheduling: Algorithms, Models and Performance Analysis*, Chapman & Hall/CRC, Boca Raton, Florida, 2004.

McKay, K.N., F.R. Safayeni, and J.A. Buzacott, "An information systems based paradigm for decisions in rapidly changing industries," *Control Engineering Practice*, Volume 3, Number 1, pages 77-88, 1995.

McKay, Kenneth N., and Vincent C.S. Wiers, *Practical Production Control: a Survival Guide for Planners and Schedulers*, J. Ross Publishing, Boca Raton, Florida, 2004. Co-published with APICS.

McKay, Kenneth N., and Vincent C.S. Wiers, "The human factor in planning and scheduling," in *Handbook of Production Scheduling*, J.W. Herrmann, ed., Springer, New York, 2006.

Meredith, Jack R., "Reconsidering the philosophical basis of OR/MS," *Operations Research*, Volume 49, Number 3, pages 325-333, 2001.

Miser, Hugh J., "Science and professionalism in operations research," *Operations Research*, Volume 35, Number 2, pages 314-319, 1987.

Mitchell, William N., *Organization and Management of Production*, New York, McGraw-Hill, 1939.

Newman, Alexandra, Michael Martinez, and Mark Kuchta, “A review of long- and short-term production scheduling at LKAB's Kiruna Mine,” in *Handbook of Production Scheduling*, Springer, New York, 2006.

Pinedo, Michael, *Scheduling: Theory, Algorithms, and Systems*, Prentice Hall, Englewood Cliffs, New Jersey, 1995.

Pinedo, Michael, and Xiuli Chao, *Operations Scheduling with Applications in Manufacturing and Services*, Irwin McGraw Hill, Boston, 1999.

Portougal, Victor, and David J. Robb, “Production scheduling theory: just where is it applicable,” *Interfaces*, Volume 30, Number 6, pages 64-76, 2000.

Smith, W.E., “Various optimizers for single stage production,” *Naval Research Logistics Quarterly*, Volume 3, pages 59-66, 1956.

Taylor, Frederick W., *Shop Management*, Harper and Bros., New York, 1911.

Thompson, C. Bertrand, *The Taylor System of Scientific Management*, Hive Publishing Company, Easton, Maryland, 1974. (Reprint of the 1917 edition published by A.W. Shaw Co., Chicago.)

Vieira, Guilherme E., Jeffrey W. Herrmann, and Edward Lin, “Rescheduling manufacturing systems: a framework of strategies, policies, and methods,” *Journal of Scheduling*, Volume 6, Number 1, pages 35-58, 2003.

Vollmann, Thomas E., William L. Berry, and D. Clay Whybark, *Manufacturing Planning and Control Systems*, fourth edition, Irwin/McGraw-Hill, New York, 1997.

Wight, Oliver W., *Production and Inventory Management in the Computer Age*, Van Nostrand Reinhold Company, Inc., New York, 1984.

Wilson, James M., Scientific management, in *Encyclopedia of Production and Manufacturing Management*, Paul M. Swamidass, ed., Kluwer Academic Publishers, Boston, 2000.

Wilson, James M., "Gantt charts: a centenary appreciation," *European Journal of Operational Research*, Volume 149, pages 430-437, 2003.

Zweben, M., and M. Fox, editors, *Intelligent Scheduling*, Morgan and Kaufmann, San Mateo, 1994.