Production Scheduling Theory: Just Where Is It Applicable?

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A proliferation of scheduling research has done little to improve production planning practice, despite calls for more comprehensive models. Using a four-factor classification of planning environments (planning level, production type, production strategy, and production cycle time) we show scheduling theory is relevant in few settings. For example, in increasingly common short-cycle environments, where production cycle times are shorter than the planning period, the order in which one processes jobs is seldom important. Moreover, even in long-cycle environments, capacity is seldom fixed, with managers often negotiating for enough capacity to make scheduling fairly easy. Based on extensive consulting experience in Australasia, we call for caution in applying scheduling theory. While complex models are pertinent in some cases, more benefit often arises from establishing appropriate performance measures, planning periods, capacity negotiation processes, and uncertainty reduction measures.

For more than 40 years academics have plumbed the depths of scheduling theory, often with little to show for their efforts beyond journal pages. Researchers venturing into manufacturing plants have found environments with little resemblance to those presumed in the literature. Many have called for reductions in the

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gulf between theory and practice [Graves 1981; Sen and Gupta 1984; Melnyk, Vickery, and Carter 1986; McKay, Safayeni, and Buzacott 1988, 1995; Buxey 1989; MacCarthy and Liu 1993]. Researchers have responded to some of these demands for realism, for example, by allowing for uncertainty (processing times, engineering changes, machine failure) and dynamic settings ("hot" jobs, preemption), but there is still a lack of understanding about applying scheduling models in manufacturing.

It would appear that classical scheduling theory has contributed little to managing real operations. Dudek, Panwalker, and Smith [1992, p. 10] commented that, "At this time, it appears that one research paper (that by Johnson 1954) set a wave of research in motion that devoured scores of person-years of research time on an intractable problem of little practical consequence." While we do not fully agree with that, our experience in a wide range of manufacturing companies shows that many scheduling problems thought to occur in practice are only apparent problems.

Classical scheduling theory may have limited applicability.

During the past decade we have consulted to nine manufacturing firms in New Zealand and Australia with regard to their problems in production planning and scheduling. In these projects, as well as our supervision of many student projects and theses, we have found that theoretical optimization-based scheduling models are rarely useful in solving the problems. Indeed, we have found only one company that a complex scheduling algorithm would help. This has led us to answer the inevitable question of why the gap between theory and practice is so wide. Our answer is that the structure of production-planning systems (hierarchy, planning periods, and so forth) renders much production-scheduling theory redundant. With our consulting experience limited to narrow markets and moderate volumes of production in Australasia, we do not claim universal applicability for our ideas, although they are being increasingly recognised in the literature and at conferences.

Of the nine companies we studied (two steel, two food, one car assembly, one furniture components, one household appliances, one paper, and one wood products), the one that could benefit from using a full-scale scheduling model was a steel-manufacturing plant in the Australasia/Pacific Rim region that we first visited in 1994. The mill is small by world standards, producing about 400 tonnes of steel annually per employee (Tokyo Steel produces 2,610 tonnes per employee), and it is not fully automated. It is, however, a fully integrated high-tech plant that includes operations for steel-slab production and mills for both hot-roll and cold-roll processing into either pipe or sheet product. In addition, it has finishing plants for galvanizing and painting the finished product. The company operates in a niche market filling mostly small orders, offering a large variety of products, and accepting most orders. Production planning must cope with complexity and avoid unsatisfactory service levels. Here the production planning required an optimization-based aggregate capacity-planning algorithm.

Typology

Production scheduling occurs within environments characterized by four factors [Portougal and Oliver 1996]:

—Planning level (company, aggregate, shop-floor),

—Production type (job-shop, batch, flow-shop),

—Production strategy (make to order, make to stock), and

—Production cycle time (long or short).

Planning Level

To make profits, companies need planning (and control) systems at both the operational (shop-floor) and strategic (company) levels. However, they generally understand [Anthony 1965] that they need at least one additional (aggregate) level to plan for the time between the immediate future and the distant future (Table 1). They may want further levels if the benefits of increased control outweigh the costs for additional administration and loss of flexibility.

The concept of planning levels is closely connected to the management structure of the organization—from company level, to division (if applicable), and so on, down to the management of shop-floor teams. It is not essential that each organizational level have a full-scale planning system. In our experience, companies always have planning systems at the top (company) and bottom (shop floor). While managers at other organizational levels may be guided by the company-level plans, they often introduce one or two artificial aggregate planning levels for purposes of control, developing procedures for planning and control for one or several organizational levels in the company.

As an illustration, the previously mentioned steel company describes its planning system as a three-level hierarchy—an 18-month corporate-planning level, followed by a three-month order-acceptance-planning level, and finally a one-week shop-floor planning level. The company does not use aggregate capacity-planning to plan production but instead uses a reactive approach, an order-assignment proce-

Planning Level (PL)	Production Unit (PU)	Planning Horizon (PH)	Planning Period (PP)	Planning Item (PI)
Company	Company as a whole	1, 2, or 3 years	1, 3, or 12 months	End products or volumes of product groups
Aggregate	Manufacturing sections or groups of processes	1, 3, or 12 months	1 week or 1 month	Assemblies or subassemblies or stages of the product
Shop floor	Groups of (or individual) machines or processes	1 week or 1 month	1 day or 1 shift	Batch of parts or single operations on batches of parts

Table 1. In these recommended planning parameters, for continuity and stability it is vital that the planning horizon at a planning level equals the planning period at the planning level one level above.

dure to book available capacity for specific orders (capacity booking), and it was here that we identified a real need for a scheduling model. Planners try to support the company's goals of satisfying customers and keeping production costs low. An order for a finished product such as galvanized sheet steel triggers a series of orders to upstream processes. When they schedule delivery dates for finished product, planners set the dates for dependent-part processes. Simple capacity balancing for each plant separately here does not work. The capacities of plant units are not in balance, causing production units to be overcommitted or idle. Delivery dates are based on the availability of feed stock. Interruptions in the supply of feed stock from upstream production units create havoc for downstream operations. The severity of the problems is a function of the number of production units affected, the number of stock lines in the production system, and the number of customer orders being processed.

Prior to an upcoming planning period, each planning level provides plans for the production unit(s) (PUs) at its organizational level(s). At the end of the period, it collects feedback on performance. The planning levels must preserve continuity, making sure the plans for each organizational level are detailed versions of the top-level plan and making sure the feedback at the top levels is an aggregation of feedback from the lower levels [Beischel and Smith 1991].

Depending on the planning level, individual PUs may correspond to a company, shop, workstation, team, or single machine, and within each planning period (PP) they are free to schedule the work required of them. The choice of planning horizons and periods is influenced by many factors, for example, the company's management system and culture, and cost and control goals. Long planning periods increase work-in-process inventory and lead times but provide a PU with freedom and flexibility to improve productivity [Bertrand, Wortmann, and Wijngaard 1990]. Recently some companies have reduced the number of planning levels or increased planning periods or both. For example, Volvo's auto-assembly works in Sweden used multiskilled teams to assemble cars. In the past, the planning period on the shop floor was one to three minutes (the rhythm of the production line) and thus every worker had an assignment (dictated by the speed of the conveyor) of what to do in each PP. Volvo management, having sufficient trust in the effectiveness of its teams, extended the shop-floor PP to one day (that is, leaving the scheduling of the work for each day up to the work teams).

While hierarchical planning is not a novel concept, planners must identify the planning level intended for any scheduling model, because each level has different problems.

Production Type

Also important is the type of production: flow shop, batch manufacturing, or job shop. (We will not consider hybrid processes and project mode.)

In operations management, production type implies relationships among variety, volume, and process. (In classical scheduling, the terms *job shop*, *flow shop*, and *open shop* are defined according to the technological constraints on sequencing and processing operations or jobs, rather than the variety of products present.) Product variety and volume are generally seen as inversely related—if variety is high, volume is low, and vice versa. This logically leads to using job-shop processes for few of a kind, and flowlines for high volumes of few products [Hill 1994]. However, market and technological forces are changing traditional paradigms of manufacturing. The market demand for flexibility and the many niche markets have made rigid flow-shop production infeasible and have promoted the rise of batch manufacturing [Womack, Jones, and Roos 1990, p. 13]. While batch manufacturing is conceptually a flow shop with modest variety (10 to 30 products) where the cost of setups has been mitigated by increased productivity, it is quite different from a flow shop from a planning and scheduling point of view. Scheduling theory, which for the most part remains directed at job-shop and flow-shop environments, provides little help here. Rather, many of the critical issues in batch manufacturing pertain to the ability of a firm to increase variety by decreasing setup times (which still comprise a large portion of capacity).

The bargaining process is seldom treated in the literature.

Production Strategy

Manufacturers either make to order (MTO) or make to stock (MTS). Firms seeking to improve their utilization of capacity and their lead times may adopt an assemble-to-order strategy, which can be considered a variation of MTS. Generally MTO or MTS dominates in an organization. Food production is, in our experience, 90 to 95 percent MTS, and steel production is typically 90 percent MTO (where the risk of high inventory-carrying costs and high manufacturing costs outweighs the benefits of short lead times for customer orders).

From a planning point of view, these are the essential characteristics of MTO and MTS strategies:

—In an MTO company, the customer's order comes first, followed by production during a quoted lead time. The due date is firm, and the goal is to meet this due date. Rescheduling an order or shipping an order late affects an external customer.

—In an MTS company, production comes first, and the customer's order comes second. Planners base due dates on the current stock of finished goods and the current utilization of capacity.

Although the only major difference between MTO and MTS appears to be externally versus internally specified due dates, planning production is strongly influenced. MTS permits greater flexibility in rescheduling, as delays affect only the stock levels (frequently only those of safety stock); planners have the scope to improve operating efficiency by adjusting the (endogenous) due dates.

Production Cycle Time

At each level, the production-cycle time (lead time) for a product is made up of two components: a technological component comprising run time (of the batch), setup time, changeover time, and travel time between work centers; and a system component comprising queueing and

	Turning, hours	Drilling, hours	Grinding, hours
Job 1	100	50	43
Job 2	27	32	45
Job 3	123	45	38
Job 4	144	68	37
Job 5	122	32	54
Job 6	90	50	51
Regular capacity Vector **P** (hours)	$P_1 = 220$	$P_2 = 110$	$P_3 = 100$

Table 2. Production requirements (turning, drilling, and grinding) vary for six jobs. The capacity available in a planning period (here one week) for each of the three production units (PUs) is shown in the last row.

waiting. The system time is a function of the variety of work undertaken.

A key factor in determining whether scheduling theory is applicable or not is the length of time a production unit requires to complete the work it is assigned in a planning period (time bucket). Where the production-cycle time is less than the planning period (CT $\leq$ PP), we have a short cycle, and the PU can produce the items allocated to it within the planning period. Where CT $>$ PP (long cycle), we have a more complex set of production-planning problems. Planners make a plan for the planning period, but few of the production stages fit within the planning period. Not all stages will start and finish inside the PP: some will start inside the PP but not end until after the PP ends and others will start prior to the PP and finish during or after the PP. In this case, managing planning and control requires a large amount of technical information and nontrivial scheduling. All theoretical scheduling problems assume long-cycle environments.

As an illustration of how long-cycle situations are intrinsically more difficult than short-cycle situations, consider a production process comprising multiple stages, with several production units (PUs) taking part in the process in a fixed sequence. This situation always occurs when the production cycle is long. Here we limit our attention to the simple case of a single resource at each production stage.

The example reflects a job-shop environment in which there are three PUs, specialized in turning, drilling, and grinding. The PUs are to produce the jobs during the planning horizon. Table 2 shows the job requirements and capacity characteristics of the PUs. The planning period is equal to one week, and the cycle time for each operation is also one week.

Planning requires considering each job as a whole, and each machine and period simultaneously. Here, the planning horizon must extend three weeks, comprising the jobs performed by each PU for each planning period (PP) in the horizon. Different plans may result in different planning horizons, job completion dates, overtime requirements, and PU utilization figures (Table 3). These should be taken into account.

PU1	Week 1	Week 2	Week 3
Job (hours)	Job 1 (100)	Job 2 (27)	Job 3 (123)
Job (hours)	Job 5 (122)	Job 4 (144)	Job 6 (90)
Production requirements vector **T** (hours)	$T_1 = 222$	$T_1 = 171$	$T_1 = 213$
Regular capacity vector **P** (hours)	$P_1 = 224$	$P_1 = 224$	$P_1 = 224$
PU2	Week 2	Week 3	Week 4
Job (hours)	Job 1 (50)	Job 2 (32)	Job 3 (45)
Job (hours)	Job 5 (32)	Job 4 (68)	Job 6 (50)
Production requirements vector **T** (hours)	$T_1 = 82$	$T_1 = 100$	$T_1 = 95$
Regular capacity vector **P** (hours)	$P_1 = 110$	$P_1 = 110$	$P_1 = 110$
PU3	Week 3	Week 4	Week 5
Job (hours)	Job 1 (43)	Job 2 (45)	Job 3 (38)
Job (hours)	Job 5 (54)	Job 4 (37)	Job 6 (51)
Production requirements vector **T** (hours)	$T_1 = 97$	$T_1 = 82$	$T_1 = 89$
Regular capacity vector **P** (hours)	$P_1 = 100$	$P_1 = 100$	$P_1 = 100$

Table 3. This is one set of feasible production schedules for the three planning units, PU1, PU2, and PU3.

Clearly, scheduling issues arise in long-cycle situations such as this. One must decide which jobs to perform in each planning period, as it is impossible to complete every job in a single (planning) period. Short-cycle situations (such as would occur if job times were reduced, for example, by a factor of five, or the capacity vector increased by a factor of five) are very different in that all jobs can be completed within the planning period. Sequencing and scheduling is not an issue.

As the CT/PP ratio depends on the length of the planning period, one way to reduce planning difficulties is to increase the planning period, as Volvo did when it increased the shop-floor planning period to one day. As the cycle time (the time for the full assembly of one vehicle) was one to three hours, Volvo had effectively transformed a long-cycle environment (CT/PP > 1) into a short-cycle environment (CT/PP < 1). In this case, the experiment actually failed, indicating that increasing the PP as a means of planning simplification must be used with caution—only when the work force is qualified to take on the responsibility of planning and organizing the production effectively.

Once management has determined a PP for a PU, it can be left to organize its own activities. In effect, the PP corresponds to a management treaty between planning levels. By increasing the PP, the higher level gives the team greater flexibility and thus greater potential for improving productivity. However, this also decreases organizational control in terms of planning. Management must be sure that the PP reflects the degree of confidence it has in the PU's ability to control its own performance.

In the steel company, the six production areas have different cycle times, the longest being three days. To provide for management processing time (the PP is set as one week, and one cannot set a lead time smaller than one PP) and a capacity buffer, planners set lead times at one week for each section (six weeks for all the processes). However, despite the capacity buffer, the firm does not achieve a dependable six-week production cycle. Since they have competing goals, units often make production decisions independently of the system, interrupting the supply of feed stock to downstream units. Clearly the culture of the organization does not warrant such a long PP. Cutting the PP down to one day would have a double benefit: it would help to reduce the lead time and at the same time restrict the freedom to make wrong decisions.

The CT/PP ratio also depends on the length of the cycle time. The other way to reduce planning difficulties is to reduce the CT. This approach, supported by the just-in-time philosophy, brings many benefits to production (for example, quality). Where, perhaps after great efforts to reduce CT, long-cycle environments remain, scheduling theory becomes pertinent.

The Rarity of Long-Cycle Environments

Theoretical scheduling models assume a long-cycle (LC) environment (multiple machines, with the processing times of some operations longer than the planning period). In our experience of Australasian manufacturing, the LC environment is rare (Table 4). With few exceptions, planning at the company level is short cycle (because companies use long planning periods), and planning in flow-shop environments is short cycle (as a result of equipment and manufacturing technology designed to reduce cycle times).

If we characterize the production environment using the four-factor typology (three planning levels, three production types, two production strategies, and two production-cycle times) which gives 36 ($3 \times 3 \times 2 \times 2$) possible combinations, scheduling may be problematic in only eight of the 36 environments: (aggregate, shop-floor) × (batch, job-shop) × (MTO, MTS) × (long cycle).

As learning organizations move towards longer planning periods and away from job-shop production, short-cycle situations (CT≤PP) are becoming even more common. For example, the two food-product companies and the wood-product com-

			Production cycle time		
Industry	Production type	Dominant production strategy	Company level	Aggregate level	Shop-floor level
Steel (two companies)	Job shop	MTO	Short	Long	Long
Furniture components	Batch	Mixed	Short	Long	Short
Food (two companies)	Batch	MTS	Short	Short	Short
Wood products	Batch	Mixed	Short	Short	Short
Household appliances	Batch	MTO	Short	Short	Long
Car assembly	Flow shop	MTO	Short	Short	Short
Paper	Batch	MTS	Short	Short	Short

Table 4. For nine Australasian manufacturers, only six of the 27 scheduling environments are long cycle.

pany in our sample of nine companies have increased their planning periods at the aggregate level from one shift to one week after adopting policies to give production teams more freedom to plan and organize their work. In short-cycle environments, the problem is not so much scheduling as balancing capacity. The simple scheduling rule here is to load jobs until you reach capacity. Sequencing the jobs is irrelevant so long as you can complete the work within the planning period. When production cycle times are long (for example, in steel production), technological constraints make the order in which jobs are performed pertinent.

Capacity Issues

Even in the eight environments (of the 36 in the classification scheme) in which scheduling may be problematic, scheduling theory may still be inapplicable, because it is based on questionable assumptions concerning capacity. At the level of a production unit (PU) responsible for multiple resources (machines or production lines), one would ideally seek to minimize excess capacity subject to the total planned workload not exceeding available capacity. (We provide a mathematical description in the appendix.) Since the primary concern is to balance capacity and workload to make implementation easy, this description of the model ignores possible technological constraints (assuming these can be transferred to the PU scheduler). However, a more fundamental concern in adopting this approach is how capacity is defined and indeed whether it can be assumed to be a fixed vector. We have observed at least four definitions of capacity in practice:

(1) Design capacity (with a benchmark of, for example, eight workers each working eight hours per day) is the maximum output that the PU has been designed to produce in ideal conditions with no restrictions or interruptions (typically assuming a fixed number of workers working a fixed number of hours per week each).

(2) Effective capacity is the maximum possible output given a particular production environment and its accompanying impediments to productivity (changeover time, setup requirements, scheduling complexity, time for machine maintenance). The magnitude of these losses is clearly dependent on production scheduling, and thus effective capacity varies with time.

(3) (Historically) demonstrated capacity is the typical real-life output rate of the PU. This figure includes all the undesirable and unplanned interruptions to production, such as machine breakdowns, operator variation, scrap material, and organization and planning inefficiencies. Demonstrated capacity may be much lower than effective capacity. In New Zealand firms, we have found many cases in which average capacity utilization (that is, demonstrated capacity/design capacity) is less than 50 percent, due to overinvestment in plant and equipment, a fairly small domestic market, and the social characteristics of the employment environment.

(4) Agreed capacity is the actual capacity negotiated between directors of production units.

Here again, classical scheduling theory, including models (for example, those incorporating setup times and costs, and machine breakdowns) seeking to address the issue of time-varying efficiency (efficiency = demonstrated capacity/effective capacity) may have limited applicability, for it is agreed capacity that really counts. All the companies we have worked with tended to use demonstrated capacity to drive company-level planning but agreed capacity at the aggregate and shop-floor levels. In practice, managers want a capacity cushion as a means of coping with variance (resulting from planning systems failing to realize a smooth, controlled flow of work to the shop; frequent emergency orders being released to the shop floor; or bottlenecks being difficult to identify or manage), and they bargain for it with their superiors. Thus negotiation theory, uncertainty reduction, and performance measurement (for poor metrics will also drive managers to seek safety capacity) may be more pertinent than classical scheduling theory in production planning.

The bargaining process is seldom treated in the literature, but it generally centers on seeking stability and reliable delivery of the final product, rather than (myopic) optimization of the individual PU. The power of the bargaining units will likely depend on the abilities and performance of the PU in question. Bad performers may eventually be reprimanded, prescribed a very short planning period, and given little discretion. Agreed (regular) capacity retains its negotiable status and hence can be temporarily increased with the right incentives. This situation is far removed from the common assumption of fixed capacity.

Appropriateness of Performance Criteria

Since the 1980s, scheduling models based on due-date criteria have proliferated [Baker and Scudder 1990; Cheng and Gupta 1989; Sen and Gupta 1984]. We think their applicability has been overstated. First, in MTS environments, flow-time-based measures are more appropriate. Second, in MTO situations, due-date criteria really apply only at the company or aggregate level. At the shop-floor level in a job shop, one should not assign a unique due date to each part of an order. Essentially, one has a common due-date problem (the due date being the end of the planning period), which is fairly easy to solve. This follows from the definition of

Scheduling is needed only in long-cycle settings.

the planning period as a management treaty between levels with no interference from higher levels in the internal scheduling. For example, in Table 3, Jobs 1 and 5 will be scheduled at a later stage by the PU1 scheduler (who can decide on the sequence, although he or she will almost certainly begin one of the jobs at time 0, as the expected spare capacity in Week 1 is only two hours!). The scheduler's only concern regarding due dates is that both jobs be finished by the end of Week 1—their common due date.

Due-date criteria with distinct due dates may appear only in the long-cycle environment, and even there they should be applied with caution. In the 27 environments we analyzed (Table 4), only one (aggregate planning in a steel company) involved setting a separate due date for each customer order at each stage of production. And even in this case, the company abandoned the policy when customer service plummeted (placing multiple due dates on a single slab of steel proved problematic!).

It is apparent from our experience that scheduling models with due-date criteria have limited applicability outside aggregate-level MTO settings with long cycles. Otherwise, planners should use scheduling models to increase the flow of products (via flow-time measures), bearing in mind the importance of stability.

Scheduling Models and the Complexity of Capacity Planning: Infinite-Capacity and Finite-Capacity Scheduling

Defining scheduling rather broadly [Morton and Pentico 1993] as planning the utilization of various resources for periods of time would include capacity planning at each level from company level down to the shop-floor level. Planners use two basic approaches in practical planning: infinite-capacity and finite-capacity scheduling; they most commonly apply theoretical scheduling models to finite-capacity scheduling.

Infinite-capacity scheduling (assuming no limitations on production capacity in any period) is typically applied at the company and aggregate level. The underlying assumption of infinite scheduling is that variations in demand can be managed either by temporarily increasing capacity (for example, by using overtime or using temporary staff) or by allocating production to later or earlier periods. Companies frequently justify the use of infinite-capacity scheduling by holding large capacity cushions for various reasons. If a company has average capacity utilization of 50 percent, it does not need to be concerned with variations of up to plus or minus 100 percent about the average workload. Companies exploit infinite-capacity scheduling to attain the desired capacity balance over time, relying on planners' experience (to reallocate production) where infinite-capacity scheduling has no mechanism to increase capacity utilization. This being said, infinite-capacity scheduling is computationally inexpensive and, in our experience, often incorporated in ready-made software (for example, in scheduling modules in some *MRPII* systems), and it generally needs little customization because most companies have similar needs. Infinite-capacity scheduling works well when capacity is flexible (that is, when the company can easily increase its capacity); otherwise the scheduler must decide what orders to move and to which time period.

Finite-capacity scheduling uses various scheduling models and is typically applied at the shop-floor-planning level. The off-the-shelf software we have seen in Australasian firms generally requires a great deal of customization for a particular company (witness the huge variety of scheduling models). When the scheduling model is simple (that is, single machine), the scheduler may develop his or her own software (for example, using spreadsheets). One food manufacturer we know of that uses the software package I2 has developed such a procedure. For more complex models, firms may seek professional help often at very high cost. The household-appliance manufacturer (Table 4) spent several million dollars just for software development, and one of the steel companies spent a comparable sum for scheduling software for its paint line.

In long-cycle production, aggregate-level scheduling generally necessitates complex scheduling models. The steel company needed such software but could not fund its development.

In summary, even when the firm's production environment justifies the use of theoretical scheduling models, the firm may not have the funds to implement such models. Companies may resort to developing and implementing infinite-capacity scheduling models instead.

Conclusion

We do not argue that scheduling theory has no application to practical production planning—only that when one finds a real application (the exception rather than the rule), one must take extreme care. Scheduling is needed only in long-cycle settings (which seem to be decreasing). Where job-shops predominate (for example, in North America and Europe), there may be valid applications. Where flow-shops dominate (for example, in Japan) and where most manufacturers use batch production and short cycles (New Zealand), few companies have real scheduling problems. In such cases, one must pay attention to defining and managing capacity and to performance criteria.

At the steel company, we made recommendations for alleviating the problems, suggesting that the company use an aggregate capacity-planning procedure (ACPP) to link corporate planning and scheduling and to determine order acceptance. The ACPP has the following features:

(1) All processing times are expressed in days with a rolling plan developed weekly for a planning horizon of eight weeks.

(2) The technological order is expressed as a linear sequence of operations, each a facility's processing of an order. A special heuristic scheduling algorithm minimizes mean flow time, using the rolling plan corrected by feedback as an initial solution and developing it while trying to avoid changes in the closest weeks.

(3) The aggregate plan for each day is transferred to each work center as its daily assignment. Schedulers then produce daily schedules, with the end of the last shift being established as the common due date (no operations exceed one shift in length). This procedure reduces the PP from one week to one day.

While financial constraints prevented immediate action, the company has now embarked on implementing our recommendations—including the adoption of aggregate capacity planning and targetting 20 percent of its production as make-to-stock.

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APPENDIX

Ideal Exploitation of Capacity in a Production Unit (PU) with Multiple Resources

Minimize $(\mathbf{P} - \mathbf{T})$

subject to the feasibility constraint $\mathbf{T} \leq \mathbf{P}$

where

$\mathbf{T} = (T_1, T_2, \ldots, T_n)$ is the projected production requirements on the production unit,

$T_j = \Sigma_i t_{ij} X_i$ is the projected workload of resource j,

t_{ij} is the volume of resource j required for processing item i (in a special case of this, t_{ij} denotes a processing time),

X_i is the planned production quantity of item i,

P = $(P_1, P_2, \ldots, P_n)$ is the capacity of the production unit (available capacity of resource j).

References

Anthony, R. N. 1965, *Planning and Control Systems: A Framework for Analysis*, Division of Research, Harvard University Graduate School of Business, Boston, Massachusetts.

Baker, K. R. and Scudder, G. D. 1990, "Sequencing with earliness and tardiness penalties: A review," *Operations Research*, Vol. 38, No. 1, pp. 22–36.

Beischel, M. E. and Smith, K. R. 1991, "Linking the shop floor to the top floor," *Management Accounting*, Vol. 73, No. 4, pp. 25–29.

Bertrand, J. W. M.; Wortmann, J. C.; and Wijngaard, J. 1990, *Production Control: A Structural and Design Oriented Approach*, Elsevier, Amsterdam.

Buxey, G. 1989, "Production scheduling: Theory and practice," *European Journal of Operational Research*, Vol. 39, No. 1, pp. 17–31.

Cheng, T. C. E. and Gupta, M. C. 1989, "Survey of scheduling research involving due date determination decisions," *European Journal of Operational Research*, Vol. 38, No. 2, pp. 156–166.

Dudek, R. A.; Panwalker, S. S.; and Smith, M. L. 1992, "The lessons of flow shop scheduling research," *Operations Research*, Vol. 40, No. 1, pp. 7–13.

Graves, S. C. 1981, "A review of production scheduling," *Operations Research*, Vol. 29, No. 2, pp. 646–675.

Hill, T. J. 1994, *Manufacturing Strategy: Text and Cases*, second edition, Richard D. Irwin, Homewood, Illinois.

Johnson, S. M. 1954, "Optimal two- and three-stage production schedules with set-up times included," *Naval Research Logistics Quarterly*, Vol. 1, No. 1, pp. 61–68.

MacCarthy, B. L. and Liu, J. 1993, "Addressing the gap in scheduling research: A review of optimization and heuristic methods in production scheduling," *International Journal of Production Research*, Vol. 31, No. 1, pp. 59–79.

McKay, K. N.; Safayeni, F. R.; and Buzacott, J. A. 1988, "Job-shop scheduling theory: What is relevant?" *Interfaces*, Vol. 18, No. 4, pp. 84–90.

McKay, K. N.; Safayeni, F. R.; and Buzacott, J. A. 1995, "'Common sense' realities of planning and scheduling in printed circuit board production," *International Journal of Production Research*, Vol. 33, No. 6, pp. 1587–1603.

Melnyk, S. A.; Vickery, S. K.; and Carter, P. L. 1986, "Scheduling, sequencing, and dispatching: Alternative perspectives," *Production and Inventory Management Journal*, Vol. 27, No. 2 (second quarter), pp. 58–67.

Morton, T. E. and Pentico, D. W. 1993, *Heuristic Scheduling Systems: With Applications to Production Systems and Project Management*, John Wiley and Sons, New York.

Portougal, V. and Oliver, L. 1996, *Production Planning System Design*, Dunmore Press, Palmerston North, New Zealand.

Sen, T. and Gupta, S. K. 1984, "A state-of-art survey of static scheduling research involving due dates," *OMEGA*, Vol. 12, No. 1, pp. 63–76.

Womack, J. P.; Jones, D. T.; and Roos, D. 1990, *The Machine That Changed the World*, Harper Collins, New York.