MANAGERIAL AND DECISION ECONOMICS, VOL. 11, 297–315 (1990)

Production Planning, Inventory Management and Scheduling: Spanning the Boundaries

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INTRODUCTION

Manufacturing managers grapple continually with a dilemma. Their companies' strategies, plans and forecasts are cast in terms of products and currencies: these measures of demand form the vocabulary of the marketplace and the financial community. Yet manufacturing management deals with products and currencies only briefly: these measures must be converted into component parts, quantities to be ordered, schedules for manufacture and receipt, and estimates of capacity requirements. The translation of demand for product into load on operational resources constitutes a critical problem that is never wholly resolved. The astute manager seeks a *process* by which the ever-present problem can be solved, rather than a specific solution.

The stream of research that has evolved from attempts to deal with this real and compelling problem is the focus of this review. Researchers have developed a vocabulary for the problem in its various aspects. It is worth noting at the outset that the research vocabulary with which we work differs from that of the practicing manager.

The problem in its real form is usually described as 'agreeing on the production plan'; the next step—'developing the master schedule'—is the phrase most commonly used and the activity most generally practiced in industrial organizations. Aggregate planning (developing the production plan) is the name given by academics to the highest level of attacks on the basic problem. At this level recognition is given to the interaction of the general schedule, overall supporting inventory positions, and capacity availabilities and requirements.

The problem of conversion from demand into load arises immediately, both in real and theoretical situations. The problem is further complicated by the fact that the planning must be brought to a level of detail that permits execution. This must be done through a series of planning levels distinguished by differing time horizons, levels of needed detail, and availability of valid information regarding resource availability and requirements. Researchers refer to this complication as the 'hierarchical nature' of the problem, conveying as well the sense of the organizational levels involved. To the practitioner this is often interpreted as the 'explosion' procedure, generally assumed to be a neutral and straightforward calculation.

Conversion of aggregated demand for the organization's products into the resulting impact on resource availabilities at various technical and organizational levels goes by several names in the research literature. Hierarchical planning, multilevel scheduling and disaggregation are the terms most often used. The research question is one that is of constant concern to practice: how can the disaggregation be accomplished so as to best meet the needs of the organization?

The question that must inevitably follow, in research and practice, is how to link everything back together again. Thus the natural extension of the first research equation—disaggregation—is a focus on coordinating, orchestrating and linking the disparate elements that have been created by the first steps in the attack on the problem. As our review will show, this second half of the problem was broached as a research issue some 30 years ago. Yet only recently has research begun to address the linkage problem.

0143–6570/90/050297–19$09.50

Our review of this three-decade stream of research traces a number of conceptual and methodological developments, focusing on a few seminal and representative works. Our selections are drawn exclusively from journal articles and are personal idiosyncratic choices. Our rationale for excluding books and textbooks is based on our focus on research. Our intention is to capture the important themes and trends of a broad research arena over a three-decade span. This review will lay the foundation for our summary of the current state of research and its future directions.

THE EXEMPLAR: 'A LINEAR DECISION RULE FOR PRODUCTION AND EMPLOYMENT SCHEDULING'

In 1955 Holt, Modigliani and Simon published the results of their research project done at the Carnegie Institute under contract with the Office of Naval Research. An earlier version of this work had been presented at the First National Meeting of The Institute of Management Sciences in 1954. Their article in *Management Science* defined the problem: . . . Setting the aggregate production rate of a factory and setting the size of its workforce . . . ' and set forth a '. . . new method which involves . . . formalizing and quantifying the decision problem . . . and calculating a general optimal solution of the problem . . . ' (page 1). Their problem definition and methodology of attack on that problem stand today as exemplary models of our research questions and attempts to find solutions to the problems of practicing managers.

This single work, and the book that followed with J. F. Muth as the fourth author, established a problem definition and research direction that continue today. The vocabulary and research methodology developed in 'HMMS' (the acronym for the work of Holt, Modigliani, Muth and Simon) are seminal and remain as a standard of excellence by which current research can be judged.

The work that has followed the HMMS lead has traced a number of paths—an example, perhaps, of the disaggregation problem itself. Of the hundreds of articles describing research on the question of how to convert aggregated demands for products into the resulting impact on resource availabilities at various technical and organizational levels, we have selected a few that serve to illustrate important themes and trends of this broad research area. Through these works we can trace the influence of this significant launching pad, identifying its successors, observing its evolution, and describing the contributions that have brought us to the present state of our art.

Three aspects of this early work are worth special notice: the writing is clear, the use of mathematical notation is limited, and the work is focused on a real factory. As this review will show, these worthy standards have not been held as high as might be desired in successive works. Modigliani and Simon received Nobel Prizes for their subsequent work in economics. Their influence on our field was probably more profound than their impact on the larger body of work in economics.

A TAXONOMY

The basic statement of the fundamental issue—conversion of aggregated demand for products into the impact on resource availabilities—was promulgated through the HMMS work in the early 1950s. Since then, aspects of the problem and approaches to solutions have proliferated. Hundreds of journal articles focused on this research topic have been generated. In order to describe the results of this body of work, we have devised a classification scheme that highlights the primary features of the research attacks.

This descriptive taxonomy was developed from examination of our personal selections of the articles that reflect the most significant and/or representative works. Our time-based taxonomy is intended to permit us to describe how the present state of our art has been achieved. The taxonomy consists of four categories:

The Theorists: These researchers focus on new constructs, dogmas or changes in thinking; they attempt to structure or define the problem anew in order to provide improved insight; some could be called 'visionaries'.

The Methodologists: These researchers focus on research methodologies, analytic procedures and techniques, or novel ways of solving the problems; in the process, the problem may be redefined in order to permit illustration of the methodology.

The Problemists: Here the focus is unquestionably on the problem itself, with methodology or technique secondary; the work is decision oriented and prescriptive. These researchers often exploit advantages provided by the methodologists.

The Empiricists: The emphasis in these works is lessons to be learned from practice. Field data are often used to examine the problem area; data are drawn from cases or individual company records; the methodologies employed may be drawn from distant research fields. Immediacy is often a concern here, with a focus on issues of practical import.

These categories are one axis of a classification scheme which help us, with time as the second dimension, show trends and developments. Our placement of a particular piece of work in one category does not mean that the work had none of the characteristics of the other categories. Rather, the placement is intended to show an important contribution of the work. Table 1 shows the categories over time, with our personal journal article selections within each category.

THE THEORISTS

These researchers focus on new constructs, dogmas or changes in thinking; they attempt to structure or define the problem anew in order to provide improved insight; some could be called 'visionaries'.

Forrester (1958), a contemporary of HMMS, developed an approach that had considerable impact at its outset. His original presentation remains a classic for showing vividly the complex interrelationships that characterize production operations. Forrester's 'Industrial Dynamics' promised to be 'a major breakthrough for decision makers'. He intended that his simulation models of the '. . . interaction between the flows of information, materials, money, manpower, and capital equipment [and] the way these five flow systems interlock to amplify one another and to cause change and fluctuation . . . ' (p. 37) form the basis of a descriptive theory of industrial management.

It was Forrester's intention that future managers would use his models to learn about the interrelationships before going into practice. Thus, the model would help with the development of robust theory and the theory would then establish the foundation for a profession of management.

There are a number of prophetic, if not seminal, aspects to Forrester's work. His was the first explicit recognition of the value of information flows as part of both the problem statement and its ultimate solution. His use of a substantial computer-based simulation model established the validity of an important research methodology that persists today. His notions of flows and their interactions are a more complex rendering of the analytic interactions that form the basis of the HMMS work.

Forrester clearly identified the second half of the fundamental problem—putting the pieces back together again: '. . . The system (meaning not the paperwork forms and procedures, but the interrelationships between all the company operations) behaves according to the characteristics of the whole and not according to the characteristics of individual parts . . . ' (p. 40). His emphasis on linkages and flows foresees the current enthusiams:

> Shape of the Future . . . the company will come to be recognized not as a collection of separate functions but as a system in which the flows of information, materials, manpower, capital equipment, and money set up forces that determine the basic tendencies toward growth, fluctuation and decline. I want to emphasize the idea of movement here because it is not just the simple three-dimensional relationships of functions that counts, but the constant ebb and flow of change in these functions—their relationships as dynamic activities (p. 52).

Forrester's successful career as a pioneer in the development of servomechanisms shows in his research in Industrial Dynamics: his is a precise and technical definition of 'feedback'. With his emphasis on flows and their interactions, he can be read as a precursor to lead-time offsetting, time-based competition and Just-In-Time (JIT). His work was the precursor of the hierarchical studies to follow, although he provided no guidance as to what specific decisions had to be made or how to make them.

Bowman (1963) brought an important point of view to the matter at hand: while we focus on specific problems associated with the organization's operation, the larger issue is managerial decision making. His 1963 article extended research into this broader content and, following a theme struck by HMMS, showed the value of incorporating managerial judgment in the solution procedure. This creative piece from MIT led to a series of further studies. The underlying philosophy of the work is a precursor to the current emphasis on decision support systems, expert systems and artificial intelligence:

Table 1. Taxonomy

1955		HMMS—The Exemplar		
1958	Forrester (1958)	Manne (1958)		
1960				
1962	Bowman (1963)			
1964				
1966		Jones (1967)		
1968				Skinner (1969)
1970	Holstein and Berry (1970)	Zoller (1971)		
1972		Hausman and Peterson (1972)	Abernathy *et al.* (1972)	Silver (1972)
				Orlicky *et al.* (1972)
1974		Lee and Khumawala (1974)		Vollmann (1973)
			Berry and Rao (1975)	
1976			Ritzman *et al.* (1976)	
	Bitran and Hax (1977)			
1978	Krajewski and Ritzman (1977)		Schwarz and Johnson (1978)	
			Biggs (1979)	Hayes and Wheelwright (1979)
1980	Buffa (1980)	Van Dierdonck and Miller (1980)		
	Wagner (1980)	Schroeder *et al.* (1981)		
1982			Billington *et al.* (1983)	Nakane and Hall (1983)
1984	Baker (1984)	Bahl and Ritzman (1984)		Ritzman *et al.* (1984)
1986		Axsater (1986)		Hayes and Clark (1986)
			Chung and Krajewski (1987)	
1988			Sridharan *et al.* (1987)	Stalk (1988)
				DeMeyer *et al.* (1989)
	THEORISTS	METHODOLOGISTS	PROBLEMISTS	EMPIRICISTS

> This paper reports some research in managerial decision making, as well as the ideas and a theory stemming from this research. Presented here is a combination of description and prescription. It combines the talents of the manager with those of the analyst in a method and in a theory. The method is pragmatic rather then utopian in that it offers one way of starting with the manager's actual decisions and building on them to reach a better system (p. 310).

While his work was a successor to the HMMS work in that the HMMS analysis is used as an example, Bowman's contribution was in a different direction. He assumed that the real troublemaker was variability (the lack of consistency) in decisions at the aggregate level. But Bowman offered no guidance as to how to make the disaggregate decision. Cost minimization remained the basic preoccupation. Bowman's work, like Forrester's, had theory development as its overt objective. His work is unique, though, in its explicit focus on the generation of ideas: 'An attempt at something like an axiomatic treatment of these concepts is presented in order to stimulate new ideas'. (1963, p. 315).

Bowman's Management Coefficients Theory has proven of less value in the long run than the concept itself—intelligent incorporation of the experience, knowledge and talent of the manager into the solution calculus. His work laid the foundation for research intended to capture and codify the wisdom of practice.

Holstein and Berry (1970) proposed '. . . a new way of conceptualizing job-shop-like manufacturing systems and [suggested] how this conceptualization might be applied in the development of planning and control procedures' (p. B-324). Their notion was '. . . work flow structure, defined as the pattern of aggregate flow through the production system'. This 'work flow structure' appears to be a derivative of Forrester's grander notions of flow, although Forrester is not cited.

Noting a relationship between process design and manufacturing control, Holstein and Berry (1970) foreshadowed the vertical axis in Hayes and Wheelwright's (1979) framework, particularly in their description of the extremes of the job shop and the assembly line. In the days before Material Requirements Planning (MRP) systems, they focused attention on the design and development of appropriate planning and control systems for production, complaining of the dearth of research on systems '. . . which lie between the assembly line and the pure job shop' (p. B-325). They also raise an issue that concerned HMMS—proposed solution procedures must stand up to the fact that change is a constant in the production environment.

The Holstein/Berry conceptualization was aimed at application: they projected '. . . the use of work flow structure information to the dispatching decision . . .' and discussed the value of information itself as part of the solution process. The impact of the then primitive computer and information technology for production planning and control could not be recognized at the time. But this work does point out the value of information as part of the solution.

Bitran and Hax (1977) described the essential ideas of the hierarchical nature of the disaggregation problem in their paper. In this and other papers, they and their colleagues have developed procedures and techniques for disaggregating plans into decisions on specific items using knapsack formulations. Their important observation is:

> To provide effective managerial support for decisions related to production planning and scheduling processes, it is useful to partition the set of decisions into a hierarchical framework. In the resulting system, higher level decisions impose constraints on lower level actions, and lower level decisions provide the necessary feedback to reevaluate high level actions. (p. 28).

Their focus was on the 'interaction mechanisms among the different hierarchical levels', echoing some of Forrester's notions and extending it to organizational structural issues. A considerable body of research has developed around the notion of hierarchical planning; it has formed the basis for more recent work on strategic planning—the top of the hierarchy. Bitran and Hax modelled the decisions that have to be made, but cost minimization remained their primary consideration.

Krajewski and Ritzman, also in 1977, surveyed problems and research on disaggregation in manufacturing and service organizations. This paper formed the basis for the first (and only) conference on the disaggregation problem. They developed a taxonomy whose purpose was to '. . . identify and classify problems, describe representative research, and identify unresolved issues' (p. 1). They did not use the term 'hierarchy' but described '. . . disaggregation decisions in a manufacturing organization

[that] may exist on one or more of the following three levels:

> 1) Given aggregate decisions on output and capacity, determine the timing and sizing of specific final production quantities over the time horizon (sometimes referred to as a master schedule).
> 2) Given the timing and sizing of final product production quantities, determine the timing and size of manufactured (or purchased) component quantities.
> 3) Given the timing and sizing of component quantities, determine the short-term sequences and priorities of the jobs (orders) and the resource allocations to individual operations (p. 1).

An analogous delineation was developed for service organizations; multiple criteria were mentioned in this regard. While they structured the literature and approaches to the problem, Krajewski and Ritzman's primary focus was the minimization of cost. The 71 references listed were described as a

> small, but representative, segment of literature to demonstrate today's state of the art. It shows that although much work has been done, a great deal still remains . . . In general, more research is needed which (i) recognizes the interface between the various disaggregation decisions and (ii) provides procedures useful for practicing managers' (p. 15).

This theme of need for linkages among the increasingly disaggregated disaggregation problem has been a growing one since Krajewski and Ritzman wrote in 1977. So has the plaint for solutions of use and value to the practicing manager.

Buffa, the Paul Samuelson of Production/Operations Management, in his 1980 lead article for the first issue of the *Journal of Operations Management* described the evolution of the field

> from a purely descriptive origin through the Management Science/Operations Research phase . . . characterized by the development of models of problems of restricted scope, the results of which could be evaluated by a single valued criterion. The most promising future is felt to be embodied in projects that are of broader managerial scope, reflecting the relationships between subsystems and interfunctional effects. Evaluative criteria should reflect the multiple criteria realities of the managerial world. (p. 1).

While his paper was aimed at the field in general, not just the slice on which we are focused, his call for increased scope and interrelationships is particularly pertinent here. So is his call for a research emphasis on the management in Operations Management: 'At the broadest level, I choose the word "implementation" to characterize the direction that productive research should take' (*ibid.*). His central concern was the development of theory for practice, as well as feedback from practice to inform the evolution of theory. Buffa was a voice in the wilderness at the time, specifically recognizing the need to consider multiple criteria.

Wagner, in a feature article for *Operations Research*, worried about the state of theory development as of 1980. His review focused on a selected set of topics

> . . . for which the current understanding among informed professionals appears still tentative, incomplete, narrow, highly specific, lacking insight, and fundamental. In choosing I repeatedly asked, 'Do today's best practical solutions rest firmly on theoretical knowledge and a scientific foundation?' My view is 'no' for the issues enumerated . . . (p. 446).

The problems that

> . . . need research and analytic attention . . . arise in the diagnostic, design, system performance, forecasting, and implementation phases of real-life inventory management improvement projects. The paper describes many of the detailed aspects of such projects, and discusses where operations research has not yet provided sufficient foundation to judge the merit of pragmatic alternatives for dealing with these problems (p. 445).

Under the heading 'Viewing the Logistics Function Broadly', Wagner criticized the tendency of researchers to '. . . build the analysis from the bottom-up' and encouraged instead 'top-down analysis'. He also argued for the use of case studies as a legitimate research tool, in addition or as an alternative to optimization: '. . . The model builder may have better success in investigating plausible solutions and, with feedback, refined versions of the alternatives, than in trying to simplify the interconnections in the mathematical structure to permit "automatic" optimization algorithms,' (p. 466). Wagner urged operations researchers to '. . . concentrate on discovering truly new options'. He made a strong case for improved theory development.

Baker represents a group of researchers who have focused on the scheduling issues within the disaggregation problem. As his 1984 article shows, this stream of research is expanding its boundaries beyond priority rules. Referring to recent 'new ideas and insights [which] have made it possible to look at [rules for priority dispatching] from a broader perspective and to discern new avenues of inquiry', Baker studied the '. . . interaction between sequencing priorities and the method of assigning due dates [and] surveys the tactical aspects of this interaction . . .' (p. 1093).

The area of scheduling has a long research history; this article is exemplary of the work intended to make the scheduling system more responsive to marketing needs—in this instance through due date assignments. Baker's simulation experiments show 'how these factors interact with the dispatching rule, and the experimental results suggest which combinations are most effective in a scheduling system'.

Summary—The Theorists

The fundamental issue remains conversion of demand for output into the impact on and need for resources. Theory development has focused on the resource-allocation aspect of the problem, with growing realization that the resources decisions are interactive and dynamic, and that they must be made again and again over time. Recently the information flows that are concomitant with their sources are being recognized as part of both the problem and its solution.

The hierarchical nature of the problem is now part of the basic problem definition. Theory development, however, has been based on the assumption that decision making moves from the top down through the hierarchy. Practice is now preaching 'bottoms-up' procedures, throwing some of these basic assumptions into question.

The early recognition that managerial judgment and values must be part of the problem definition and solution continues to be a factor. As the next section will show, methodologies that permit the implementation of this complication are developing rapidly.

While many researchers have cried for multiple criteria for evaluation, the fact is that cost dominates as the single criterion. Again, methodological and technological evolution are making it possible to respond to this serious criticism. Criteria other than cost would include market priorities, long-run profitability, or the elusive concept 'competitiveness'.

Isolation of the disaggregation problem within the confines of the manufacturing function is increasingly viewed as an inappropriately narrow view. Effective theories must now encompass not only the 'vertical' aspect of the hierarchical problem but also the 'horizontal' one of organizational relationships. The need to address linkages with other organizational functions—or perhaps the structural redefinition of these functions within the organization—are becoming increasingly obvious requirements for successful theory development.

THE METHODOLOGISTS

These researchers focus on research methodologies, analytic procedures and techniques, or novel ways of solving the problems; in the process, the problem may be redefined in order to permit illustration of the methodology.

Manne (1958) wrote a pioneering piece that showed how setup time and costs can be introduced into a lot-sizing model without having to introduce integer decision variables. Recognizing early that the aggregate planning problem statement was not broad enough, he considered capacity constraints as part of the lot-sizing decision. Manne's work laid the foundation for research to follow, both in problem construct and in the methodological approach to a combinatorial problem:

> This paper studies the planning problem faced by a machine shop required to produce many different items so as to meet a rigid delivery schedule, remain within capacity limitations, and at the same time, minimize the use of premium-cost overtime. It differs from alternative approaches to this well-known problem by allowing for setup cost indivisibilities (p. 115).

The machine shop was an Original Equipment Manufacturer (OEM) for the U.S. government armed services, providing a reality check on the problem statement.

Manne's results meant that a linear programming solution could '. . . provide a good approximation whenever the number of items being manufactured [was] large in comparison with the number of capacity constraints'. His overall approach was that of the economist, using fundamental insights from economic theory to develop insights into the production planning problem:

> Paradoxically enough, successful decentralization requires that the manager of each activity have a longer 'span of control' than the size of the individual lot in a particular time period. It is necessary for each manager to be familiar with the entire program of labor inputs that is implied by his particular sequence of output for the individual part (p. 131).

While the focus of Manne's work was narrow, he did devise an optimization-based methodology that proved useful in following work. He did incorporate capacity constraints, as many later studies failed to do.

Jones referred directly to HMMS in his 1967 article, offering a heuristic approach to the determination of workforce and production levels: 'In more complex and more realistic situations, the results obtained by Parametric Production Planning (PPP) may be superior to those achieved by a linear programming approach or a linear decision rule' (p. 843). Jones was one of the early proponents of heuristics which have become a dominant influence in Operations Management.

A theme that was common in these works deriving from the HMMS article appears here: a new approach is described, then tested against the HMMS paradigm. This bow towards scientific replication is still used, as various rules and heuristics are tested against one another and against one another's test data. A unique feature of Jones's work was the test of HMMS and PPP using the Harvard Business School's Management Simulation Game.

Jones considered the problem statement of aggregated planning correct, but felt that the cost assumptions were insufficient for effective implementation. The problem statement used here does not recognize the larger hierarchical problem; this work is important for its development and use of heuristics and simulation, not for the PPP itself.

The research described in this article was done in FORTRAN on an IBM 1401—the first of the widely available second-generation machines. This was the era of solving ever more complex and realistic problems by pushing existing computer technologies to their limits. The steps involved in this PPP system can be veiwed as attempts to build an interactive decision support system before any of the hardware and software technology—or vocabulary—existed.

The first three of Jones's 13 'tentative hypotheses' were the opening volley for heuristics and simulation for practice:

> 1. The scarcity of examples of successful applications of optimizing techniques to problems of aggregate work force and production may indicate a need to look for new ways to assist managers in making these decisions.
> 2. One of the barriers to the wider use of these optimizing techniques may be the difficulty of forcing the manager's understanding of the relationships in his firm to the strict mathematical forms required by the optimizing techniques.
> 3. Simulation is one technique which allows a freer form for expressing the cost and production relationships (1967, p. 864).

By the time Jones wrote, the lack of success of optimization approaches had been noted. He implied that this failure might be due to management's lack of understanding of the mathematics involved. His methodology was based on simulation and heuristics, focusing on cost minimization and only at the aggregate level.

Zoller's 1971 article is representative of a class of early works on disaggregation. His is another in the many attempts to move away from a linear programming solution to the problem, with the hope of increasing the practical relevance of Aggregate Production Planning (APP).

The technique developed by Zoller was to be used '. . . for disaggregation when product contributions are nonlinear. It [relied] on decreasing marginal contributions as an evaluation criterion' (p. B-533). The method was illustrated by application to a hypothetical production and sales planning problem. Zoller provided a clean statement of the problem:

> Given an aggregate production plan, some disaggregation method is required which will convert P_t [the production rate at time t] and W_t [the workforce size at time t] into a detailed production program, i.e., allocate P_t and W_t to products. Assuming an objective of profit maximization, this allocation should be made to

comply with a profit or contribution maximizing sales program. Optimal disaggregation, then, requires the derivation of an optimal sales program from anticipated aggregate sales, F_t, based on which P_t and $I = I_t - I_{t-1}$ may be disaggregated and W_t allocated to products.

The methodology was designed for situations where product contributions are nonlinear. Zoller also attempted to disaggregate to the product level. His methodology was based on optimization and assumed certainty as well as several other simplifications.

Hausman and Peterson, in 1972, developed a 'dynamic programming formulation for this general problem, point[ed] out its practical limitations and consider[ed] some alternative heuristic approaches' (p. 370). The problem they addressed was '. . . abstracted from an actual production scheduling problem faced by a garment manufacturing firm producing style goods'.

Their focus was on methodological development, in particular a dynamic programming approach. The limitations to which they refer include the fact that the formulation was '. . . not computationally feasible if two or more products are considered'. Their solution to this problem was the development of three heuristics for use in the multi-product situation. They recognized an important shortcoming of their approach, '. . . the omission of setup costs and their corresponding impact on available productive capacity . . .' (p. 383) and suggested this as a fruitful direction for further research.

The basic theme of Hausman and Peterson's approach was to begin with an optimization method and then move to heuristics. This general idea was followed by many subsequent researchers. While Hausman and Peterson recognized the need to incorporate setup time in capacity constraints (as Manne had done), they did not incorporate this notion into their approach.

Lee and Khumawala compared four models against a live volunteer in their 1974 paper. Their concern was

> . . . to explore this implementation problem: (1) by developing a simulation model of an operating firm, (2) by using this simulation to compare the performance of aggregate production planning models, and (3) by formulating a generalized methodology for implementating quantitative planning models into the decision procedures of the firm (p. 903).

In direct succession from HMMS, Bowman and Jones (all cited), their work was focused on technique selection rather than problem enrichment. Rather than offering their own solution procedure, Lee and Khumawala provided evaluations of those already available—the Linear Decision Rule (LDR) from HMMS, the Management Coefficients Model (MCM) from Bowman, Jones's Parametric Production Planning Model (PPP), and the Search Decision Rule (SDR) developed in 1968 by Taubert. Their conclusions were:

> 1. Given the perfect forecast, all four rules perform creditably, with the SDR and LDR achieving the best results, followed by the MCM and PPP.
> 2. Given the more realistic imperfect forecast, a wider variation in performance occurs. The SDR performs best, followed by PPP, LDR and MCM approaches (p. 906).

Their work used simulation to make comparisons among aggregate planning approaches. The major criterion Lee and Khumawala used was cost.

Van Dierdonck and Miller offered another look at the context within which the aggregate planning problem exists. In 1980 they presented a 'contingency model designed to explain aggregate differences in the specifications for production planning and control systems across firms' (page 37). A unique feature of this work was the reality check on the model and its concepts: 'An analysis of data from a limited sample of companies, and a panel of managers, provides insights into the applicability of the concepts used in the model, and its potential usefulness.' The authors concluded that:

> . . . the successful production control system must consistently reflect a firm's competitive strategy. The model that was prepared to reflect this premise makes this link in two steps. The first step includes the derivation of the production planning task (characterized by the amount of uncertainty, complexity, a toleration for slack) from the competitive strategy. The second step is the determination of the appropriate system characteristics given the task, more specifically, the degree of information processing systems involvement (IPSI) and integrativeness . . . An intensive analysis of data from a limited number of field cases provides some encouragement that the model is a useful representation of

the relationships between production control tasks and systems (p. 45).

Schroeder *et al.* (1981) showed that survey-based research can be a useful and acceptable approach to examination of the problem. Their mail survey of practice in the midwestern United States focused on the benefits and costs of Material Requirements Planning (MRP) systems. From these data the authors were able to correlate factors related to benefits. They concluded that 'These models indicate that companies should stress a broad approach to implementation; there is no one overriding factor which guarantees MRP success' (p. 1).

This study was one of the first empirical analyses of MRP implementation conducted. Its findings have proven valuable for defining boundaries on parameter values for simulation studies to follow. It has provided practitioners with benchmarks for evaluation of their own systems.

Bahl and Ritzman developed a model in 1984 that served as a powerful tool for linking master schedules with lower-level plans. An important contribution was the recognition of capacity constraints. This provided methodological help to managers struggling with both the disaggregation problem and the subsequent need to link everything back together again:

> Although material requirements planning (MRP) allows managers to better plan hierarchical production and inventory systems, much is still left to the planner's intuition and experience in devising realistic master production schedules. Decisions are made sequentially, rather than simultaneously, with no real assurance of satisfactory performance. This research proposes an integrated model for facilitating these decisions. A mixed-integer nonlinear programming model is formulated such that it can be solved by a heuristic procedure (p. 389).

Capacity planning was introduced as an essential part of the problem and its solution. The intention of the work was to augment MRP systems, making them more effective. Incorporating capacity constraints into the disaggregation problem was no trivial matter. But Bahl and Ritzman were using cost minimization as the single fundamental criterion.

Axsater addressed one of the more perplexing issues in disaggregating upper-level product decisions in a manner that maintains the overall optimality of the system. In the other words, how do you know when you perform an aggregation of products that you will be able to successfully disaggregate them later? In his 1984 article, Axsater provided an example of the sort of mathematics necessary to handle this problem. This is the same problem referred to by Zoller 17 years before, although Axsater did not cite Zoller:

> We consider a situation in which a hierarchical planning system with two levels is applied to a multistage prpduction process. The higher level aggregate production plan, expressed in terms of product groups, is disaggregated at the lower level into a detailed plan for individual items. We describe constraints imposed upon the aggregate level product groups that will guarantee the existence of a feasible disaggregation at the lower detailed level into a detailed plan for individual items . . . The possibility of formulating suitable constraints is closely related to our choice of product groups and the aggregation of product data (p. 796).

This work demonstrates that optimal disaggregation requires severe problem simplification. An important conclusion to be drawn from this is that we remain a long way from providing optimality for problems of realistic size and complexity.

Summary—The Methodologists

The methodological stream that began with HMMS's calculus of variations approach to the problem has moved systematically through LP (linear programming) attacks, integer programming and simulation, and ultimately to heuristic approaches. Relaxation of the linear assumptions became necessary in order to more accurately reflect the character of the real problem. Similarly, simplification of the problem to fit the available methodology has progressed as the methodologies themselves have evolved. With the recent introduction of sampling methodologies, it is likely that the problem needs—or perhaps more accurately can now accommodate—redefinition.

A dichotomy between prescriptive and descriptive methodologies remains unresolved. The early years were dominated by searches for optimality, requiring reduction of the problem to meet the methodologies. Sampling has provided a new set of tools that have not yet been fully brought to bear on the problem. It can permit redefinition of the problem in the light of practice, feeding back structural information as well as problem parameters.

In 1958 Manne introduced the issue of capacity constraints, but the problem was getting sufficiently out of hand that this nuance had to be ignored for a time. The hiatus is ending as recognition of capacity constraints returns, along with methodologies and technologies that permit the handling of this important aspect of the basic problem.

Methodological developments, enhanced by the evolution of computation technology, have permitted examination of problems with complexity more closely mirroring reality. At this point methodologies based on heuristics appear to hold the most promise for operations research studies. We have only begun to see the impact of sophisticated sampling-based studies on problem definition and theory development.

THE PROBLEMISTS

Here the focus is unquestionably on the problem itself, with methodology or technique secondary; the work may be decision oriented and prescriptive; these researchers often exploit the advantages provided by the methodologists.

Abernathy *et al.* (1973) expanded the scope of the problem as delineated by HMMS. They argued that 'The aggregate planning models that have been developed for goods-producing organizations are not appropriate for ... service organizations' (p. 693). This early attempt to broaden the disaggregation problem to include service operations —in this instance, nurse staffing—has not been followed by a substantial research stream. The manpower aspect of the basic problem has received less attention than materials and equipment. Their conceptualization of a process for staffing based on three levels of decision making is an early recognition of the hierarchical nature of the problem, both as an important conceptual issue and as a very practical problem.

A distinctive focus of Abernathy *et al.*'s work is its culmination in the development of information 'that can be generated for policy and organizational analysis and to guide staff planning and control activities' (p. 703). The authors intended the work to serve as the basis for a practical nurse-staffing process.

Berry and Rao (1975) focused on one part of the general problem—critical ratio scheduling in a job shop under an order-point system. They included some of the earliest references to computer-based systems for manufacturing control in job shops. Their work compared four versions of the slack time and critical-ratio rules, using queue time and inventory status information as additional evaluation criteria:

> These results provide further evidence that the dynamic adjustment of order due dates using inventory status information can reduce the shop and inventory system performance when heavy work loads are placed on the manufacturing facility ... it is clear from these experiments that the feedback of inventory status information to the shop floor for adjusting order due dates must produce a reduction in the order lateness variance before an improvement in inventory system costs can be realized ... These experimental results also indicate that very little benefit was derived from the collection and processing of queue waiting time data for use in making scheduling decisions (p. 200).

Although later work refuted some of their findings, Berry and Rao did show clearly the interrelationships between the inventory control system and scheduling decisions. But they did not recognize the dependent demand relationships between products that provided the focus for much of the research that would follow.

Ritzman *et al.* (1976) focused on the manpower aspect of the problem, using a heuristic approach involving man–machine interaction:

> The heuristic decision rules employed in the example analysis reflect the managerial considerations made when actually deciding upon tour assignments. [Results] demonstrate that the biased sampling procedure is superior to merely employing each decision rule separately (p. 1214).

Their approach in 1976 was tailored to the specific situation: a multi-stage workforce scheduling problem—construction of tour assignments in a post office. The complexity of the real problem and the multiplicity of objectives made an optimizing approach impractical if not impossible ('... only of academic interest,' to quote the authors). Thus the attempt to grapple with a realistic conceptualization of the problem forced the use of non-optimizing methodologies.

Schwarz and Johnson (1978) are included here as an example of the negative. They reported in 1978 that no companies were found to be using the HMMS Linear Decision Rule that was figuring so prominently in the research literature. They hypothesized that:

> . . . the reason for this [implementational] failure may be a very simple one: the incremental benefit of aggregate planning (i.e., the coordinated optimization of aggregate work force, production and inventory) over improved aggregate inventory management alone may be quite small (p. 844).

Describing the concept of co-ordinated optimization of aggregate work force, production and inventory as 'natural and elegant they went on to suggest faults that might lead to implementation failure. The inability of HMMS to handle integer variables and/or constraints would mean a methodological inadequacy; the difficulty of developing cost functions and measures would mean an environmental inadequacy. 'The problem of dis-aggregation' was suggested as a third possible explanation of the lack of implemented HMMS systems.

Having proposed three possible explanations, Schwarz and Johnson went on to test, and prove to their own satisfaction, their proposition that improved aggregate inventory management alone would provide the cost savings associated with the LDR. In their view the most important impact of the LDR was the introduction of a set of compelling new research questions, in particular as the vehicle for the identification of the aggregate planning problem.

Biggs (1979) used computer simulation to 'determine the effects of using various sequencing and lot-sizing rules on various performance criteria in a multi-stage, multiproduct, production-inventory system using MRP' (p. 96). The problem as described in this work is approaching the problem as it appears to managers. This was an early, although not the first, introduction of MRP into the research arena. He concluded that:

> . . . there is an interaction effect between lot-sizing rules and priority-sequencing rules for the four-system performance criteria. This has been interpreted to mean that these two rules should be selected together, rather than independently, to maximize the performance of a multistage, multiproduct, production-inventory system . . . In addition, a side issue that has been pointed out is that no single combination of rules will maximize all four of the performance measures; thus, the decision maker will have to make trade-offs in arriving at this selection (p. 111).

His results also pointed to some conclusions of considerable importance. Small lot sizes (lot-for-lot, for example) can reduce inventory and improve customer service in dependent demand situations where capacity is limited. This finding is consistent with today's JIT emphasis. Further, static lot-sizing rules can actually outperform dynamic rules, due to less lead-time variability, the cushion from remnants, and uncertainties from capacity limitations. This finding shook the 'nonremnant' assumption that was proved optimal by earlier researchers. The assumption remains a cornerstone of many Operations Research (OR) models to this day.

By 1979 MRP systems were increasingly common in practice and were providing opportunities for the use of research results, as well as data and a structure for research investigation. Biggs's work represents the beginning of the research recognition of this important change in practice.

Billington *et al.* (1983) offered an even more realistic view of the problem in their work:

> . . . the capacity/lot-size/lead-time determination problem can be viewed as being embodied in a large stochastic problem where demands, yields, and lead times are uncertain, where the amount of finished goods and component-safety-stock inventory have an effect, and where many other factors influence the correct approach to solving for production schedules (p. 1139).

The paper was modestly controversial when it appeared, largely because of the comments about MRP system failures. Their solution procedure, 'Product Structure Compression', offered a method for reducing the size of the problem without losing optimality. This was necessary since their fundamental approach was based on Mixed Integer Linear Programming (MILP). Their appreciation for the real problem was of more importance than the details of their solution procedure.

Chung and Krajewski (1987) attempted to match up aggregate plans and Master Production Schedules (MPS). Their work was not written for the practicing manager, but it did focus on the practitioner's problem—integrating the levels in a hierarchical production planning process to best effect. It also recognized the value of taking improved data into consideration as it becomes available:

> Two managerial implications can be drawn from this study. First, for most cost environments a rolling horizon feedback procedure is at least as good as not using one; in some environments it is imperative . . . Second, our experiments point to setup costs as a key factor in choosing a planning horizon and deciding on the usefulness of a rolling horizon procedure. Managers of environments with high setup costs should choose planning horizons equal to the seasonal cycle and they should use a rolling horizon procedure—regardless of smoothing costs (p. 408).

The work is unusual in its direct advice to practicing managers, in spite of its appearance in a journal not known for its practitioner audience. The focus, however, is still on cost minimization.

Sridharan *et al.* (1987) offered the first rigorous research on freezing a MPS and using a rolling horizon approach for this problem level. Prior to this work, consultants had published rules of thumb but no one had tested them. Previous literature on the subject was anecdotal. They concluded that:

> Freezing a small portion of the MPS, up to as much as 50% of the planning horizon, has a relatively small effect on such costs [production changeover and inventory carrying costs for end products]. However, when the frozen portion of the MPS exceeds 50% of the planning horizon, the impact on cost can be substantial, depending on the freezing procedure used. When long freeze intervals are used, the conventional method of freezing the MPS on a period basis is relatively more costly than the order based alternative (p. 1147).

Their research design treated only a single product with assumptions of demand certainty. No capacity constraints were recognized.

Summary—The Problemists

Over time, the 'problem' has been expanding, incorporating more than the strict manufacturing aspects of the original conception. There has been consistent movement toward identification of the hierarchical nature of the problem, as well as the necessity for recognizing interfaces with other decision areas within the organization. The research thrust, however, has not been taking aim at the linkages which are being recognized as increasingly important.

The expanded problem statement has, in many instances, gone beyond the ability of the methodologies to provide a reasonable attack. The research, however, attempts to span inventory, scheduling and capacity issues, often having to retreat to a simpler conceptualization in order to provide insight. There is increasing recognition of the interdependencies caused by parent–component relationships and shared capacity constraints. There are also extensions into the service environment, handled as a separate version of the problem.

A common thread among the problemists is consideration of practical matters emanating from real operating environments. Hence we see attempts to deal with shift schedules, master production scheduling, lot sizing and scheduling rules, and shop-floor control.

Information technology has had a significant impact on practice and we see the effects here. Increased information availability in practice has contributed to the broadening of the problem definition.

THE EMPIRICISTS

The emphasis in these works is lessons to be learned from practice. Field data are often used to examine the problem area; data are obtained from cases or individual company records; the methodologies employed may be drawn from distant research fields. Immediacy is often a concern here, with a focus on issues of practical import.

Skinner (1969) first introduced the notion of manufacturing as '. . . a competitive weapon or a corporate millstone. It is seldom neutral' (p. 136). Taking a broad managerial approach to the problem, he pointed out that 'Few top managers are aware that what appear to be routine manufacturing decisions frequently come to limit the corporation's strategic options, binding it with facilities, equipment, personnel, and basic controls and policies to a noncompetitive posture which may take years to turn around'.

In 1955 Holt *et al.* had noted that

> The decision problems involved in setting the aggregate production rate of a factory and setting the size of its work force are frequently both complex and difficult. The quality of these decisions can be of great importance to the profitability of an individual company, and when viewed on a national scale these decisions have a significant influence on the efficiency of the economy as a whole (p. 1).

Skinner's basic message expanded on this insight for the firm in its development of an effective strategic posture.

The research behind this classic article was carried out through case development for the Production and Manufacturing Policy courses at the Harvard Business School. It is probably the most widely read and cited article in our field, striking themes that are the centerpieces of the current MRPII (Manufacturing Resource Planning) and JIT (Just-In-Time) enthusiasms.

This distinctively managerial view recognized the complexity of the situation and introduced the organizational and structural aspects of the problem. The work was prescriptive, recommending that 'The place to start . . . is with the acceptance of a theory of manufacturing which begins with the concept that in any system design there are significant trade-offs . . . which must be explicitly decided upon' (p. 144). This is reflective of Forrester's earlier notion of the completely interlinked system.

Coming at the disaggregation problem from an entirely different perspective, Skinner summarized his conclusions drawn from the systematic observation of practice:

> Conventionally, manufacturing has been managed from the bottom up. The classical process of the age of mass production is to select an operation, break it down into its elements, analyze and improve each element, and put it back together . . . What I am suggesting is an entirely different approach, one adapted far better to the current era of more products, shorter runs, costly accelerated product changes, and increased market competition. I am suggesting a kind of 'top-down' manufacturing . . . [which] starts with the company and its competitive strategy; its goal is to define manufacturing policy (p. 145).

The "current era" described above is 1969!

Silver (1972) directed his ("state of the art") article at practitioners, deliberately using a minimum of mathematics and offering a problem definition with available approaches for the time:

> . . . how, under seasonal demand conditions, to rationally set work force sizes and production rates. The production supervisor desires long runs of individual items so as to reduce production costs; the marketing personnel wish to have a substantial inventory of a wide range of finished goods; those concerned with labor relations desire a stable work force size; finally, the comptroller generally wants as low an inventory as possible. It is clear that these objectives are conflicting in nature. Therefore, a cross-departmental (or systems) approach to the solution of the problem is essential (p. 15).

Focusing on 'medium range planning, on the order of six to eighteen months' (p. 16), Silver organized the basic approaches to the problem into three 'fundamental groups':

> 1. . . . essentially non-mathematical in nature. The philosophy here is that the decision maker is either unaware of mathematical solutions to his problem or he does not believe that the mathematical models are representative enough of the actual situation.
> 2. . . . mathematical models for which theoretically optimal solutions are obtainable. Usually, however, such models have built in assumptions that may not be realistic. . .
> 3. . . . various heuristic (or plausible) decision rules are tested out until a reasonably good solution is obtained. Quite often a computer search routine is used to home in on a good set of parameter values (pp. 21–2).

This summary of the problem definition and methodological situation as of 1972 was supplemented with brief descriptions of such approaches as 'Non-quantitative haggling' through HMMS's Linear Decision Rule and manual approaches.

Orlicky *et al.* (1972) were responsible for substantial change in the manufacturing environment in the early 1970s. As part of the MRP (Material Requirements Planning) Crusade sponsored by APICS (American Production and Inventory Control Society), they aimed directly at the practicing manufacturing manager. The MRP Crusade was intended to modernize manufacturing management by bringing then-state-of-the-art computation to bear on the problem.

A consequence of this crusade was the necessity for education about the fundamental manufacturing problem—disaggregation, as researchers call it. These three experts were not researchers in the traditional sense. They were manufacturing consultants with broad experience. Much of the results of their experience was conveyed through seminars and speeches. They also wrote texts intended primarily for manufacturing professionals.

Orlicky *et al.*'s article is unique in that it bears all three names. It points up a critical problem in the design of an effective MRP system—structuring the bill of material, a problem that is arising again in attempts to install Just-In-Time (JIT) systems. The issue is proper positioning of inventory—towards the top or bottom of the bill of material. This issue remains an open question today.

Vollmann (1973) offered a painstaking look at a real situation—the way production was scheduled at the Ethan Allan Co. in 1966. His rendition of the gradual development of systems to help with the scheduling provided a sharp contrast with the problem as described by other researchers. His conclusions were based on his own attempts to implement 'state of the art' solutions, with a resulting system that evolved as the users themselves developed in their understanding of the problem and methodologies available for its resolution. In this regard, Vollmann noted that 'It is only believing users who can implement a system that can evolve rapidly as their understanding of the problem increases' p. 69).'

Commenting on the difficulty of applying existing models and approaches, Vollmann noted that '. . . no one in that company made decisions at the level of aggregation considered in the linear decision rule and other aggregate capacity planning models . . .'. The original problem definition dealt with capacity through workforce availability, Vollmann's comment suggests, however, that this fundamental aspect of the problem was often ignored:

> The commonly advocated idealized time-series approach kicks the capacity problem under the rug. If enough overcapacity exists, few problems are observed and as capacity gets more and more tight, we tend to get 'blivits' (ten pounds in a five-pound bag) (p. 70).

Hayes and Wheelwright (1979) followed the lead established by Skinner in their article. Although no research methodology was presented, case writing and analysis did form the basis of their work. Companies are used as examples to illustrate the matrix that they introduced.

The perspective taken by Hayes and Wheelwright was strategic, moving above the level of the aggregate problem, providing insight for the manufacturing policy determination suggested by Skinner:

> . . . we suggest that separating the product life cycle concept from a related but distinct phenomenon that we will call the 'process life cycle' facilitates the understanding of the strategic options available to a company, particularly with regard to its manufacturing function (p. 133).

Their product/process life-cycle matrix identified 'key management tasks' by process life-cycle stage and 'dominant competitive modes' by product life-cycle stage. The key management tasks are factors that will have significant impact on the aggregate planning problem, although Hayes and Wheelwright do not acknowledge this fact explicitly.

Nakane and Hall (1983) offered an early entry in the Just-In-Time (JIT) crusade. Apparently based on experience with Japanese practice, their article lays out the definitive path to manufacturing success: 'Experience shows that you can get there from here—if you follow the right path' (p. 84). 'Here' was cost reduction, high quality and flexible production.

This perspective piece offered anecdotal evidence of success and failure, urging manufacturers to a combination of general wisdom—'dedicate themselves to a vision of the future that includes automation of entire companies'—and details as specific as 'Reduce [setup times] first by simple means and then by flexible automation' (p. 90). The fundamental disaggregation problem was addressed by this statement:

> Develop stable, level production schedules with the knowledge and concurrence of the people responsible for marketing and manufacturing policy.

An important factor ignored by much of the literature was brought out at the end of Nakane and Hall's article:

> Rewards for managers should not rest on short-term efficiency reports or on maintenance of the

status quo but on progress toward the goal. Put simply, stockless production will never be successful if a company's performance measurements conflict with it.

Ritzman *et al.* (1984) offered results from a traditional research model supplemented by empirical data from a panel of practicing managers and model validation against a real factory setting. The focus was on the real world for information and problem understanding, with this feeding a substantial computer simulation model (MASS—Manufacturing Simulation System).

The research was intended to provide information about system choice—Reorder Point, MRP, Kanban, in particular. All of these systems address the basic problem differently. The research therefore necessarily provided information about environmental conditions—'levers' that can be pulled. Comparisons of manufacturing systems through simulation yielded clear results:

> . . . it is not Kanban but the manufacturing environment that counts. Correctly understood, Kanban is but one convenient way to implement small-lot production with a minimum of paperwork and to make problems in the production process readily visible (p. 151).

With respect to the manufacturing environment, the research showed that:

> There is no magic formula, no quick fix. But, as our MASS simulation shows, there are clearly identifiable levers for boosting performance—key among them:
> — Reducing lot sizes and setup times.
> — Improving process yields.
> — Smoothing capacity.
> — Increasing worker flexibility.
> — Improving product structure (p. 152).

Hayes and Clark (1986) approached the problem from a different empirical perspective. Using a '. . . continuing, multiyear study of 12 factories in 3 companies . . .', they attempted to '. . . clarify the variables that influence productivity growth at the micro level' (p. 66). Reflecting HMMS's concern for the manager's actions, Hayes and Clark offered the results of their analyses of practice across 12 sites during 1982:

> With the foglike distortions of poor measurement systems cleared away, we were able to identify the real levers for improving factory performance. Some, of course, were structural—that is, they involve things like plant location or plant size, which lies outside the control of a plant's managers. But a handful of managerial policies and practices consistently turned up as significant. Across industries, companies, and plants, they regularly exerted a powerful influence on productivity. In short, these are the managerial actions that make a difference (p. 68).

The explanations for more productive performance were converted into prescriptions:

> — Invest capital—Our data show unequivocally that capital investment in new equipment is essential to sustaining growth in TFP [Total Factor Productivity] over a long time . . .
> — Reduce Waste—We were not surprised to find a negative correlation between waste rates and TFP, but we were amazed by its magnitude (p. 69).
> — Get WIP out—The positive effect on TFP of cutting work-in-process (WIP) inventories for a given level of output was much greater than we could explain by reductions in working capital . . . A long-term program for reducing WIP must attack the reasons for its being there in the first place . . .
> — Reducing Confusion—Defective products, mismanaged equipment, and excess work-in-progress inventory are not only problems in themselves. They are also sources of confusion (p. 70).
> — Value of learning—We are convinced that a factory's learning rate—the rate at which its managers and operators learn to make it run better—is at least of equal importance as its current level of productivity . . . the two essential tasks of factory management are to create clarity and order (that is, to prevent confusion) and to facilitate learning (p. 71).

Stalk (1988) shifted conceptualization of the problem: 'In fact, as a strategic weapon, time is the equivalent of money, productivity, quality, even innovation' (p. 41). His prescriptions were presumably based on experience with Japanese companies, likely consulting clients. Citing Forrester, Stalk interpreted that earlier work as one that established '. . . a model of time's impact on an organization's performance' (p. 47). From this he developed his theme of 'time-based manufacturing', noting that:

> In general, time-based manufacturing policies and practices differ from those of traditional manufacturing along three key dimensions: length of production runs, organization of process components, and complexity of scheduling procedures.

DeMeyer *et al.* (1989) represent research teams from INSEAD (in Fontainebleau, France), Boston University and Waseda University (in Tokyo). For the past four years they have administered an annual survey on the manufacturing strategies of large manufacturers in Europe, North America and Japan. Their unique program of research—called the 'Manufacturing Futures Survey'—is survey-based, longitudinal, and international in scope. Its objective has been '... to understand the competitive environment in which the large manufacturers have to operate, and the types of manufacturing strategies and policies they develop in order to provide a response to this environment' (p. 135).

Survey-based methodologies are commonplace in the work of our colleagues in marketing and, to some extent, within the field of macro-economics. The PIMS program (Profit Impact of Marketing Strategies) has provided valuable insights into the marketing practices of organizations, as well as evaluations of the impact of those strategies. The Manufacturing Futures Survey is intended to provide similarly valuable information for manufacturing operations. It is deliberately planned to complement the case- and experience-based results of researchers like Skinner, Hayes and Wheelwright. The ultimate intention is the development of explanatory theories that can be validated by data from practice.

The questionnaires, which in 1986 were completed by 574 manufacturers, focus on four broad categories of questions:

(1) Company or business unit profiles;
(2) Competitive priorities that will be pursued in manufacturing;
(3) Management's concerns about manufacturing;
(4) Actions and efforts in which respondents firmly intend to invest over the ensuing two years.

The research focus is not on the disaggregation problem as originally defined by HMMS, but the results of the research provide insights into appropriate evaluation criteria that might be employed within the context of the classical problem. The preliminary conclusion of the research at this point is worth noting: 'The next competitive battle will be waged over manufacturers' competence to overcome the age-old trade-off between efficiency and flexibility (p. 143).

Summary—The Empiricists

A consistent, even compelling, theme is the cry for linking corporate strategy and organizational infrastructure to the 'disaggregation' problem. The problem is viewed contextually, therefore demanding linkage upwards toward the business strategy and horizontally across traditional functional lines. Theories are badly needed, as are methodologies for analysis of the problem and for support of the development of practical approaches to ongoing solution procedures.

These studies tend to identify "what is" with some suggestions as to 'what should be'. The research ranges from the anecdotal to the analytic; given the prevalence to methodologies that do not stand up to the rigor of scientific scrutiny, the consistency of conclusions is somewhat surprising.

An issue rarely addressed directly in these studies is the availability and quality of data. Survey-based research is in its infancy in our field, from the important task of questionnaire design through sample selection and validation, through procedures for analyses of the resulting data. Case studies may overcome the data quality issue, but then may not prove to represent a sufficient sample for generalization.

It is here that we find the proponents of 'next frontiers'. Looking at them with hindsight, we see the old crusades and enthusiams evolving into the new ones, with little attention to similarities. As these 'solutions' come and go, we see evidence of 'contests' as new approaches are introduced—EOQ versus MRP, MRP versus JIT, for instance.

The Empiricists are as one in looking to practice as the key source of insight. In this regard, they can be viewed as the descendants of Bowman, who offered the earliest insistence on incorporating the lessons of practice into our research. Thoughtful consideration of the manufacturing environments is the *sine qua non* for the development of decision support systems and solution procedures.

SUMMARY

The four streams of work, focusing on theory and methodology (the scientists) and on the problem and practice (the engineers), have taken us a far distance from the problem and methodology introduced by HMMS in 1958. There are, however, themes and concepts introduced in the 1950s that persist or, in some cases, return after a hiatus. It is possible, with 20/20 hindsight, to see the seeds of our latest insights in the writings of HMMS, Forrester and Bowman. We can also see the impact of computer and information technology—and can only wonder what some of our early colleagues would have done with it!

To a considerable extent, we are attempting to emulate our colleagues in the physical sciences. The research aimed at theory and methodological development is the obvious example, but there are some important differences. For one, our finding does not typically come from the practice arena. Compared with work in other disciplines, ours is relatively inexpensive. Only a very few institutions are willing and able to support the expense of practice-based research; analytic approaches and computer-based simulations offer less costly alternatives.

A peculiarity of our work is the lack of true replicability. Studies are roughly comparable, but true replication is rare to nonexistent. One cause may be the fact that our journals are very unlikely to publish a study that confirms previous work—'not original,' 'already done,' the referees would say. We hesitate to suggest that weakness in the theories themselves accounts for the lack of replication studies.

The research is almost exclusively the result of our graduate schools, doctoral programs in particular. This raises the interesting prospect of our newest and least experienced being asked to respond to the needs of an increasingly complex and demanding field of practice. Yet the need for linkages—vertical and horizontal—and for integration with broader issues within the organization suggests that our most senior and most widely experienced minds should be directing the research.

The challenge for the future, in responding to such dilemmas, is to meld the efforts of both young and senior researchers, whether their orientation is primarily that of the Theorist, Methodologist, Problemist, or Empiricist. Each orientation brings something unique and valuable to our knowledge base, but each is insufficient by itself. Combining efforts is probably the best path to theories and methodologies that more effectively span the unnecessarily confining boundaries between production planning, inventory management, and scheduling.

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