Accelerating the Diffusion of Production Management Innovations Among Small to Midsized Enterprises Via Electronic Marketing

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Abstract

This report presents the results of an exploratory study of factors affecting the diffusion of production management innovations among small to midsized manufacturing firms (SMEs), and argues for several market-oriented extensions to current government programs that would help reverse declines in real wages in this sector by accelerating innovation diffusion. The principal production management innovations introduced in the US over the last 30 years include manufacturing resource planning systems (MRP II), just-in-time systems (JIT), theory of constraints/optimized production technology (TOC/OPT), and finite capacity schedulers (FCS). According to published surveys, the adoption levels for these systems among SMEs is no more than 40-50%, compared to an estimated 75-95% for large firms. Based on a 1993 National Research Council study of smaller manufacturers and a detailed evaluation of available systems, it is hypothesized that most SMEs are psychographically 'late adopters' of these kinds of innovations and that this, as well as economic factors, accounts for their low adoption levels. In particular: (1) SMEs as a group have a more conservative attitude toward innovation than larger firms; (2) they are less aware of potential benefits to firms their size; (3) incentives to adopt are weaker compared to the perceived cost; (4) they have relatively few opportunities to learn from, or be influenced by, positive peer experience; and (5) vendors don't create the kind of scaled-down low-cost packages and marketing approaches that fit this size enterprise until the higher profit, large enterprise markets have been saturated (if then).

The federal program that is most clearly focussed on innovation diffusion, and involves the broadest spectrum of small to midsized manufacturers, is the Manufacturing Extension Partnership (MEP), administered by the National Institute of Science and Technology. Although this program has been extremely effective (including an economic benefit to surveyed client firms of eight times federal investment in 1994), it is currently relies on a labor-intensive approach that severly limits the number of companies that can be helped with available resources. Six new ways to pool, package, and disseminate expertise electronically are proposed, aimed specifically at late adopters, that would shift parts of the consulting and education currently performed by MEP field engineers to interactive software. In addition, it is suggested that the MEP program establish a liaison with technology vendors to stimulate them to repackage their offerings to better match the needs of the late majority market. Synopses of production management concepts and of the evolution of MRP systems are given as appendices.

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1. Introduction

This report presents the results of an exploratory study of factors affecting the diffusion of production management systems and technologies among small to midsize enterprises (SMEs), and argues for several market-oriented extensions to current government programs for improving manufacturing performance in this sector. By production management *systems* we mean the manual procedures, objectives, methods, and techniques, as well as computerized systems, that people use to manage the operation of a production facility (factory, job shop, etc.). By production management *technologies* we mean classes of tools, embodied in hardware and software, that generate, store, and/or process production management information. *SMEs*, also called *small- and medium-sized enterprises*, are manufacturing firms employing fewer than 500 people. An introduction to production management is given in Appendix I.

Originally, the purpose of this research was to assess the expected capabilities of next-generation production management software against the needs of SMEs, and networks of SMEs, in Europe, Japan, and the US. What came to light, however, is that virtually all advanced software being developed in all three regions, both by vendors (Teresko 1994; Staiti 1993; Greene 1992) and by researchers in government sponsored projects (TIMA 1995; AMI 1995; CIME 1995; US Department of Commerce 1994; Globeman 1995), is oriented towards the needs of large enterprises (LEs). Many of these needs simply do not arise for most SMEs. For example, most LEs have many plants to manage; most SMEs don't. LEs often have plants and offices in several countries; most SMEs don't. LEs often have different computing platforms in different plants and in different departments of the same plant; SMEs don't. Many LEs have already installed sensors on production lines and equipment to collect real-time status information; relatively few SMEs have done so. Most LEs produce their products in high volumes; a large fraction of SMEs engage mainly in small-batch, custom manufacture.

More importantly, for those production management functions that every manufacturer must perform, such as inventory control, customer order management, and shop floor scheduling, all studies in the literature indicate that the fraction of SMEs who have yet to adopt even one current-generation system or technology is high -- somewhere between one quarter and one half of the population. In contrast, almost all LEs installed some version of a modern production management system years ago, and many are embarked on upgrading their technology. Hence the research focus shifted to investigating what it is about current systems, technologies, and SMEs that is limiting SME uptake of these tools.

1.1 Why SMEs?

According to census figures (US Department of Commerce 1992), more than 98% of manufacturing establishments in the United States are small to midsize and they employ about 40% of the total manufacturing workforce. About 90% of US manufacturing establishments are *small*, employing fewer than than 100 people.[1] The actual counts (in 1990, in round numbers) were 368,000 small to midsize establishments, 32,000 midsized establishments, and 336,000 small establishments.

[1]A *manufacturing establishment* is the total facility occupying a single physical site, such as a plant, where manufacturing operations are performed. It is not necessarily identical to a single company or enterprise, which may have one or more establishments.

Several recent surveys have determined that SMEs, as a group, consistently exhibit a lower level of adoption of new methods and technologies of all sorts than do LEs (Industrial Technology Institute, 1990; US General Accounting Office 1991; US Department of Commerce 1994). That is, at any point in time, the fraction of SMEs who have begun to use a particular method or technology in their business is always less than the fraction of LEs in the same industry who have begun to use that same method or technology.

The largest of these surveys was conducted by the Bureau of the Census in 1993 (U.S. Department of Commerce 1994). The sample consisted of nearly 9,000 companies that employ more than 20 people, in five basic manufacturing industries.[2] The survey reviewed the use of 17 manufacturing process technologies,[3] and how this varied by industry, by size of plant, and by several other company characteristics. In every case, the proportion of SMEs who had adopted the technology was less than the proportion of LEs. While some of these technologies may not be appropriate for small plants (e.g., automated guided vehicles) and some may not be justifiable on a payback basis (e.g. pick and place robots) even suitable, affordable technologies had lower levels of adoption among SMEs than LEs. Comparison results for four technologies widely used by LEs are shown in Figure 1-1.

Whether this should be a matter of concern at the federal level has been the subject of debate among policy makers and analysts. On one side are those who have faith in market economics and the power of the invisible hand to make individual decisions sum up to the best course for society as a whole. To this group, SMEs who have not adopted some relevant technology have made a rational economic choice based on market conditions.

On the other side are those who feel either (1) that SMEs deserve some amount of special government assistance, analogous to the assistance provided to small farmers, or (2) that SMEs play such a vital role in global US competitiveness that it is in the national interest to help them modernize. Although smaller companies are not major exporters of goods themselves, the component parts they supply to larger manufacturers constitute as much as 60% of the manufacturing cost of the final end products (Industrial Technology Institute 1991). Hence, if small company modernization reduced these costs, it could have have a substantial effect on the price competitiveness of the goods exported by their customers.

A similar statement can be made regarding the impact of smaller firms on defense procurement costs. Over 20% of prime contract dollars go to small business. Of the 80% that does not go to small business directly, 34% of that dollar value is subcontracted to small business (Williams 1994). Thus, small businesses supply about 50% of the dollar value of DOD procurement, and cost reductions in this portion would significantly affect the total.

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[2]fabricated metal products (SIC -- standard industry classification -- 34), industrial machinery and equipment (SIC 35), electronic and other electrical equipment (SIC 36), transportation equipment (SIC 37), and instruments and related products (SIC 38)

[3]computer aided design (CAD), CAD controlled machines, digital CAD, flexible manufacturing systems (FMS), numerically controlled and computer numerically controlled (NC/CNC) machines, materials working lasers, pick and place robots, other robots, automated storage/retrieval systems, automated guided vehicles, raw material inspection sensors, finished goods inspection sensors, local area networks (LANs) for technical data, factory LANs, intercompany computer network, programmable controllers, computer use on factory floor

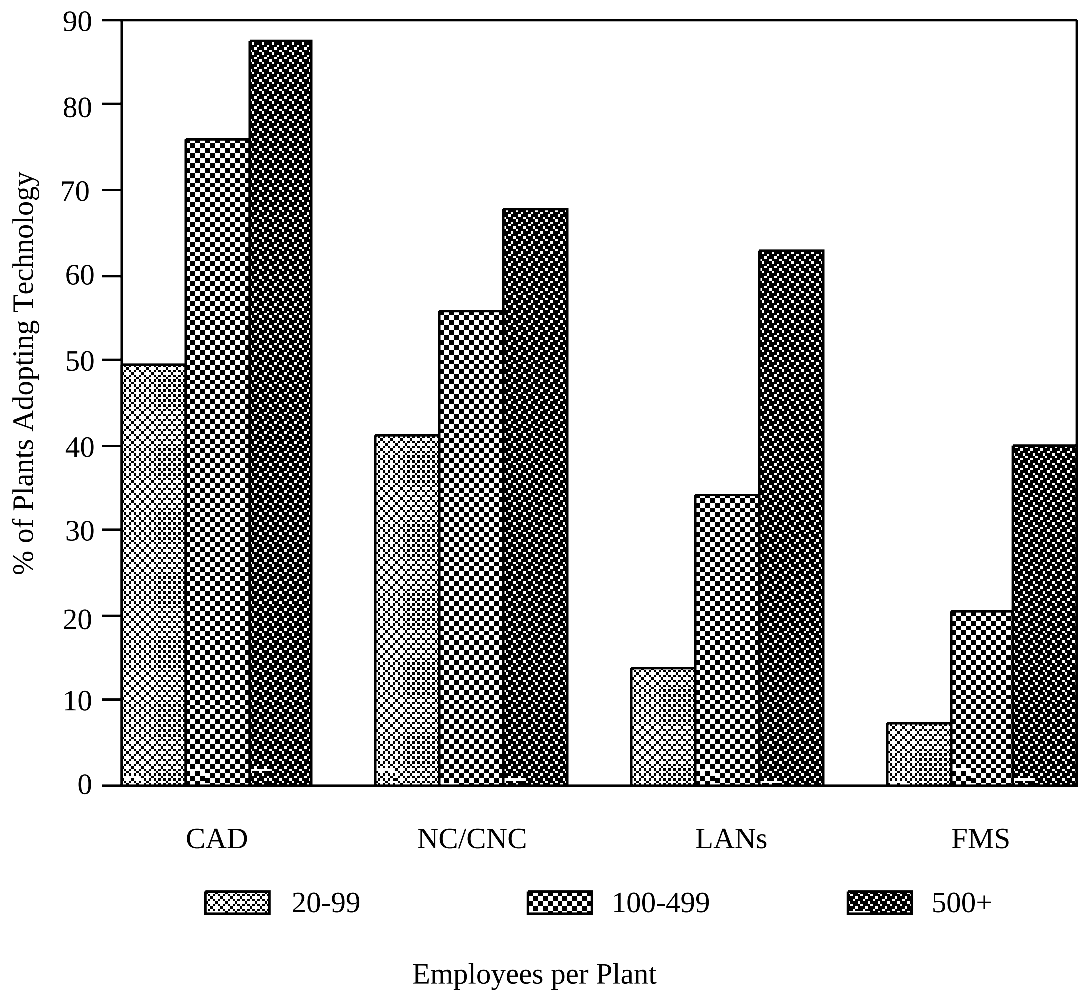

Figure 1-1: Adoption of Manufacturing Process Technologies by Size of Plant (1993)

Finally, what the government's role should be in promoting technology adoption is part of the larger policy question of what the government can and should do to reverse declines in real wages experienced in the US over the last decade. The SME sector is a case in point. In a 1994 study, using data on 1400 small to midsized plants collected by the Performance Benchmarking Service (Luria 1995), Luria showed that the failure to adopt relevant technologies and methods has had a direct negative effect on this sector's income. In particular, this study found that about half of SMEs in most industries responded to price competition by seeking to reduce wage payments, fringe benefits, and other labor outlays rather than by increasing productivity through the the installation of new technologies and methods. Consequently, the average employee wage in these shops is lower. In other words, the employees of firms that don't modernize suffer a lower standard of living so that their employers can remain cost competitive.

Unfortunately, the low-wage/low-innovation strategy seems to be successful over time. When Luria compared productivity data from 1992 to that of 1994, he found that firms employing this strategy represented a growing fraction of total manufacturing employment. Moreover, the proportion of firms using this strategy was also growing. Thus it seems likely that average wages will continue to fall, and modernization will continue to be slow, unless productivity improvement becomes a more attractive choice.

One way for a firm to raise productivity is to replace the tools, techniques, and procedures it uses to manage production with new ones that have proven to be superior. Better production management methods can improve a firm's profitability without reductions in direct labor expense. This is because production management is concerned primarily with overhead cost components, such as the cost of carrying inventory, the cost of inefficient resource utilization, and the cost of production control and administration.

Due to changes in technology, systems, and the general understanding of how these are related, it now appears possible for many more smaller manufacturers to obtain the benefits of innovations pioneered by larger firms. The remainder of this report is organized as follows. Chapter 2 describes the production management systems and technologies that are currently available, the benefits that can be obtained from using them, and survey data on adoption levels. Chapter 3 presents two models of innovation adoption and diffusion that offer a number of insights into the slow uptake of technologies and systems by SMEs. Finally, Chapter 4 outlines several novel ways to accelerate the diffusion of these innovations, which exploit new ways to market them made possible by the spread of personal computers, the Internet, and the World Wide Web.

2. Current Systems of Production Management

Production management is that part of manufacturing management which is responsible for coordinating the stocks and flows of materials in a manufacturing plant with sales, production, and purchasing activities. The purpose of such coordination is to assure that:

1. the stocks of salable items -- finished goods -- are at all times sufficient to meet customer demand;
2. the flows of salable items into stock are sufficient to maintain finished goods inventories at appropriate levels;
3. the stocks of component materials -- raw materials, fabricated components, and subassemblies -- are at all times sufficient to meet the input needs of production processes; and
4. the flows of components into stock, both purchased and manufactured, are sufficient to maintain these inventories at appropriate levels.

In achieving the above goals, however, the various inventories should not be allowed to get too large. Holding inventory incurs a cost, and the longer an inventory item is held without being used, the higher the cost. In fact, there are two costs: the interest cost (paid or foregone) on the money invested in the material, and the out-of-pocket cost of storage (incremental rent, insurance, security charges, etc.). Holding inventory is analogous to not receiving any interest on a deposit in a bank and, furthermore, paying storage charges to keep it there.

Production management is also responsible for coordinating the work required to perform production operations with the shop floor resources available to perform that work. A production operation is a task, such as drilling a hole or attaching a flange to a cabinet, that is performed on each item in a batch of material as one step in a production process. In general, performing an operation will require the utilization of a worker with certain skills, tools, equipment, floorspace, and perhaps other resources for some period of time. If suitable resources are not available at the time an operation could be performed, the operation must be delayed. The sum of operation times and delays determines the total time it takes for material to flow through a production process. These flowtimes, in turn, determine the times at which completed items flow into inventory. Coordination is required to assure that enough capacity (resource hours) of the right kind is available at the right time to achieve the flowtimes that maintain the right inventory levels. But, there shouldn't be too much capacity available, because the money paid to extra workers and the expense incurred for unused plant and equipment does not contribute to salable output and so is wasted.

To achieve coordination, production managers must plan, track, and control all the factors that affect material flow and resource utilization. These include:

- the layout of the shop,
- workforce levels and composition,
- inventory levels and locations,
- production process flowtimes,
- process yields and scrap rates,
- the allocation of inventory to internal operations and external demand, and
- the allocation of shop floor resources to operations over time.

Production *planning* is concerned with decisions that must be made in advance in order to put materials and resources in place at the right time. Production *control* is concerned with carrying out those decisions, revising plans, and deciding what to to do when things can't be done according to the original plan. *Tracking*, or course, is maintaining accurate, up-to-date status information, and making it available to those who need it for planning and control purposes.

Production management is a complicated problem. First, there is a lot to plan for and keep track of. The number of end item, intermediate component, and raw material item types in most factories is in the hundreds, and for many it is in the thousands and tens of thousands. Similarly, the number of production operations performed per day is at least in the hundreds and can range upward to tens of thousands. On top of that, there are many workers, many pieces of equipment, many inventory locations, and many production processes in use, and many batches in process, at every moment. The operation of even a relatively small plant may involve 25-50,000 individual pieces of information (Vollmann *et al.* 1988).

Second, neither the ultimate demands for output, nor the internal production processes, nor the performance of vendors who supply the purchased materials is necessarily controllable, stable or even predictable. End item sales are always different in some way from forecast, the output rate of production processes vary from day to day, machines unexpectedly break down, vendors are sometimes late and sometimes short on their deliveries, etc. These sorts of fluctuations make production a stochastic process, which must be taken into account. Unexpected deviation from plan will destroy coordination unless extra resources are built into the plan to compensate.

Third, how to allocate resources to operations to achieve required flowtimes is a tough scheduling problem. It is impossible in practice to compute a truly optimal schedule, and difficult to construct a good one, because there are so many interdependencies to consider. Consequently, tradeoffs are generally made between achieving high capacity utilization and meeting flowtime constraints.

Finally, the amount of inventory present at any moment is not a controllable managerial variable. Rather, it results from the net difference between inflows and outflows of material, batch sizes, and the amount of time material is in process. Inventories are residuals that measure unsold, unused, and unfinished material. They are not management levers in their own right. Similarly, capacity utilization is not directly controllable, but results from the net difference between the work done in different periods and the capacity available. Thus, two of the most important measures of manufacturing performance are measures of the whole system of production management employed, not one component of it.

The following sections present the three current systems of production management and the tools they provide for planning and control.

2.1 MRP Systems

In 50s and 60s, as computers came into commercial use, manufacturers who could afford them began to use them for the clerical aspects of production management, such as keeping stock records. The first major innovation to affect planning and control was the development of software that could translate a master production schedule -- the quantities of product a plant is to produce in future time periods -- into orders to buy components and orders to make components at certain times to satisfy that schedule. The first set of orders then becomes a purchasing plan for vendor-supplied materials, and the second becomes a production plan for manufactured components that together exactly coordinate with scheduled product output.

This software, and the technique it used to establish the size and timing of the orders, was called MRP, for *material requirements planning*. Prior to the use of MRP, the vast majority of manufacturing firms bought material, or commenced to manufacture material, when stocks on hand were running low, regardless of the needs that could be projected from scheduled product output. Firms that used formal methods kept statics on usage rates, replenishment time, and replenishment cost to determine how low inventory should get before reordering, and to determine the most economical quantity to order (Fogarty *et al.* 1991). A considerable body of practice, methods and art grew up around MRP systems, which was eventually collected and codified in the early 70s, e.g. (Orlicky 1975).

The second major innovation was the development of software that embodied these new methods. In particular, programs were written to create the master production schedule from a more aggregate description of planned sales, to update the master production schedule in response to actual customer orders, and to project the workload that would be imposed on shop resources by a given schedule. The result was a software system and a method for using it called *closed-loop MRP*. The "loops" are loops in the planning process that users are supposed to follow to (a) revise the master production schedule and (b) modify plans for future shop capacity so as to stay in step with revised sales plans and with product sales that have already materialized.

The third and last innovation was the addition of many financially-oriented functions, and simulation capabilities, to the closed-loop MRP base. The basic stimulus for this innovation was the recognition that a good deal of the information that is input to these functions already existed in the data files being maintained to run MRP, and it could be further exploited by integrating new functionality with it. Since the main intent of these additions was to support planning and control for more kinds of resources, including money, a change of name was made to *manufacturing resources planning*, with a revised acronym, MRP II (Wight 1981). Today, all software systems in the marketplace that include closed-loop MRP are called MRP II systems and virtually all of them include at least some MRP II enhancements. The term MRP I is now used to denote just the material planning and control components.

2.1.1 Components

Software is central to MRP production management. The guiding vision at each stage of MRP development has been that automation is the key to improving manufacturing performance. The first element of this vision is that all data required to plan and control inventories and production should be captured in a comprehensive database. Second, software modules should be provided to support decision making at each level of the production planning and control hierarchy (see Figure I-2). Third, the whole package should be integrated in the sense that the output of every module should be stored in the database where it can serve as input to any other module that might require it. Fourth, production and inventory should be managed analytically and quantitatively, via the database, rather than by informal methods. Finally, the database should be exploited as much as possible to perform other administrative functions, such as order entry and accounting.

Today's commercial MRP II systems include the following 18 core modules (CPI, 1993):

- *Master production scheduling* -- used to generate and maintain the master production schedule of product items, so that it coordinates with sales forecasts and current customer orders;
- *Material Requirements Planning* -- used to generate and maintain planned shop and purchase orders for components, so that they coordinate with the master production schedule for end items;
- *Capacity Requirements Planning* -- used to project the detailed resource requirements (e.g. workcenter hours by period) for producing the items called for in current and future shop orders, so that this load can be coordinated with detailed future in-house capacity and subcontracting plans;
- *Order Release* -- used to launch a new shop order by creating the database entry or hardcopy for it, and allocating inventory to it;
- *Purchasing/Receiving* -- used to launch and track purchase orders;
- *Shop Floor Control* -- used to direct and track the progress of orders through the shop;
- *Item Master/Inventory Management* -- used to update and report current inventory status;
- *Bill of Materials Data Management* -- used to update and report current bills of materials;
- *Workcenter/Routing Data Management* -- used to update and report current workcenter and routing data;
- *Sales forecasting* -- used to estimate future demand from historical sales data as part of sales planning;
- *Rough-Cut Capacity Planning* -- used to project the gross resources required (e.g. total labor hours) to produce the end items called for on the master production schedule, so that gross future in-house capacity and future subcontracting can be coordinated with this load;
- *Customer Order Management* -- used to quote prices, check inventory availability, allocate inventory to orders, and update inventory records on-line to reflect allocations;
- *Job Costing* -- used to collect and report actual costs associated with orders and lots;
- *Product Costing* -- used to sum up the unit cost of a manufactured item using bill of materials information;
- *Accounts Receivable* -- used to generate invoices, maintain customer account records, record receipt of payments;
- *Accounts Payable* -- used to record vendor invoices, maintain expense account records, generate vendor checks;
- *Payroll* -- used to maintain payroll data files, print paychecks;
- *General Ledger* -- used to produce financial statements.

The first nine modules constitute a minimal MRP system, approximately the smallest package a vendor would sell. Additional functionality is priced by the module. Besides the core modules, nearly all MRP vendors offer additional options. A more detailed discussion of all of these modules, the methodology prescribed for their use, and some of the difficulties users face in applying this methodology appear in Appendix II.

2.1.2 Benefits

The benefits of using MRP systems for managing production fall into three categories: (1) automatic inventory planning, (2) inventory reduction, and (3) increased coordination between sales, production and purchasing. Since there are no MRP tools for generating capacity plans (as opposed to analyzing proposed plans), or for detailed shop floor scheduling, MRP systems are only marginally helpful in making capacity utilization more efficient. This fact is not widely appreciated (cf. Section II.6).

2.1.2.1 Automatic Inventory Planning

MRP systems were originally designed for production environments in which batches of finished goods are made from a large number of components and subcomponents. For products like these, bills of materials are long and have many levels. Consequently, production and purchasing plans for components are extensive and complex. The ability to generate these plans automatically is a major productivity benefit of the MRP algorithm.

2.1.2.2 Inventory Reduction

Two large surveys of MRP users in the 1980s (see below) indicated that, on average, adopting an MRP system of production management reduces inventory by about 34%. In addition, better planning has the effect of reducing stockouts by about 40%. This amount of improvement can be significant even to a small firm. For example, a firm with $5 million in annual sales and an initial inventory turnover ratio of 4 would have $1.25 million in working capital invested in inventory over the course of a year. An inventory reduction of 34% would free up $425,000. If this amount were invested (or not borrowed) at an interest rate of 10%, the net return would be $42,500 per year.

2.1.2.3 Increased Coordination

The MRP system of production management emphasizes both static and dynamic coordination of sales, production, and purchasing activities. Generally, before an MRP system is installed in a factory, procedures are quite informal, some important information may not be written down, and different types of information are maintained privately by different managers. A firm may not even have part number identifiers for items, and it may not keep track of its current inventories. Consequently, decisions made by different parties in different departments that should be coordinated are not, because they are based on an uncoordinated base of information.

Activities are coordinated statically, as of a moment in time, in the MRP system by requiring all departments to make formal plans for future actions based on a shared specification of goals -- the master schedule -- and a shared specification of current state, constraints, and resources -- the MRP database. Departments that have not paid attention to coordination in the past can use the formal MRP planning mechanisms to at least plan to coordinate in the future. Moreover, departments can use the MRP control mechanisms to keep plans and status information in step with reality, as goals and constraints change, and events occur that deviate from plan. In particular, the ability to use computerized tools to revise plans dynamically based on new status information allows a firm to coordinate its response to changing conditions across departments.

2.1.2.4 Survey Reports of Performance Improvement

In the late 70s and early 80s, many large and midsized firms adopted closed-loop MRP systems for inventory control and production management. Two major surveys were conducted at that time to determine the state of practice and the results that were being achieved. The first, summarized in (Anderson *et al.*, 1982), elicited responses from 679 companies located in about a dozen northern states from the Dakotas to Western Pennsylvania. These responses were obtained by sending questionnaires to approximately 1700 members of the American Production and Inventory Control Society (APICS) residing in those states who were asked to either complete the questionnaire or forward it to the materials manager, the individual responsible for production and inventory control, or simply the individual most knowledgeable about the MRP system in their firm. The second, reported in (LaForge and Sturr, 1986), elicited responses from 107 companies out of a population of 300 drawn at random from firms located in South Carolina having 100 or more employees. The idea behind the second survey was to assess the generalizability of the Anderson *et al.* survey findings by administering the same questionnaire to a *random sample* of manufacturing firms in a *different geographical area* of the United States.[4]

The measures of operating performance solicited in both surveys were the following:

- *inventory turnover*: the ratio of yearly sales revenue to the average cost of inventory on hand during the year. The reciprocal of this measure is an indicator of inventory holding cost since when multiplied by sales it gives the dollar amount of inventory that has to financed out of working capital over the course of a year. The higher the inventory turnover, the better.
- *delivery lead time*: the average number of days from customer order entry to product shipment. This is determined jointly by accuracy of customer demand forecasts and the manufacturing cycle time for end products. The lower the delivery lead time the better.
- *delivery dependability*: the percentage of deliveries shipped on the day promised. The higher the better.
- *frequency of backlogged orders*: the percentage of orders that are split into immediate shipment and backlog due to unavailable material at the time of order. This is a measure of stockouts. The lower the better.
- *number of expeditors*: the number of personnel employed to push rush orders or late orders through the shop. The lower the better.

These measures cover the three areas in which production management can affect manufacturing performance: inventory cost, delivery performance, and administrative cost (here, the cost of the expeditors).

As it turned out, the average performance improvement on each measure following adoption of MRP was almost identical in both studies. These results are shown in Table 2-1. It is noteworthy that the baseline performance estimates in the second study are almost all better to start with, and better after MRP, than in the first study. Obviously this can't be explained by MRP adoption.

At this point it is important to clarify what "adopting MRP" meant in the firms studied. A closed-loop

[4]The underlying information technology employed was not an issue in these surveys. It is likely that for both it was the same -- mainframes and minicomputers, remote terminals, and a substantial usage of printed reports.

Study 1 - 1979	Pre-MRP Estimate	Current Estimate	Improvement
Inventory Turnover	3.2	4.3	34%
Delivery Lead Time	71.4	58.9	17%
Delivery Dependability	61.4%	76.6%	24%
Frequency of Backlogged Orders	32.4%	19.4%	41%
Number of Expeditors	10.1	6.5	40%
Study 2 - 1985			
Inventory Turnover	4.5	7.9	34%
Delivery Lead Time	55.6	41.7	18%
Delivery Dependability	73.9%	88.6%	25%
Frequency of Backlogged Orders	29%	13.5%	40%
Number of Expeditors	10.8	5.1	37%

Table 2-1: Operational Performance Gains from MRP Adoption

MRP system has many components, and a firm might be said to have adopted MRP if it is using any of them, ranging from formalized and computerized inventory records up to full use of the closed-loop planning tools. In both surveys, respondents were asked to place their firms into one of the following categories of MRP usage. (These classes were originally invented to characterize the stages of development observed in firms that "adopt MRP".)

> *Class A.* Closed-loop system is used for both planning and control, and for both material and capacity requirements. The master production schedule (MPS) is leveled to match fixed shop capacity as well as possible, and is used by top management to run the plant. Most deliveries are on time, inventory is under good control (i.e. the inventory records are kept accurate and up to date), and little or no expediting is done.

> *Class B.* Closed-loop system with capability for both MRP I and capacity planning. However, the MPS is somewhat inflated to cover shortfalls resulting from inaccurate capacity planning. Top management

does not give full support. Some inventory reductions have been obtained, but capacity is sometimes exceeded and some expediting is needed.

Class C. Order launching system based on MRP I only. Capacity planning is done informally, probably with an inflated MPS. Expediting is used to control the flow of work on the shop floor. A modest reduction in inventory has been achieved.

Class D. The MRP system is used for planning, not control. Many records are inaccurate. The informal system is largely used to run the plant.

While these definitions are pretty vague, the general idea is that MRP control procedures are fully utilized in Classes A and B, partially utilized in Class C, and not utilized in Class D. Capacity planning is fully utilized in Class A, partially utilized in Class B, and not used at all in the other classes.

Table 2-2 shows how respondents classified their firms in both studies. Note that a larger fraction of

MRP Class	Study 1	Study 2
A	9	25
B	29	31
C	49	41
D	13	3

Table 2-2: Percent of MRP Firms in Each MRP Usage Class

firms are using capacity planning to some extent in the second study than in the first. This does not seem to have made the performance improvements any greater in the second study than in the first.

The relatively low percentage of Class D MRP users in the second study is probably explained by the relatively high percentage of firms in that study who had computerized their inventory system, order release, and purchasing functions. Table 2-3 shows the degree of computerization by function reported by firms in each study. In both studies, the vast majority of firms had fully computerized their MRP I planning (bills of material, parts explosion). For all of the other functions, more firms in the second study had computerized them than in the first. In both studies, less than half of the firms were capable of computerized closed-loop capacity planning.

Two important conclusions may be drawn from these data. First, it appears that the performance improvements shown in Table 2-1 are almost all due to the use of MRP I. Only a minority of the firms surveyed actually employed capacity planning. Second, one can surmise that the relative amounts of improvement shown (percentages) are about the most that one can expect from adopting MRP I. The results of both surveys are in remarkable agreement. Higher MRP usage ratings and higher levels of computerization by firms in the second study did not make a big performance difference.

2.2 JIT Systems

JIT is an acronym for "just in time". Literally, this term means to produce or receive something exactly when it is needed, not earlier (resulting in inventories) or later (resulting in shortages). However, this term has come to refer to a whole constellation of techniques for improving manufacturing performance

	Study 1	Study 2
Inventory stock system	64	94
Bill of materials	87	88
Parts explosion (MRP I)	87	85
Order release	50	76
Purchasing	43	73
Forecasting end items	43	67
Master production scheduling	52	61
Operations scheduling	36	55
Shop floor control	31	52
Capacity planning	38	42

Table 2-3: Relative Computerization by Function for MRP Firms (%)

by:

- maximizing product quality;
- reducing inventory;
- minimizing flowtimes;
- synchronizing material supply to demand;
- minimizing shop floor overhead.

One consequence of employing the JIT system is that material is received and items are produced just in time for use, which gives the system its name. Another is that products are shipped exactly on time, so delivery dependability is maximized. The main reason that JIT was developed, however, was to reduce product costs, raise product quality, and lower manufacturing overhead (Shingo 1981).

A key insight underlying the JIT approach is that it is not always necessary to tradeoff one performance goal for another, as is assumed in the MRP system of production management. For example, carrying high levels of finished goods inventory is not absolutely required for high levels of customer service, long work-in-process (WIP) queues are not absolutely required to get high capacity utilization, and extensive data processing is not absolutely required to coordinate material supply with production usage demand.

Rather, under certain circumstances, high levels of performance on almost all dimensions can be obtained at the same time by managing production so as to eliminate "waste". Waste is defined as anything on the shop floor that adds cost but does not add value to the product. This includes inspection steps, unnecessary movement of materials, equipment setup time, scrap, rework, storage and holding of inventory, and all shop-floor paperwork and overhead activities. Total elimination of these activities is an ideal, and might not be achievable in practice. It is put forth to clearly define what JIT considers to be the highest level of manufacturing performance and to drive a firm toward that level.

The primary strategy used to make progress toward the JIT ideal is to alter the physical aspects of production, and the responsibilities of shop floor personnel, so that waste is not generated in the first place and the need for associated activities disappears. In general, the physical aspects are simplified, or made to require less effort, while responsibilities are enlarged. Special emphasis is placed on inventory reduction. Not only does holding inventory add to overhead cost, but holding high levels of inventory makes it too easy to ignore conditions that generate waste. In particular, high levels of inventory can conceal poor scheduling, poor vendor delivery, poor manufacturing quality, and inaccurate record keeping.

JIT is a holistic, comprehensive system of manufacturing management that goes beyond the boundaries of production management. For example, it is possible to reduce elements of waste by redesigning products so that they can be manufactured with fewer subassemblies, fewer operations, and less chance for workers to make mistakes that generate scrap. Product lines can be redesigned to have parts in common, so that fewer distinct production processes are needed. Production processes can be redesigned to use equipment that can be setup more quickly. However, the rest of this section will only consider aspects of JIT that relate to production mangement.

2.2.1 Components

2.2.1.1 Waste Reduction

JIT defines five basic categories of waste: defects, material movement, setup time, shop floor overhead, and inventory. A number of tactics and techniques are prescribed for reducing or eliminating each of these. Techniques are specific actions to be taken or methods to be applied to achieve tactical objectives. Of the five categories, only defects can be completely eliminated, and driving defects down to zero turns out to be most important to achieving JIT ideals, because it has a significant impact on the other categories. The following paragraphs outline the main tactics and techniques that can be applied without making engineering changes to product or production process designs. Details may be found in many references, from the classic (Schonberger 1982) to the contemporary (Harmon 1992).

To eliminate defects:

- Embed quality control at each step of the production process, e.g. by:
    - reducing process variance using statistical process control;
    - making production operators responsible for and capable of inspecting their own work.
- Require the highest quality standards, e.g. by:
    - authorizing operators to stop a production line and fix a quality problem when it is detected.
- Expose and eliminate the root causes of quality problems (rather than just detect problems) so that production operators can realistically achieve zero defects, e.g. by:
    - recording the immediate cause of a detected defect;

- modifying operations to eliminate causes of mistakes, e.g. by color coding;
- using cause and effect diagrams to identify root causes;
- establishing quality circles to devise long-term solutions to quality problems.

To reduce material movement:

- Reduce the distance material must travel between workcenters, e.g. by:
  - arranging the workcenters involved in a manufacturing process into a dedicated flowline corresponding to the routing sequence for that process;
  - grouping several machines into one "cell" so that several operations in a process can be performed in one place, with essentially no movement of material;
  - reducing the number of levels in the manufacturing bills of material so that there are fewer subassemblies and more operations performed in each flowline.
- Reduce the distance material must travel into and out of stocks, e.g. by:
  - eliminating centralized stockrooms in favor of point-of-use stocking;
  - locating raw materials inventories next to initial "gateway" production processes, and finished goods inventories next to final assembly lines.

To reduce setup times:

- Design a standard setup process to be used by all operators, e.g., by:
  - video taping the current setup process for analysis;
  - preparing setup process sheets listing the elemental tasks to be performed.
- Provide additional equipment just to reduce setup time, e.g.:
  - for large dies, reduce transport time by using a standard table to roll the die into position;
  - for small tools (e.g. power hand tools), use duplicates to avoid changing bits, disks, chucks, etc.

To reduce shop floor overhead cost:

- Reduce transaction volume, e.g. by:
  - treating each flowline as a one-step process for planning purposes so that internal operations need not be tracked or scheduled independently;
  - eliminating inventory transactions for material entering the line by post-deducting from inventory the component parts that should have been used, according to the bill of materials, to make the number of items leaving the line (backflushing).

To reduce WIP inventory:

- Reduce lot sizes, e.g. by:
  - eliminating safety stock;
  - reducing buffer stock;
  - eliminating long setup times.
- Stabilize the production facility, e.g. by:
  - establishing a rigorous schedule of preventative maintenance to prevent equipment breakdowns from causing material to back up;

  - educating, training, and involving workers in the new production management approach, and rewarding them for their contribution to meeting its objectives.
- Synchronize the operations performed in each flowline, e.g. by:
  - reducing the variance in time taken to perform each operation;
  - balancing workcenter capacities so there are no bottlenecks;
  - training workers in multiple production tasks so they can shift to different lines or stations as the load changes.
- Disallow production of material by an upstream process until production is requested by a downstream process (pull system control/Kanban), e.g. by:
  - using the return of an empty container, a card, or some other token, to the upstream process area to signal the need to produce more;
  - requiring the supervisor of the upstream process to visually monitor the inventory space of the downstream process, and commence to replenish it when the stock there is reduced to a specified level.

To reduce raw materials and finished goods inventory:

- Synchronize supplier deliveries to production process demands, e.g. by:
  - establishing long term, cooperative relationships with suppliers;
  - using nearby suppliers to reduce average delivery times and their variance;
  - increasing frequency of deliveries;
  - communicating order release schedules, and revisions of them, to suppliers in time for them to schedule their own operations.
- Synchronize end item production rates to sales rates, e.g. by:
  - manufacturing all end item models every day or every week, proportionate to the sales mix (mixed-model production);
  - reducing variation in master schedule volumes across periods.

JIT is an elegant concept. Although the different tactics and techniques were presented above as if they were independent, they actually interlock and reinforce each other synergistically. For example, one way to reduce material movement is to create dedicated flowlines. The existence of dedicated flowlines then enables a reduction in overhead cost by eliminating the need to schedule the operations interior to the line. In the area of inventory, one way to reduce WIP is to reduce lot sizes. But when defects have been eliminated, and the shop has been stabilized, and end item production has been synchronized to sales, and dependable supplier deliveries have been secured, there is no more need for safety stock, which translates into smaller lots.

2.2.1.2 Continuous Improvement through Total Worker Involvement

JIT prescribes a gradual implementation process that involves the workforce at every step and, ideally, never ends. The first step is to make workers aware of the objectives, tactics, and techniques of JIT and to demonstrate that management is committed to them. (This is sometimes accomplished simply by cleaning up the shop, or taking a picture of it and hanging it on the wall with the label "BEFORE".) Then, the workers themselves are to discover how the techniques can be applied to their situation. Improvement is gradual because it takes time for this to happen. Although industrial engineering consultants might identify a number of improvements faster, in-house worker know-how is preferred as the primary source of improvement proposals because (1) it is essentially free, (2) they already know well the processes that the engineers would have to learn, and (3) a natural by-product of the effort is that workers take pride of ownership in the results. Staff and consulting projects in general are avoided in JIT because their results tend to be imposed on workers unilaterally (which workers resent), and the goal is for improvements to be made on an on-going basis, forever.

JIT emphasizes worker flexibility, worker responsibility, worker authority, and worker problem-solving. Work rules are made more flexible, where they were rigid, and cross-training in multiple production operations is supplied. Workers are also rewarded for taking on additional responsibilities, such as doing their own inspection, performing some of the preventative maintenance, and keeping to the schedule. Workers are given the authority to control their work, and incentives to make suggestions at any time that improve performance.

2.2.1.3 Production Planning

The net effect of applying the techniques to reduce waste is to considerably simplify the coordination problems that need to be solved via production planning. For example, when the number of BOM levels is small, end item demand is stable, and variances from plan are rare, computing purchase order quantities and lead times can be done with pencil and paper. Similarly, it is easy to coordinate the work to be done with shop capacity day-to-day because the shop has been designed for the work.

2.2.2 Benefits

The benefits of the JIT system are explicit in its top-level objectives: high product quality, low inventory, short flowtimes, high delivery dependability, and low overhead costs. Results of a 1985 survey of firms who had implemented JIT in the preceding five years are shown in Table 2-4 (cited in (Vollmann *et al.* 1988, p. 245)).

In general, performance improvements reported for JIT system implementations are all larger than those reported for MRP system implementations. Moreover, much of the improvement can be attained with almost no capital investment. This would seem to indicate that making appropriate physical changes is simply a more effective strategy than better planning and control, when those changes are possible.

The three cornerstones of JIT, waste reduction, continuous improvement, and total worker involvement, should be of benefit to any shop. Many of the tactics, such as setup time reduction, shop stabilization, and defect elimination are likely to be applicable in the vast majority of production facilities. However, not all JIT techniques can be applied to every shop. For example, dedicated flowlines are typically not economic without a substantial volume of production of the same mix of end items for an extended period of time. Low-volume, high-variety jobshops that manufacture all products to order do not meet this requirement. Or, it may be impossible to make the physical changes that would reduce setup times or increase process yields to 100%, especially without investing in new equipment. Older equipment may not have been designed with quick changeover in mind, and some production processes involve more "black art" than science. Finally, it may be impossible to stabilize vendor supplies or customer demand schedules sufficiently to allow much reduction in inventory or synchronization of supply with demand.

	Improvement	
	Aggregate % (3-5 years)	Annual %
Mfg cycle time reduction	80-90	30-40
Inventory cost reductions:		
Raw materials	35-70	10-30
Work-in-process	70-90	30-50
Finished goods	60-90	25-60
Labor cost reductions:		
Direct	10-50	3-20
Indirect	20-60	3-20
Space requirements reduction	40-80	25-50
Quality cost reduction	25-60	10-30
Material cost reduction	5-25	2-10

Table 2-4: Performance Benefits of Adopting the JIT System

2.3 TOC/OPT Systems

In the early 1980s, a different line of innovation was begun by Eliyahu Goldratt, a physicist by training, who came to design a production management system to help a friend who operated a chicken coop plant. His key contribution was to find a way to exploit the idea that not every shop resource is equally important to manufacturing performance all the time (Goldratt 1981). The innovation that resulted was a software system, called OPT (for *Optimized Production Technology*), that combines material requirements planning and shop workload projection into a single, fast module. This module replaces the closed-loop tactical planning in an MRP system. Moreover, OPT was the first system to incorporate the concept of resource bottlenecks into an automatic shop floor scheduler.

As OPT was improved and expanded, and other products exploiting the same basic idea were developed, the term *Theory of Constraints*, or *TOC*, was coined to refer to the underlying ideas. However, since much of the published literature is based on OPT, this report will use the term *TOC/OPT*. The TOC/OPT system of production management has three essential features:

1. A strategy for planning and control that focuses on resources which constrain material flow, referred to as "bottleneck" resources;
2. A decision support architecture that unifies bottleneck capacity planning with material requirements planning in a single software module that automatically generates a feasible plan for both at the same time (sometimes called *threaded simultaneous FCS/MRP* (Hansen 1995));
3. A philosophy of performance improvement that prescribes reduction of constraints, but *not* necessarily to zero, and *not* to balance the capacities of shop floor resources.

A very important feature of TOC is that, unlike pure JIT, it does not require high levels of environmental stability or long-term repetitive flow production to achieve substantial performance improvements.

Bottleneck resources are resources whose capacities are less than the loads placed upon them. E.g., if a firm is planning to assemble 2000 bicycles a day, it will need 2000 frames and 4000 wheels per day. If the workcell that produces frames can turn out 1500 per day and the one responsible for wheels can turn out 5000 per day, the former is a bottleneck. On the other hand, if 2500 frames can be produced and only 3000 wheels, the workcell producing wheels is a bottleneck.

The top level goal of a TOC/OPT system is to maximize potential revenue from unit sales, given the current set of shop resources. Maximum potential revenue per period will occur when production output per period, i.e., throughput, is maximal. (If every end item has a buyer by the time it is produced -- demand equals or exceeds supply -- a firm will actually realize this potential.) Consequently, the most important operational goal is to maximize throughput, irrespective of overall capacity utilization. In fact, and contrary to conventional wisdom, the intensity of utilization of some resources is simply irrelevant.

The fundamental insight underlying TOC/OPT is that throughput is limited only by bottleneck resources. Basically, these resources define a critical path through the shop for each item. Operations performed on non-bottleneck resources are off the critical path, so they have no effect on throughput. Hence, all performance improvement and decision support efforts should be devoted to maximizing utilization of bottleneck resources. This fact has a number of implications:

- An hour lost on a bottleneck resource is an hour lost to the output of the entire factory but an hour lost on a non-bottleneck resource has no real cost (assuming one has already paid for the resource anyway).
- Since high utilization of bottlenecks is crucial to plant throughput, it is beneficial to place WIP buffers in front of them, to ensure that they keep busy despite variations in processing time and input material arrival rates.
- Also to achieve high utilization of bottlenecks, it is beneficial to run relatively large lots through them, to reduce the time lost to setting up.
- Bottlenecks govern inventory as well as throughput.
- Fixed lead-time planning, as in the MRP system, will not maximize bottleneck utilization, so production planning must explicitly schedule these resources at the outset, not leave it as a detail to be resolved after an order has been released to the shop floor.

All of these prescriptions are built into the decision support architecture for a TOC/OPT system.

2.3.1 Components

2.3.1.1 Planning and Scheduling Software

While the original OPT used its own representation of MRP database information, most TOC/OPT systems today interface with the database, database management, and transaction processing modules of an underlying MRP II system. Three new software components augment this MRP base. First, a *master production planning and scheduling*[5] component, is used to identify an initial set of bottleneck resources. A bottleneck is a resource whose load is found to consistently exceed its capacity. This component combines the MRP algorithm with the CRP workload projection procedure to generate load profiles from an initial master production schedule. However, the lead time offsets for MRP include no queueing time.

[5]In the original OPT, this component is called SERVE load analysis.

At this point, a user may consider modifying the future capacity plan, or substituting alternate routings for some items, to eliminate one or more bottlenecks, as in MRP production planning.

Second, if any bottlenecks remain, a *bottleneck scheduler*[6] is used to create a compact schedule for the bottleneck resources. Operations are assigned to these resources starting from the current date, so successive utilization intervals are reserved in the forward direction. Non-zero queue time may be specified for operations performed on bottleneck resources to compensate for variability in the times taken to perform operations. The effect of these added delays is to insert WIP buffers of a certain size in front of bottleneck resources. This component also computes the size of the batch to be processed on each bottleneck (which determines the minimal time between setups), and the sizes of batches to be transferred from one resource to another. In general, operations in a given routing will overlap when transfer batches are less than process batches, thereby reducing the flowtime for the entire process. The result of bottleneck scheduling is a complete schedule for bottleneck resources that does not exceed any of their capacities.

Finally, a *non-bottleneck scheduler*[7] fills in the schedule of operations for the non-bottleneck resources. Operations in a routing that involve only non-bottleneck resources are back scheduled from their due dates all the way back to raw materials, just as in MRP. Operations in routings that are upstream of an operation performed on a bottleneck are back scheduled from the start time of that operation. Operations that are downstream of a bottleneck are forward scheduled from the completion time of the bottleneck operation. When this component has completed its work, all operations and resources will have been scheduled, the schedule will be feasible, and projected material receipts from both purchases and manufacturing processes will be completely coordinated with the schedule.

The latest versions of TOC/OPT software provide for real-time updating of both inventory and capacity reservations. Complete dependency information between orders, reservations, and actual capacity consumption is maintained so that the consequences of cancelled sales orders, unexpected yield losses, early/late vendor deliveries, and early/late shop order completion can be propagated through the schedule almost instantaneously (Hansen 1995). Some systems can be used to set feasible due-dates for end item shipments (rather than just evaluating given due-dates for feasibility) by simulating the insertion of a new order into the current schedule.

2.3.1.2 Performance Improvement Strategy

Production planning must always take two complicating factors into account. First, variance from plan will destroy coordination unless it is eliminated, or some compensation for it is built into production plans. Second, the fact that material flows through a succession of workcenters in a routing means that variances from plan arising upstream will propagate downstream. If several routings go through the same workcenter, variances from plan will cascade in unpredictable ways.

In the MRP system, both of these complications are dealt with by allowing relatively large amounts of

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[6]In the original OPT, this component is called the OPT module.

[7]In OPT, this component is called SERVE, since the idea is to serve the bottlenecks.

WIP inventory everywhere in the system, via safety stocks and long lead times. The idea is to make so much material available to work on that resources will seldom be starved and due-dates will infrequently be missed. In the JIT system, physical changes are made so that the variances are eliminated and flows become synchronized, thereby producing the desired coordination.

The TOC/OPT system prescribes a strategy that lies in between these two (Goldratt 1986). First, WIP buffers are to be placed in front of bottleneck resources, but nowhere else. Second, physical changes are to be made to bottleneck resources, and operations performed on them, to reduce the likelihood of variance. Thus, when the physical changes that JIT requires cannot be made, the TOC/OPT strategy can still improve performance. Moreover, identifying bottleneck resources allows production managers to focus their attention on reducing waste in just just those operations where it matters most.

2.3.2 Benefits

Qualitatively, TOC/OPT systems are much more sophisticated than MRP systems, and make specific provision for capacity allocation as well as inventory planning. They do not permit the generation of an infeasible master production schedule. They replace managerial judgment about lot sizes, lead times, and setup batching with calculations. They produce shop floor schedules as well as inventory plans. Consequently, bottleneck capacity is utilized more intensively. Any firm that can understand and exploit this level of sophistication will necessarily do a better job of production management with TOC/OPT than with MRP.

No survey results were found in the literature that show average performance improvement for a population of users. However, several case studies involving large manufacturers suggest that inventory can be reduced by 50% or more, and manufacturing cycle time can be reduced by 90% or more, compared to the use of an MRP system (Manning 1983; Callahan 1989; Bond 1993). In addition, (Manning 1983) reported very fast run times, on the order of minutes on a 1983 IBM mainframe. But, these authors also point out that to obtain these benefits requires even more discipline than using an MRP system, and the adoption of new control objectives in the area of capacity utilization that are contrary to traditional practice.

2.4 Finite Capacity Scheduling Software

A finite capacity scheduling (FCS) system is a software product that automatically, or semi-automatically, generates a schedule for allocating shop floor resources to operations over time. Many MRP systems offer FCS modules as an option, and many more FCS systems are available from third party vendors (Melnyk 1995). In Germany, interactive, graphical FCS systems are called *leitstands* (Adelsberger & Kanet 1991). The essence of FCS is to pre-schedule blocks of time on shop resources to handle the work required by all operations in some set of orders given as input. Only as much work as a resource has capacity (time) for can be reserved, hence the name 'finite capacity'.

The TOC/OPT scheduling components described in the last section exemplify a small subclass of FCS tools that schedule inventory and capacity simultaneously. Most FCS tools don't consider inventory at all. For example, the FCS options offered for MRP systems don't consider inventory, because shop and purchase orders for material have already been scheduled by the MRP algorithm. One might use an FCS tool that ignores inventory in a shop where inventory is unimportant, e.g. when it is inexpensive and bought in bulk, or when it is bought only after a specific order has been received. In these cases, allocating capacity is the main issue, so an FCS tool could be used even without an MRP system.

The typical FCS tool has five components:

- a *graphics component* that can display a Gantt chart for each shop floor resource;
- a *schedule editor* for manually generating and manipulating schedules (e.g., by inserting and rearranging the Gantt chart bars on the display)
- a *database* that holds the information relevant to scheduling, plus some communication component that connects the database to other production management software, such as an MRP package, a shop floor data collection system, etc.
- an *evaluation component* for determining the validity of a schedule and for assessing its quality;
- an *automatic scheduling component* for generating and modifying schedules automatically.

There are many ways to perform automatic scheduling systematically. The simplest is just to simulate dispatch rules. Commercial systems offer many combinations of possibilities (McCarthy & Barber 1990).

The result of either manual or automatic scheduling is a prediction and a visual display of how the shop will be loaded into the future. The advantages of having this information are that (a) both operation and order completion times are determined in a way that takes shop load and resource contention into account, (b) future problems become visible before they become actual problems, and (c) the schedule can be juggled (by manipulating the display) to eliminate the problems. In addition, FCS tools offer speed and flexibility advantages over constructing schedules on paper, and many include quite sophisticated scheduling strategies.

2.5 Current Levels of Adoption

2.5.1 MRP Systems

In 1992 an estimated 72,000 MRP II systems were installed in the United States (Greene 1992). Compared to the total number of US manufacturing establishments in 1990, roughly 374,000, the adoption level is on the order of 19%. However, it is reasonable to assume that very small firms have no need for MRP software because their manufacturing operation is not complex enough to warrant it. So, if firms employing fewer than 10 people are excluded, the adoption level rises to 38%. If firms employing fewer than 20 people are excluded, the adoption level is 56%. An informant at the Southwestern Pennsylvania Industrial Resource Center (the Manufacturing Extension Partnership (MEP) center for the Pittsburgh region) suggested that one would be unlikely to find a full-time production manager in companies with fewer than 60-70 employees. Yet, some firms employing less than 50 people use must be using MRP (or Greene’s estimate is too low) because there are only about 69,000 manufacturing establishments left after excluding this group.

Unfortunately, there seem to be no surveys of US firms that would tell us exactly how small "very small" might be. Indeed, in a study of 12 small Swedish firms (Ovrin *et al.* 1990), one firm using MRP employed only three people! The closest approximation is a survey conducted for the northeastern

Pennsylvania MEP center in 1991 in which 98% of 250 respondents were firms employing less than 100 people (Applied Research Services, 1992). The reported MRP adoption level in that survey was 36%.

For larger firms, the current adoption level is higher, as shown in a survey of 107 manufacturing firms in 9 New England and Midatlantic states who employed 50 people or more taken in 1992 (Trussler & Prave 1993). Eighty-seven of these firms were SMEs and 20 were LEs. Relative levels of computerization for each group are shown in Table 2-5. This may be compared to results from Study 2,

	SMEs	LEs
Inventory stock system	73.6	100
Parts explosion (MRP I)	48.3	95
Purchasing	60.1	90
Forecasting end items	39.1	65
Master production scheduling	55.2	95
Operations scheduling	35.6	55
Shop floor control	25.3	85

Table 2-5: SME (50-500 employees) vs LE Computerization by Function -- 1992 (%)

(LaForge & Sturr 1986) cited in Section 2.1.2.4, in which only 24% of respondents making 100 or fewer end items had MRP, whereas 48% of firms making 1,000 or more end items reported having MRP. Likewise, the percentage of MRP shops rose from 21% for firms using 200 or fewer component parts to 56% for firms using 3,000 or more. Although no data were given on firm size, it would appear that the firms in Study 2 were basically smaller than those in Study 1. Study 2 firms made an average of 1,836 end items, compared to 3,002 for Study 1, and used an average of only 10,798 components, compared to 25,782 for Study 1. It is probably reasonable to conclude from all this is that the overall adoption level of MRP technology among SMEs in the US is around 40%, with small firms somewhat less, and midsize firms somewhat more.

Comparative survey results for foreign countries were obtained in 1987 from a sample of 469 companies in China, Japan, Korea, Europe, and Japan (Young *et al.* 1992). This survey covered two industries, machine tools and textiles, and is interesting both because of the large number of comparisons it provides and because of the questions it asked. The sizes of the firms involved, and the sampling procedure, were not spelled out, but it is likely that some effort was made to make the results representative of the industries and regions surveyed. These results are reproduced in Table 2-6. The line ’difficult implement’ means that an implementation was in progress, and was taking longer than expected.

The most striking feature of these results is the extremely low level of adoption in Japan, although this

Young *et al.* -- 1987	China	Japan	Korea	Europe	USA
Machine Tools					
Never heard of it	48	67	49	24	7
Benefiting from it	7	6	9	44	38
Using, not benefiting	9	17	8	3	2
No need for it	7	0	0	12	20
Beginning to implement	7	0	0	9	24
Difficult implement	20	6	30	3	9
No response	2	4	4	6	0
Overall adoption level	43	29	47	59	73
Textiles					
Never heard of it	55	83	39	46	26
Benefiting from it	0	0	9	38	20
Using, not benefiting	7	8	18	4	0
No need for it	7	0	0	8	24
Beginning to implement	7	0	0	0	18
Difficult implement	20	6	30	4	12
No response	4	0	8	4	0
Overall adoption level	34	14	57	46	50

Table 2-6: Worldwide Levels of Adoption of MRP -- 1987 (%)

has been reported before without substantiating figures. The Japanese level of MRP adoption was the lowest in all the regions surveyed. So also was the level of awareness of this system, and the fraction of users who felt they were not benefiting from their use. Less than 6% of Japanese respondents to this survey had anything good at all to say about MRP.

The next most interesting thing is that all Asian countries are not alike. Both China and Korea exhibited higher levels of adoption and much higher levels of awareness of MRP than was found in Japan. In Australia, a different survey of 231 firms conducted in 1990 showed levels of adoption and awareness almost as low as in Japan: 25% and 40% respectively (Lowe and Sim 1993). But in Singapore, a survey of 128 firms also conducted in 1990 (Sum and Yang) reported an overall adoption level of 46%, and 69% if companies employing less than 50 people were excluded. (The SME adoption level in this survey was 45.9% compared to an LE level of 75%.)

Finally, it is worthy of note that the level of awareness of MRP was highest in the US, much higher than any other region, in both industries. But the fraction of non-using firms who felt they could use MRP was the lowest.

2.5.2 JIT Systems

Four studies conducted in the late 1980s allow us to place an upper bound on the level of adoption of JIT in the United States:

- A survey of 700 North American manufacturers by Touche Ross showed that 30% of these firms had JIT implementations in place, although 50% at that time were in the planning or setup stages (Giffi *et al.* 1990, p. 224);
- A survey of 230 manufacturing vice presidents and directors indicated that 36% of these companies were involved in JIT activities (Giffi *et al.* 1990, p. 224);
- A study of 134 US firms that included small and midsized companies conducted in 1988 found that 39% had implemented JIT methods (Gilbert, 1990);
- The international study cited above, (Young *et al.* 1992), also assessed JIT adoption. It found that about 20% of the US sample were using JIT and 33% more were in the process of implementing it. Full results are shown in the table below.

So, in 1988, across all the surveys, somewhere between 20% and 39% of firms had adopted the JIT system. If implementation projects going on at that time were not abandoned, the adoption level today among the surveyed firms would be 53-80%.

Young *et al.* -- 1987	China	Japan	Korea	Europe	USA
Machine Tools					
Never heard of it	48	11	39	9	4
Benefiting from it	0	22	1	18	13
Using, not benefiting	0	6	0	3	2
No need for it	23	39	0	32	42
Beginning to implement	0	0	9	12	18
Difficult implement	27	11	47	24	18
No response	2	11	4	2	3
Overall adoption level	27	39	57	57	51
Textiles					
Never heard of it	55	47	36	50	22
Benefiting from it	0	0	0	13	24
Using, not benefiting	0	6	0	0	4
No need for it	5	22	0	25	22
Beginning to implement	0	6	12	8	18
Difficult implement	23	17	42	4	8
No response	17	2	10	5	2
Overall adoption level	23	29	54	25	54

Table 2-7: Worldwide Levels of Adoption of JIT -- 1987 (%)

In Table 2-7, the low overall level of JIT adoption reported by Japanese firms is even more striking than their low level of adoption of MRP shown in Table 2-6. Other articles from the same time period reported that JIT was essentially the standard system of production management in Japan (Voss 1989).

The low adoption level among textile manufacturers is also surprising, since a relatively high percentage of US firms in that industry had adopted JIT and were benefiting from it.

Finally, as was the case with MRP, the level of awareness of JIT was highest in the US, higher than in any other region for both industries, but the fraction of firms who felt they could use it was lowest (save for European textile firms). Apparently, the information environment in the US makes it more likely for a firm to become aware of a production management innovation, compared to a firm in a foreign country. On the other hand, one may wonder why US firms seem to be more resistant to adopt an innovation they've heard about, compared to foreign firms.

Except for Gilbert's study, the fraction of small manufacturing companies represented in the sample populations was not mentioned. Gilbert found that about 18% of small firms in his sample had adopted JIT, and 24% of midsized firms. The survey of small manufacturers in northeastern Pennsylvania found that 41% of firms had implemented JIT (Applied Research Services 1992).

2.5.3 TOC/OPT Systems and Finite Capacity Scheduling

No surveys in the literature were found that attempted to determine adoption levels of TOC/OPT or FCS systems. In 1989, there were only 60 OPT systems in the US and only about 60 in Europe in the same time frame (Fry *et al.* 1992). There are currently about 100 FCS vendors in the US (Melnyk 1995), and those contacted for this study had between several dozen and a few hundred systems installed. The data in Table 2-5 regarding the computerization of operations scheduling suggest that the adoption level of shop floor scheduling software of some kind is quite high. But, given the year these data were collected, this probably indicates the level of usage of the MRP order release module rather than finite capacity scheduling.

3. Predictive Models of Innovation Adoption and Diffusion

MRP systems, JIT systems, TOC/OPT systems, the components associated with each of these, and shop floor scheduling software are all innovations that have been introduced into US manufacturing firms during the last 30 years. In the language of economics, an *innovation* is the commercial embodiment of an *invention*, i.e., a class of product, process, service, or system that comes into existence when an invention is first used in commerce. *Innovation adoption* is a decision made by an individual or firm to become a regular user of an innovation, having not been so before. It is convenient to call the individuals or firms who are potential adopters of an innovation its *customers*.

It is often difficult or impossible to define the population of customers exactly. In some cases, an innovation may be applicable to a whole industry or sector, whose limits are easy to define, but there are also many innovations which seem suitable for application to only a certain type of production within an industry. On the other hand, it is generally impossible to determine the limits of an innovation at any point in time, because the effects of subsequent modifications and improvements can extend the applicability of the innovation and cannot be foreseen.

For example, MRP systems were once thought to be unsuitable to repetitive flow shops (i.e., shops that are mainly assembly lines) because material does not move through these shops in batches and so there is nothing to associate with a shop order, and no reason to track inventory through each step of the flow. However, a modification was introduced whereby quantities of items to be produced were associated with particular days, rather than batches, and inventory was updated according to a day's production volume, not batch completion. Likewise, JIT systems were once thought to be suitable *only* to a repetitive flow shop because a stable, and large, end item demand seemed to be necessary to justify the cost of setting up a dedicated flowline. But, ingenious make-to-order jobshop managers found that they could put equipment on wheels and set up temporary flowlines for particular orders (Hobbs 1994).

The collective result of individual adoption decisions made by members of a customer population over time is a continuing increase in the number of adopters. The spread of adoption throughout a population is called innovation *diffusion*. The *rate* of diffusion at any point is the rate at which customers are becoming regular users at that point, i.e., the rate at which the number of adopters is increasing. The *level of adoption* at any point in time is the proportion of the total population who have adopted an innovation. The *lifetime* of an innovation starts when some form of it is first introduced to customers and ends when diffusion ceases, i.e., when no new adopters are forthcoming.

3.1 The Economic Model

Because of its importance to economic growth and the international distribution of wealth, innovation and its diffusion have long been studied by political economists (Mansfield 1968). They see the adoption of an innovation as basically an investment decision and diffusion as the outcome of a set of such decisions. Moreover, the likelihood of adoption by a particular firm is seen as a function of the projected payoff of adopting, the risk that the payoff will not materialize, the scale of investment required, and the amount/quality of information available for decision-making. The rate of diffusion under this model depends on the rate of diffusion of information of the sort needed to project risks, costs, and benefits.

The flow of information into a firm about an innovation is partly determined by the firm and partly by its environment. The investment decision itself is actually the last stage of a process in which information first impinges on a firm, then is actively sought, and finally is assembled into a coherent whole to make a decision. In all there are five observable stages in the process:

1. *Awareness*. Individuals within a firm become aware of an innovation during the normal course of events, but lack information about it. They alert the firm to the fact that this innovation may be of use. These individuals must be decision-makers, or people who could influence decision-makers to investigate further.

2. *Interest*. The firm is stimulated to seek out information from various sources -- suppliers, competitors, trade associations, seminars, published literature, etc. Eventually, a lot of information is accumulated, although it is not always consistent.

3. *Consideration*. If the benefits appear attractive enough, the firm undertakes a more systematic evaluation to assess whether it would make economic sense to try the innovation, given the special characteristics of the firm and its circumstances. Are there investment funds available? Would there be a payback on the investment? How much? How certain is it? How long would it take to recover the cost?

4. *Trial*. If preliminary evaluation is positive, and it is possible to try out an innovation before making a full commitment to it, the firm tries the innovation on a small scale to improve his estimate of its value.

5. *Adoption*. If the decision is made to commit to the innovation, adoption takes place.

The last stage could, of course, be rejection.

Although economists have found that a host of variables can affect the rate of diffusion of a particular innovation through a particular population, the rate of diffusion of information is universally important. Information of one sort or another is a precondition to each stage of the adoption process. Based on a set of studies done in the early 1970s (Nasbeth and Ray 1974), Nasbeth concludes that the diffusion of information about new techniques is a quite a slow process. For example, the timelag from the first firm in a sample of US firms to become aware of numerically controlled machine tools to the last was found to be 11 years. In that same study, the adoption level tended to lag the awareness level by about four years. E.g., in 1961, 90% of the sample was aware of numerically controlled tools, but it wasn't until 1965 that 90% had adopted.

There are three main limitations of the economic model. First, innovations are not static: the products, processes, etc. that embody them evolve over time. Especially in the early stages, further development, modification, and enhancement are almost continuous as user experience with the innovation accumulates, and feedback from the marketplace suggests adaptations that were not thought of initially. As an innovation matures, ways are found to reduce its adoption cost. Consequently, the innovation package presented to later adopters is not the same as that presented to earlier ones. Second, it turns out that the decision-making criteria applied by earlier adopters is different from that applied by later ones. As a result, the definition of benefit, the relative importance of risk, and the types of information sought during the interest and consideration stages all change over an innovation's lifetime. Third, the fundamental nature of an innovation can make it easier or harder to adopt. These factors are addressed in the adoption lifecycle model.

3.2 The Adoption Lifecycle Model

The adoption lifecycle model is based on numerous studies of customer populations through which innovations have diffused over time (Rogers 1962). The main empirical results of these studies are:

1. Diffusion rates plotted against time almost always follow a bell shaped curve. They rise at an increasing rate at the outset, level off when approximately 50% of the population has adopted, and then decrease.
2. Subgroups exist in customer populations whose members characteristically adopt innovations earlier or later than members of the other subgroups.
3. The number of customers in each subgroup is a predictable portion of the whole.

These results may be summarized graphically by dividing the diffusion rate curve into segments corresponding to each customer group (Figure 3-1). The earliest customers to adopt are called the

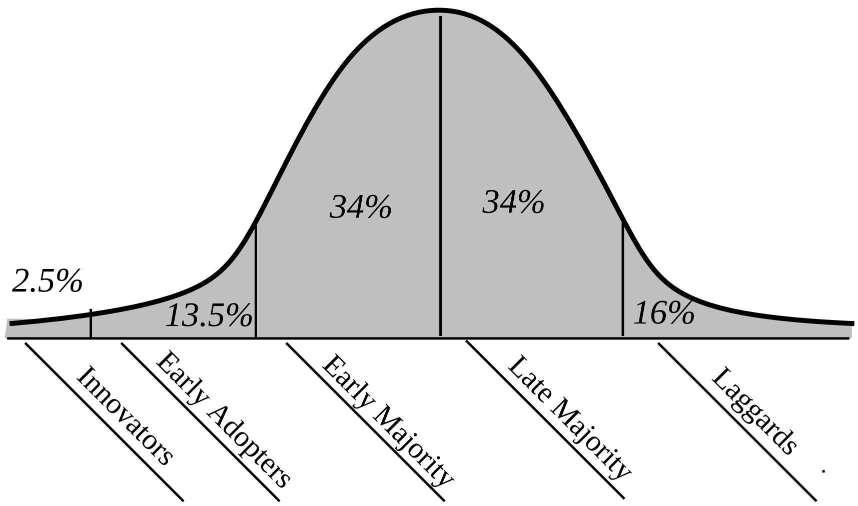

Figure 3-1: The Adoption Lifecycle Model

innovators. This group typically comprises about 2.5% of the whole population. Successive groups in the progression are named according to their relative time of adoption. The percentages shown indicate the size of each group as a fraction of the whole population.

The different groups are distinguished from each other by the fact that each has a different attitude toward adopting innovations. These attitudes have the greatest impact on diffusion when adopting the innovation would require a customer to both (1) learn how to use it and (2) modify the environment that supports this usage. Innovations that make these demands on a customer are called *discontinuous innovations*. The contrasting term, *continuous innovations*, refers to innovations (generally products) that can simply be substituted for something the customer has been using without a change in behavior.

For example, a new car that provides better gas mileage or faster acceleration is a continuous innovation, since one's interaction with this car will be essentially the same as with the car it replaces. A new car powered by electricity, however, with a limited cruising range and the need for recharging over night, would be a discontinuous innovation. One needs to limit one's trips and one also needs to arrange to plug the car in every night. In between continuous and discontinuous lies a range of possibilities, since discontinuity is a matter of degree. E.g. a car with all-wheel steering would require some learning of new steering techniques. A discontinuous innovation requires both learning new behavior and changes in supporting infrastructure.

The degree of discontinuity depends very much on the nature of the innovation itself. For example, the higher the *complexity* of an innovation -- the degree to which it is difficult for customers to understand -- the more learning is required and the greater the discontinuity. Customers already understand a continuous innovation, and how to use it, since it substitutes directly for something they already use. Similarly, the higher the *compatibility* of an innovation -- the degree to which it fits the context in which it is to operate -- the less change in infrastructure is required and the less the discontinuity. Continuous innovations do not require customers to change the way they do things because the innovation simply helps them do these same things a little better.

Modern systems of production management are among the most discontinuous innovations ever invented for manufacturing firms. All of them have many components that interact in many ways. It takes an entire book to describe how to use them. Putting one in place not only requires users to learn new tools and procedures but also to abandon their old practices. A new system alters communication between departments and requires changes in job descriptions for many people within each department. Managers must often give up control prerogatives that they had under the old system. Changing to a computer-based system almost always requires new computing equipment, and establishing the appropriate support for it. Moreover, most of this is unavoidable, since part of the point changing over to a new production management system is to eliminate practices that were detrimental to manufacturing performance.

Given a particular innovation, the adoption lifecycle model predicts the order in which people with different attitudes toward innovation will adopt it. The real import of the model, however, is that it also outlines the characteristics that can be reliably ascribed to members of each adopter group. In a very influential book (Moore 1991), Geoffrey Moore describes these characteristics in terms of a set of *psychographic profiles*. A psychographic profile is a unique combination of psychological and social factors that makes one group’s response to innovation different from that of other groups. Since Moore is a marketing consultant primarily interested in high-tech products, his profiles talk about ’buying decisions’ rather than ’adoption decisions’, and ’technology’ rather than ’innovation’. However, with the appropriate generalization of terms, his profiles also provide insight into the diffusion of process and method innovations.

In brief, Moore’s profiles of technology customers are listed below. Comments on their relationship to production management systems and technologies are inset in italics.

Innovators pursue new technology products aggressively. They seek them out. This is because technology is a central interest in their lives, regardless of the function it performs. At root, they are intrigued with any fundamental advance and often make a technology purchase just for the excitement of seeing how it works. They appreciate the technology for its own sake. They want the latest. Psychographically, these sorts of persons are "technology enthusiasts". As a buying group, they are most often found in the advanced development groups of large corporations, and in other R&D organizations chartered to keep abreast of technological developments.

Most of these characteristics would not seem to apply to production management technologies since they are so narrowly focussed on particular tasks. However, there also seem to be "task enthusiasts" who try everything that comes out that relates to their task. They were the ones who built their own MRP systems in the 1960s. They were the first to develop experimental interactive jobshop scheduling programs in the 1970s. They were the first to set up quality circles in their organizations in the 1980s when no one knew quite what these were for.

Early adopters buy a new technology product early, not to be the first to play with it, but to be the first to exploit its benefits in their industry. By being first, they expect to get a jump on the competition. Early adopters are people who find it easy to imagine, understand, and appreciate the benefits of a new technology and to match these benefits to a strategic business opportunity. They are willing buy a new product (and the concept behind it) based on their intuition and vision of how it can be applied, without reference to other previous users of the product. They are capable of translating this vision into a high-visibility, high-risk project, and have enough influence to get the rest of their organization to buy into that project. Price is not a decision factor, since they expect to see an enormous return on their investment in the form of a dramatic competitive advantage. They expect a radical discontinuity between the old ways and the new. They are prepared to champion their cause against entrenched resistance. Psychographically, early adopters are "visionaries".

The successful results of early adopter projects are often written up in the literature as case studies. In production management, certain companies have been early adopters of all three systems as they came out. For example, Black and Decker implemented MRP in the 1970s (Hall and Vollmann 1978), JIT methods in the 1980s (Wyman 1987), and is now working on a TOC/OPT project. The Tennant Company, an early adopter of MRP (Bevis 1975), was also an early adopter of JIT methods (Hale 1989), and had a TOC/OPT pilot project.

The *early majority* have some appreciation of new technology, but ultimately they are motivated by practicality. They know that many inventions end up as passing fads and so are content to wait to see how others in their industry peer group have been making out before they buy themselves. They are willing and able to learn the new technology, and to modify their environment to support it, if necessary, but they want to see well-established reference cases before investing in it. They are willing to pay a reasonable amount if the cost is justified by getting a better return on resource expenditures than before. But, they prefer evolution, not revolution. They are looking for an incremental, measurable, predictable improvement in operations. They want technology to enhance, not overthrow, their established ways of doing business. Members of the early majority are "pragmatists".

The adoption decision procedure used by pragmatists is essentially just the economic model presented earlier. There is first a systematic identification of alternatives, then a cost/benefit analysis, and finally a selection based on projected payback, adjusted for intangibles. The case of MRP II adoption described in (Ormsby et al. 1900) is a good example. One factor that has undoubtedly slowed the diffusion of production management innovations is the extreme difficulty of projecting overall return on investment *given the large change in infrastructure that these innovations require.*

The *late majority* are also motivated by practicality, and they rely on the experience of peers, but its members are not as eager to adapt themselves to a new technology product. They are not as willing to learn how to use it, perhaps not as able, and are inherently averse to disrupting their current infrastructure and practices. They are not confident that they will be able to choose the right product or technology from all those being offered. As a result, they wait until something has become such a fixture in their peer group that it becomes very inconvenient, or impossible, not to adopt it themselves. Other firms expect them to have it. This group buys products when they are extremely mature, extremely easy to use, and carry a relatively low price. They prefer not to pay for support or configuration services. Although they need more education in the technology and its application than the early majority, they are not as willing to pay for it. They like to buy preassembled packages, with everything bundled, designed specifically for their kind of business, at a heavily discounted price. They are looking for a significant, demonstrable reduction in overall operating expense dollars to justify the investment and provide a short payback period. They need a high degree of trust in the vendor before they will buy. Psychographically, the late majority are "conservatives".

The data presented in Chapter 2 strongly suggest that any new US adopters of MRP are in the late majority, since various ways of estimating the current level of adoption all tend to put it above 50%. The evidence is not as clear for JIT, since all the large-sample survey data in the literature is more than eight years old, and different surveys didn't yield the same results. A more recent (1991) small-sample survey (19 firms) showed very high usage (75%+) of JIT techniques by both large and small companies (Lopez and Haughton 1993). Now, five years later, it is hard not to conclude that JIT is also in the late majority stage. A shift in marketing to satisfy late majority customers is not yet evident. No vendors have developed the kind of low cost, turnkey, industry-specific packages that match the psychographic preferences of the late majority. The prediction that late majority customers will adopt when it becomes very inconvenient not to seems to have been borne out in Australia, where increasing requirements for electronic data interchange induced manufacturers to adopt related production management software who otherwise would not have done so (Mackay 1993).

Finally *laggards* are averse to a new technology, usually for both personal and economic reasons. The only time they buy a technological product is when it is buried so deeply inside another product (as when a microprocessor is buried inside of a clock radio) that they don't even know the technology is there. Psychographically, laggards are "skeptics". Vendors generally believe that laggards are not worth pursuing as customers for innovation.

The differing needs of successive adopter groups has a number of implications for vendors who want to keep an innovation moving through the adoption lifecycle. In order to transition from one stage to the next, they must successively repackage the innovation so as to:

- make the benefits more predictable and visible in the customer's context;
- create versions that are complete solutions for narrower market niches;
- reduce the acquisition and installation costs;

- reduce the amount of learning required;
- reduce the amount of user-specific customization required;
- increase the ease of use;
- institutionalize the functionality;
- reduce the cost of marketing.

In addition, they must take steps to inform customers that these changes are occurring, especially customers who pay less attention to technology and innovation and more attention to the immediate needs of their business.

That a less expensive product would appeal to a wider market is not surprising, and accords with the economic model. That an innovation also needs to be repackaged to make it easier to adopt in later stages -- by making it simpler, easier to use, more narrowly focussed, and more of an industry standard -- is an important contribution of the lifecycle adoption model to explaining innovation diffusion.

3.3 Why SMEs are Typically Late Adopters

In Chapter 1 we saw that the proportion of SMEs in the United States who have adopted new manufacturing process technologies is lower than the proportion of LEs who have done so. In Chapter 2, we saw this same difference for production management systems and technologies. Why should this be so?

For the special case of production management innovations, it should be clear from Chapter 2 that a lower level of SME adoption might be explained simply by firm size. The central problem of production management is coordinating the activities of a manufacturing plant, and the size of this problem increases with the size of the plant. Very small firms do not have a significant coordination problem. Imagine, for example, a 4-person woodworking company that only buys materials after a job has been booked, and works on three or four jobs at a time. Very informal production planning and control methods will suffice, requiring no more "technology" than pencil and paper, and no more "data" than the specification of the jobs and rules of thumb about how long various operations will take. Since a full third of SME plants in the US employ fewer than five people, almost a third (.33 x .98) of all plants are unlikely customers for the kinds of innovations we have been discussing.

There remains, however, that portion of the SME population typically surveyed: plants employing more than 19, more than 49, or more than 99 people. This portion employs the majority of workers in this sector. At some point the coordination problem becomes significant -- imagine a 40-person woodworking firm that works on 30 or 40 jobs at a time. What accounts for their lower levels of adoption?

From the economic model, one can hypothesize any of the following:

- A larger proportion of SMEs are unaware of these innovations, or are unaware that they are applicable to their situation, or have not been motivated to seek out information on potential benefits.
- A larger proportion of SMEs don’t perceive enough of a benefit to their operations from these innovations to warrant all the costs of adoption.

- A larger proportion of SMEs perceive the risk of investment in these technologies to be greater than the risk of not adopting.
- A larger proportion of SMEs find that the scale of investment required exceeds the amount they are willing or able to commit.
- A smaller proportion of SMEs are able to try out these innovations on a small scale.

From the adoption lifecycle model, the following explanations are also possible:

- A smaller proportion of SMEs try to get ahead of the competition by being early adopters, and a larger proportion of them are inherently conservative or skeptical toward innovation.
- A larger proportion of SME peer groups have not accumulated enough specific, measurable, positive, experience with these innovations to stimulate interest in the bulk of the group.
- None of these innovations has become such an established standard in markets where SMEs predominate that conservative firms are motivated to adopt them.

A 1993 study (National Research Council 1993) has provided support for almost all of these hypotheses. This study found, for example, that SMEs are indeed less likely to be aware of changes in technology, of how these changes apply to them, and of what that means to them operationally. It found that many smaller firms perceived investment in innovations as risking the solvency of the company, not only because of the financial cost, but also because of the resulting disruptions in ongoing production activities. It found that in-house training programs to teach new techniques were viewed as too costly. It found that some kinds of innovations were out of reach to many firms because the investment required would be a major portion of the firm's net worth. It found that banks were unwilling to make loans to small companies to fund such investments. And it found that owner-managed small firms that had been in business for a long time tended to be less interested in growth, expansion, and the expenditure this would require, and more interested in maintaining the status-quo.

Although a conservative attitude toward innovation is clearly evident in these findings, so is the effect of the limited financial resources available to smaller firms. The latter may, in fact, partially explain the former. But the National Research Council study brought out other factors as well. For one thing, smaller firms employ disproportionately fewer staff personnel than do larger firms, and so the technical expertise that a large staff provides is lacking. As a consequence, smaller firms have less confidence in their ability to successfully select and effectively assimilate new technologies and systems into their operations. The "staff" that does exist is most likely also the management, and so must devote most of its time and energy to managing the day-to-day operations of the business. This leaves relatively little time for keeping up with new developments or evaluating their potential.

In addition, the study found, smaller manufacturers have limited contact with examples and sources of innovation relevant to them. Many executives and managers of smaller firms have very little association with other manufacturers in the same or similar industries -- even when located in the same community. Therefore, they have little opportunity to learn from peer group experiences. Much of the published material on improving manufacturing performance is focussed on the adoption of innovations by larger firms, and many smaller firms can't, or don't want to, take the time to adapt the presented techniques to their situation. They want to see the innovations at work in other plants like theirs. External agents, such as vendors and consultants, who promote innovation to large firms, are not as effective with smaller firms. The information and advice provided by technology vendors is hard to evaluate for most firms, but especially so when a firm is unfamiliar with a technology in the first place. Smaller firms often consider vendor recommendations to be self-serving. Consultants are viewed as expensive. Both consultants and vendors prefer to concentrate on larger accounts rather than small ones. As a result, SMEs don't get much help understanding how an innovation might benefit them.

Finally, it is a natural consequence of the lifecycle adoption model that those customers with small budgets, limited technical competency, and low aspiration levels will not be served by technology vendors until the more profitable market segments have been fully exploited. And perhaps not even then. Moore suggests that the conservative market is currently perceived more as a burden than an opportunity. The opportunity, in this regard, is to greatly extend the market for high-tech components that are no longer state-of-the-art. The burden is a low profit margin and the need to redesign the product and its sales strategy for conservative buyers. Moore concludes that success in this market will "require a new kind of marketing imagination tied to a less venturesome financial model".

Thus, small to midsized enterprises tend to be late adopters of production management innovations because on average (1) they have a more conservative attitude toward innovation in general, (2) they are less aware of the potential benefits to firms their size, (3) they lack the technical, organizational, and financial resources of earlier adopters, (4) incentives to adopt are weaker compared to the perceived cost, (5) they have relatively few opportunities to learn from, or be influenced by, peer experience, and (6) vendors don't create the kind of scaled-down low-cost packages and marketing approaches that fit this size enterprise until the higher profit, large enterprise markets have been saturated, if then.

4. Accelerating the Diffusion of Production Management Innovations

Neither the economic model nor the adoption lifecycle model include the effects that government activity in the marketplace can have on the rate at which innovations are taken up by a population of customers. There are two obvious extreme cases. On the on hand, a government can compel, or nearly compel, the use of certain technologies and methods by setting standards that can only be met by their use. Thus, auto manufacturers were essentially compelled to use catalytic converter technology to meet air emissions standards. The 1993 Census Bureau survey of manufacturers showed that a much larger faction of US metalworking plants making products to military specifications were using NC machine tools, compared to plants making no mil spec products (US Department of Commerce 1994). It would certainly be possible for a government to decree that by a certain date all of its contractors would be required to use a technology related to production management, such as electronic data interchange, or to impose standards on delivery lead time and delivery dependability that could only be met by the innovations described in Chapter 2. Conversely, a government can prohibit the use of certain innovations, either universally or in some situations. In the 1980s, the Department of Defense essentially prohibited its contractors from using MRP accounting systems because these systems did not adequately segregate manufacturing expenses chargeable to DOD contracts from other expenses.

Usually, however, governments use other mechanisms to promote the development and adoption of innovations. The federal government currently has in place a broad array of programs to assist small business in general, manufacturers in general, manufacturers in the defense industry, and smaller manufacturers. All federal departments and some agencies now have Small Business Innovation Research (SBIR) programs to fund research and development by small businesses. The federal laboratories are required by legislation to transfer technology they develop to the private sector, and a National Technology Center has been established as an information clearinghouse for technology transfer opportunities. The Department of Defense manages the Manufacturing Technology (ManTech) program, which is aimed at helping the defense industry develop production technologies considered too risky or defense-oriented to be undertaken by manufacturers on their own, and at promoting shop-floor modernization. These and many other programs are described in more detail in (National Research Council 1993).

4.1 The Manufacturing Extension Partnership

The program that is most clearly focussed on innovation diffusion, and involves the broadest spectrum of small to midsized manufacturers, is the Manufacturing Extension Partnership (MEP), administered by the National Institute of Science and Technology (NIST). In 1988, Congress authorized NIST to create and support Regional Centers for the Transfer of Manufacturing Technology. These centers were originally chartered to:

- transfer manufacturing technology and techniques developed by NIST to the centers and, through them, to manufacturing companies;
- solicit the participation of individuals from industry, universities, state governments, other federal agents, and NIST in cooperative technology transfer activities;
- make new manufacturing technology and processes usable by small and midsized companies in the US;

- disseminate scientific, engineering, technical, and management information about manufacturing to industrial firms, including small to midsized firms;
- utilize, when appropriate, the expertise and capability that exists in federal laboratories outside of NIST.

Each center must be sponsored by another organization, typically an agency of the state in which it is located, which is to provide at least 50% of its funding. Federal funding is provided at declining levels for six years, after which the center is to be self-supporting. This program was renamed the Manufacturing Extension Partnership Program in 1993.

In 1991 The Government Accounting Office (GAO) reviewed the performance of the first three centers for the first thirty months of operation (General Accounting Office 1991). It found that the major benefit of the program was not that it succeeded in transferring the latest technologies to the client, but that it provided the appropriate, and generally low-tech, solution that satisfied the client's immediate needs. In particular, productivity gains for the client were normally achieved using low cost, proven technologies and methods. The transfer of advanced technologies, emphasized in the original legislation, did not meet the immediate needs of most small and midsized manufacturers.

As of October 1995, there were 60 MEP centers in 42 states plus Puerto Rico. The array of services they now provide reflects the GAO study results, and is similar to the manufacturing assistance provided to SMEs in foreign countries (Bessant and Rush 1993). These services include:

- assessment services to identify problems existing in individual firms and to provide expert advice on solutions to those problems;
- consulting support for project management, strategy formulation, and other areas where a client firm's managerial competence is lacking;
- training and education to update and broaden the skills of technical and managerial personnel;
- seminars, demonstration facilities, and publication programs aimed at raising the level of awareness of available technology;
- infrastructure development, primarily through the establishment of better human communication channels between academia and industry;
- direct financial support -- loans or grants -- for capital expenditure and for development costs.

Individual MEP center offerings are generally customized to meet the specific needs of clients in their region and of the industries that predominate in that region.

MEP centers that have been in operation for some time have found that one-on-one contact between center agents, called field engineers, and company managers is the most effective way to carry out the program. This typically involves an intensive telephone interview, followed by a site visit. Then, the field engineer produces a diagnostic report to the client outlining his assessment of the client's operations and possible areas of improvement. In the area of production management, field engineers typically stress the benefits of adopting JIT methods, such as setup time reduction, redesigning plant layout, defect elimination, preventative maintenance, and cross-functional worker training. Subsequently, the field engineer, or an outside consultant affiliated with the MEP center, may work with the firm to put into effect the recommendations accepted by the firm's management. Thus, field engineers provide the staff expertise in identifying problems, evaluating the relevance of innovations, strategic planning, and project implementation that smaller manufacturers lack.

This approach has produced some impressive results (MEPD 1995). In a survey of 55 companies who received service from three centers in 1991, the following increases in technology adoption and manufacturing performance were obtained. Percentages compare actual company performance in 1990 to 1992 using company data:

- computer usage: increased 56%
- inventory turns: increased 43%
- scrap rates: decreased 28%
- manufacturing cycle time: decreased 20%
- revenue per employee: increased 17%
- average annual employee salary: increased 4%

Results of surveys of companies who received technical assistance from 13 MEP centers in 1994 indicate that the return on federal investment in this program also is high. Economic benefits anticipated by the 610 firms responding to the surveys totaled $167 million, as a result of sales increases and net cost savings attributable to actions undertaken with MEP assistance. Since federal funding for these 13 centers totaled $20 million, the total benefits are about eight times the amount spent.

4.2 Leveraging MEP Resources with Information Technology

Although the one-on-one approach is effective, it severely limits the number of companies that can be helped with available resources. The National Research Council study noted this situation and suggested that each MEP center should be encouraged to identify problems common to manufacturers in its region that would be amenable to less labor-intensive means of assistance, such as classes and workshops. Some MEP center managers are trying to expand the role of affiliated consultants (Holley 1995).

In the case of production management, we believe there is a way to reduce the effort of field engineer assistance, without reducing one-on-one client interaction, by the application of information technology.[8] The key, we suggest, is to pool the experience and expertise from MEP centers nationwide and package it in such a way that it can be reused. Unlike problems with technical manufacturing processes, which tend to be product- and equipment-specific, the same kinds of production management problems tend to occur in all firms that have the same production environment (Umble 1992). Moreover, the solutions to those problems tend to be the same.

For example, suppose a field engineer is reviewing a shop that makes 150 different kinds metal boxes, from 16 different materials, at a rate of about 2000 boxes a week, in batches of 200, using a jobshop layout, with a manual inventory control system, and experiences a machine breakdown every other day. There are stacks of racks of boxes at several workstations. A number of problems would immediately

[8]Many of the ideas in this section were developed in collaboration with Stephen E. Cross while he was Director of CMU's Information Technology Center.

spring to mind, as would their standard solutions. Manually, it typically takes a few days, out of a five day evaluation cycle, to write up the report that describes the problems, explains their significance, indicates the solutions, and recommends a course of action. With an information tool, this report could be assembled from components and then modified to include the nonstandard particulars.

The idea of pooling experience and/or packaging it for reuse is already being used in two information services currently available to MEP field engineers. In one, the Performance Benchmarking Service (www.iti.org/pbs), quantitative measures of a firm's current financial and manufacturing performance are collected from field engineer/client interviews via a questionnaire. These data are then compared to profiles of hundreds of other firms that have been reviewed by MEP centers to determine a relevant peer group and then to rank the firm against its peers on each measure. The resulting benchmark report is sent back to the field engineer to help formulate an assessment. This turns out to be quite a revelation to most SMEs, who are typically unaware of their manufacturing performance compared to peers.

The other service, called TECnet, is a World Wide Web site accessible to field engineers (www.tecnet.org). It maintains a number of databases and serves as a starting point to locate many types of information. Included, for example, are:

- searchable directories -- of MEP field engineers and their areas of expertise, of other organizations affiliated with the MEP and the services they provide (training, consulting)
- a list of service packages that are available from different MEP centers (e.g. various kind of assessment tools)
- a set of bulletin board newsgroups where field engineers post questions and receive replies
- an e-mail service
- a directory of links to other Web sites related to business, manufacturing, economics, engineering, and many other topics

A few field engineers have used the bulletin boards to solicit advice and opinion on MRP systems, scheduling, and production management problems in general. In general, these solicitations and the replies to them are short, more a less along the lines of "Does anybody know about system X for a plastic extrusion firm?" and "Yes, give me a call".

But these efforts have clearly just scratched the surface of what could be done, and our earlier sketch of a more sophisticated service to support operations assessment is just one possibility. We can imagine applications in three areas related to the innovation adoption process: stimulating interest in new technologies and methods, evaluating options, and facilitating small-scale system trial.

4.2.1 New ways to Stimulate Interest

4.2.1.1 The Production Management Gallery

In October, 1995, a unique new service, called the Micro Gallery, was opened to the public at the National Gallery of Art in Washington, DC (Lewis 1995). Museum visitors can now sit down at one of 13 20-in touch-screen monitors and take a virtual tour of 1,700 works of art in the museum's permanent collection. Touch "M" and then "Monet", and one can view any one of the museum's 24 Monet paintings. Touch the screen again, and one can examine the brushwork at close range.

But the service encompasses much more than just images. By touching different menu items on the screen, visitors can follow numerous pathways through a rich collection of information about the paintings and sculptures depicted. There are short explanations of the history and significance of different works. Browsers can clarify concepts they'd never really completely understood, such as color theory in impressionist painting, or perspective in early Renaissance art. One option takes the visitor through in-depth examinations of certain paintings, each with an array of animation and detail. For example, in the discussion of van Eyck's 15th-century painting "The Annunciation", one sees on the screen that "This painting is full of objects with special meaning". By touching the menu of objects, one can learn the meaning of each one -- the lilies, the angel Gabriel's robe and smile, etc. -- in the context of Christian iconography, with illustrative animation.

The goal of the National Gallery is to accomplish what other forms of promotion have failed to do: increase public interest in the museum's permanent collection of art. Although crowds have lined up for special exhibitions, interest in equally great art that is available all the time is much less. Development of the Micro Gallery took three years with a staff of eight, funded by a grant from American Express for $1.5 million.

An analogous service could be developed for the staff and managers of small to midsized enterprises who are trying to find out more about production management innovations they've heard of. Instead of great art, the subject matter would be great examples of innovation-based improvement in small shops. There would be examples of each relevant combination of production environment variables -- jobshop vs. flowshop layout, make-to-stock vs. make-to-order inventory strategy, predictive vs. reactive master scheduling strategy, material-intensive vs. labor-intensive products, etc. Graphics would include pictures of each shop and representative products, diagrams of material flowpaths and inventory stocking points, bill of material trees, graphs of demand vs. inventory over time, work-in-process queues, MRP records, and so on. It might be possible to animate some of these, or at least step them through time, via simulation.

Zooming in on details would essentially follow the hypertext paradigm. Click on an inventory icon and an explanation of how it was planned to evolve over time appears. Click on the shop foreman icon and a description of his production control strategy is given. Technical terms in these descriptions would have hypertext links to definitions and illustrations.

For history, there should be a description of the shop and its performance before the improvement effort was undertaken. This could be illustrated with the same kind of graphics as above. The concerns that led to the improvement project, the goals that mangement hoped to achieve, and the uncertainties they confronted could all be narrated and illustrated. Finally, there would be before- and after- performance comparisons, and a breakdown of the cost of the effort. Case studies in books and articles are typically four to six pages long, so we imagine that the essential story to be told in each history would involve that much text. The graphic augmentations and explanations would, or course, make the cases much richer and more vivid. This service could be provided either at MEP centers, or, with less ambitious graphics, over the Internet.

Almost all the case studies we've reviewed have been inspiring (in particular, see (Chin and Rafuse 1993; Sohal and Naylor 1992; Barker 1994; and Santacecilia 1992)). Not only did a plant improve its performance, but the study authors very often reported a new vitality in operations, a new enthusiasm in the workforce, and follow-on benefits such as increases in sales. While the number of these studies is large, they appear in technical journals, government reports, and the files of MEP field engineers. They are not easily accessible to the managers of smaller manufacturing companies, and, in some cases, perhaps too academic for them to relate to. If improvement cases were made more accessible, in an attractive package, the interest they would stimulate in production management technologies and systems could be substantial.

4.2.1.2 On-line Performance Benchmarking

Another, and much simpler, idea would be to put performance benchmarking services on-line. Currently, this service is provided via field engineers. One reason for this is that firms being benchmarked for the first time need to be educated in the concept, need help assembling the data and answering the questions, and need to be prevented from entering "guesstimates". Another is that it is felt that benchmarking without a direct link to the operations reviews and diagnostic expertise provided by field engineers is of little value. Finally, the field engineers are essentially the sales force for the service.

These are all good reasons -- for the first benchmarking report. But there should be a second benchmarking, after some improvements have been made, and perhaps others, later, that would show the benefit of continuing improvement. The need for field engineer involvement in obtaining subsequent reports would not seem to be as critical.

If follow-up benchmarking came to be a common practice, we suggest that both field engineer support and the manual processing of paper questionnaires might be replaced with an on-line service. Certainly the data entry functions could be automated in this way. We don't know how much of the analysis that is currently performed by hand and how much of report generation could be automated. But, if there were enough demand, and automation were feasible, and the cost of automated report production were low enough, performance benchmarking could become a new, self-supporting public service.

4.2.2 New Resources for Selecting Tools and Techniques

4.2.2.1 Structured Assessment

At present, MEP field engineers rely on their own personal experience and knowledge to assess the operations of a client firm and make recommendations. There are no standard guidelines or checklists, and not every field engineer is familiar with every production management technique that might be beneficial to the client. One way to systematize the assessment process, and make individual field engineer experience available to all, would be to deploy a knowledge-based system that matches production environments to suitable production planning and control techniques.

A prototype system of this sort has been developed at the University of Manchester in England (Kochhar and McGarrie 1992). Based on detailed analysis of case studies, 42 variables were identified (out of approximately 300 analyzed) that have a major impact on the selection and effective implementation of different types of production control techniques in different environments. The variables are grouped into four categories:

- *complexity variables*, such as the number of product options, the number of BOM levels, the new-product introduction rate;
- *uncertainty variables*, such as the regularity of the demand pattern, supplier delivery reliability, and defect rates;
- *flexibility variables*, such as degree of part commonality across end-items, number of multi-skilled workers, and average setup times;
- *attitudinal variables*, such as degree of commitment to improvement, education, and data accuracy.

These variables are linked to advice via rules. For example, if a company introduces more than five new product types per year, a Kanban control system is not likely to be workable, and CRP-level capacity planning is likely to be required. The software uses a number of rules like this one to either select appropriate components or assess the current state of implementation of a given control system, in order to suggest a plan of action that will achieve an effective implementation in a given environment. Although this system was developed primarily for larger manufacturers, the approach could be extended to include variables and rules for smaller firms.

4.2.2.2 The Non-Expert Buying Guide

Once a particular collection of planning and control components has been identified as appropriate to a given firm, and implementation requires software, a particular product (or products) needs to be selected. Buyers guides to manufacturing management software, listing products and features, are published in trade magazines, e.g. (Melnyk 1995). There are also several, much larger, guides for MRP products available commercially, e.g. (CPI 1993). These are intended to be complete enough for a user to develop an RFP without employing a consultant. One of these includes an expert system, *Buy Smart*, that helps the user to narrow down a set of candidate products to those that have essential and desirable features for his or her shop.

The Great Lakes Manufacturing Technology Center (GLMTC), one of the MEP centers, has developed a similar selection system that covers a wider set of products, including electronic data interchange, order entry, accounting, and the like (GLMTC 1996). This system has recently been made available to all field engineers. They will access it by filling out two questionnaires about a client firm, and sending the answers to GLMTC. GLMTC will return to them a listing of software components and features appropriate to the client, a list of the top ten products that provide the best overall fit to these needs, a product/feature comparison matrix, and vendor/product information sheets.

We think that the impact of software selection services like these could be extended considerably if they were made Web accessible, and embedded in a framework that provided education, navigation, demonstration, and marketing services as well. This idea was inspired by the Washington Post’s Internet book review service. Not only does it provide the Post’s review of a book, but also a copy of the first chapter, which the user can read.

In the service we envision, there would be a searchable directory of product classes and subclasses, indexed by all the synonymous ways of referring to products in the classes. E.g. ’leitstand’, ’finite scheduler’, ’finite capacity scheduling’, ’FCS’, ’capacity scheduling’, ’finite loading’, ’schedule board’, and other terms would all link to the FCS product class. This directory would also be indexed by activity terms, e.g. ’production control’, ’shop floor scheduling’, ’rescheduling’, etc.. The goal here is to include all indexing terms that would help direct a a customer who is aware of a technology to the relevant classes of products. A thesaurus network of terms might be displayable to assist in browsing. (This would be analogous to adding an index to the book service to look for books one might like to read.)

Then there would be a link to a tutorial about each product class, preferably in hypertext, that explains the products in the class, how they function, what they are used for, what problems they solve, and the various features included in different products. Part of this would be similar to a tutorial journal article, and part would be like the on-line tutorials and help that come with modern PC packages, but set at the level of a product class rather than a particular package and command set. This tutorial would be vendor neutral. The trade association associated with each product class should be involved in the construction of the thesaurus and tutorial. There should also be at least one real-world case study associated with the tutorial, and it would be better if there were several so as to cover different production environments. (This would be a little like adding a literature course lecture to the book service, focussed on a particular subclass or genre of books.)

Next, there would be a directory of the actual products in the class, searchable by features that subcategorize the class into the market segments served by the different products (e.g., platform, price, industry specialization, targeted manufacturing environment, etc.). The point of these features is to make a gross match between customers and vendor offerings, so that customers don’t waste time reviewing information on products they would never buy, and vendors don’t get inquiries from customers they don’t want to sell to. The GLMTC selection service could be attached at this point. The entries in the directory would be a combination of objective specifications (feature lists) and technical advertisements provided by product vendors. The objective part would always be based on the concepts and terminology of the tutorial. It would be most useful if the vendor advertisements also subscribed to this structure as much as possible. The whole directory would be available for browsing.

One advantage of making this sort of information available on-line is that the product information could be kept up-to-date more easily. But on-line access provides other opportunities for associating information with products and product classes. For example, there could be:

- links to full text reviews of a product;
- on-line demonstrations, either slide shows or working models, that the customers could manipulate;
- video clips of satisfied buyers, showing how they use the product and explaining how it helped them;
- answers to frequently asked questions about a product;
- links to courses being offered that relate to a product class;
- links to MEP services for SMEs that are related to a product class and/or the activity supported by that class;
- links to published material not available on-line (from this service) such as books and

articles.

All of this could become a new kind of advertising medium that (1) has more technical content than can be put in a paper ad, (2) a reader can select his own path through, and (3) offers possibilities for dynamic interaction. The advantages of this to the customer are that the product selection phase of the technology adoption process (part of Consideration) is easier, faster, and centralized in one virtual market place.

But, in order to work, there must also be some advantage to the vendors over their current marketing practices. We see two. First, by shifting some of the information delivery currently performed by salesmen to interactive software, it might be possible to use this new medium to reduce marketing expenses. Here is the opinion of one vendor (Capron, 1993):

> When the vendors look at these small companies, they see a sale of approximately $40-80,000, unknowledgeable and inexperienced users, implementation headaches ... and to make matters worse, the prospect is probably looking at more than 10 systems. The vendor's response in this very competitive, yet relatively low-margin arena is to do whatever possible to cut the cost of sales -- the margins just do not support wooing the customer.
>
> These vendors address the small manufacturers by: not responding to detailed functional requests for proposals; sending literature in lieu of the RFP response; not giving demonstrations unless it is down to the short list; not guaranteeing system changes.

Second, customers who do finally make verbal contact with a vendor will be more qualified buyers.

> The worst scenario in software selection is played out every day at dozens of locations. The vendor is demonstrating his product to an attentive audience, hoping for a sale. Either group may be the first to come to the realization: this is the wrong product for the prospect, either because of functionality, cost, ease of use ... it doesn't matter which, but in most cases the bad-fit decision should have happened much earlier, before either the buyer or the seller spent time and money on a dry hole.
>
> So how do you avoid this situation? Qualification is the answer. If the right questions are asked up front, qualified vendors will be matched with qualified prospects, reducing greatly wasted efforts on both sides.

We can contrast the Non-Expert Buyers Guide with the current way of gathering product information about production management software products:

1. Manufacturing software is not sold at stores. It is sold at trade shows, through advertising in trade journals, by direct mail, and by salesmen calling on customers. This means that if one is a potential customer, the first thing one has to do is find the marketplace -- the trade society/show/journal/directory that serves a particular product class.

2. After the customer discovers the marketplace, he still has to go to the show, and/or join the society, and/or request the literature from vendors, and/or make an appointment with a salesman. This is slow and takes up time.

3. To make a rational purchase, the customer needs to get some overview of the product class he is interested in. This function is currently performed by review articles in trade magazines and/or buyers guides. These have to be located and secured. For product classes that aren't standardized (e.g. manufacturing execution software, or finite capacity schedulers), and for classes whose products don't cost much (e.g. SPC software), there may not be a tutorial guide.

4. Finally, the customer needs to obtain comparable information from vendors, and determine which product(s) are most likely to benefit his operation. This is the slowest process of all, since it involves sending for literature, talking with salesmen, and/or preparing an RFP and

evaluating the responses.[9]

At present, traversing these steps takes weeks or months, and considerable effort, especially if the customer is trying to be reasonably thorough. With an on-line service, the process could be shortened to days.

4.2.3 New Facilities for System Try-out

Because the implementation of a new system of production management requires so many changes to a firm's current practices and infrastructure, it is hard to tell in advance how much benefit (if any) it will produce in this firm's particular situation. A larger manufacturer may be able to try out a system in one of its several plants, to resolve some of this uncertainty, but a smaller manufacturer does not have that luxury. A smaller firm may be able to adopt some components of a system incrementally, but may not be comfortable committing to a major change, such as cutting over to MRP purchase order generation, or to Kanban shop floor control.

The classic technique for system try-out before installation is simulation. We found several production management simulations in the literature that could be adapted to MEP use. For example, one article describes how the authors used a graphical simulation of Kanban to demonstrate its advantages to the managers of a small clothing company (Gravel and Price 1991). These managers had not been convinced by numerical results, but eventually adopted this technique after seeing the graphical output. Several articles describe MRP simulations that are being used for teaching purposes, e.g. (Berry and Mabert 1992), and a simulation game has been developed, based on OPT, in which players can make profits or go bankrupt depending on how well they schedule a manufacturing plant (Waters 1986). The game was used as a marketing tool to sell OPT. Clearly, production management games and simulations could be used not only to reduce evaluation uncertainty, but also as another way to stimulate interest.

4.3 Repackaging Innovations for Late Adopters

From the data in Chapter 2, we can infer that different production management technologies and systems are at different stages in their adoption lifecycles. TOC/OPT and FCS systems, for instance, are pretty clearly in the early adopter stage. While some visionary SMEs have already bought one of these kinds of products, we don't expect to see a high proportion of SMEs using them any time soon, if current market forces remain the same. Moreover, the adoption lifecycle model predicts that the only way to influence later adopters to adopt sooner is to compress the entire adoption lifecycle.[10] Compressing the lifecycle is exactly the goal of the information services sketched above.

On the other hand, as mentioned in Chapter 3, both MRP II and JIT are almost certainly in the late majority stage of adoption in the US. We believe that MEP field engineers have already evolved an

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[9]Although we found a few directories on the Web that include production management software, as of this writing they contain only a small minority of the products and vendors actually in the marketplace. The directory entries are minimal -- basically one-page product specifications plus one-page vendor descriptions. Relatively few of the vendors advertising in the American Production and Inventory Control Society's trade magazine, *APICS -- The Performance Advantage*, have a website, although this number is growing.

[10]For an opposing view, though, see the description of a TOC/OPT-like system in (Constantopoulos *et al.* 1989) that has been designed explicitly for SME adoption.

effective package for promoting JIT to late adopters. But, something different needs to be done for MRP systems and components because these are products whose characteristics are controlled by vendors.

Recall that the product characteristics that appeal to the late majority are:

- complete solution for a narrow niche market;
- the benefit is a demonstrable reduction in operating expense;
- both acquisition and implementation costs are low;
- easy to learn, easy to use;
- little user-specific customization required.

Concrete examples fitting this description are the products that have come out in the PC accounting package market in the last five years. There are accounting packages for car dealers, different ones for carpet retailers, different ones for hardware stores, and so on -- a different product variation for each kind of business. The psychographic profile of late adopters predicts that a similar 'nichefication' would accelerate the diffusion of MRP within this group. MRP vendors, however, do not currently have very close ties with smaller customers, and are not paying much attention to the unique characteristics of late adopters, even though this group constitutes all of the remaining untapped market potential.

Therefore, we suggest that some liaison be established between the MEP centers and vendors who could supply new production management technology products to the SME market. There are many possible ways to do this. For example, no one really knows which production management environments are most common among firms of different sizes in different industries. There is virtually no market research done on low-end customers for technology products. But this would be highly useful in selecting a target niche of opportunity. So, one possible way to connect vendors to MEP information is via a statistical database of relevant SME characteristics. Another way would be to convene a small conference of interested field engineers and interested vendors. A third way would be for MEP centers to host more vendor software demonstrations. If this liaison proves fruitful, vendors will repackage their technology for the late market, and strive to diffuse it in this market, just as they have in the earlier markets.

4.4 Summary and Conclusions

There is little doubt that wider and more rapid diffusion of currently available production management systems and technologies would be good for SMEs, their employees, and the manufacturing sector as a whole. There is also little doubt that some factors affecting innovation diffusion, such as conservative attitudes and limited financial resources, are uncontrollable. However, as described in the preceding sections, there are many opportunities for changing the current market infrastructure to step up the pace of diffusion with new information services directly keyed to the innovation adoption process. While some of these services might eventually become self-supporting, or vendor-supported, the natural laboratory for initiating them is the Manufacturing Extension Partnership. By pooling, packaging, and disseminating expertise electronically, the reach of each MEP center can be extended beyond the individual client to whole classes of clients with comparatively modest incremental cost.

Appendix I. An Overview of Production and Production Management

I.1 Stocks and Flows of Material and Information

Regardless of whether they are large or small, manufacturing firms are distinguished from other businesses by the fact that their main activity is converting purchased materials into tangible products that are then shipped and sold to customers. By contrast, companies in the extraction industries (agriculture, forestry, fishing, and mining) hardly ever purchase the materials they convert into products (they own them already, or have special rights to them), construction companies don't ship their products (they build them on site), and the other non-manufacturing business render services rather than produce products.

The overall flow of material through a production facility is shown in Figure I-1 (adapted from (Vollmann *et al.*, 1988)). Generically, the term *item* is used to refer to any sort of material that a firm

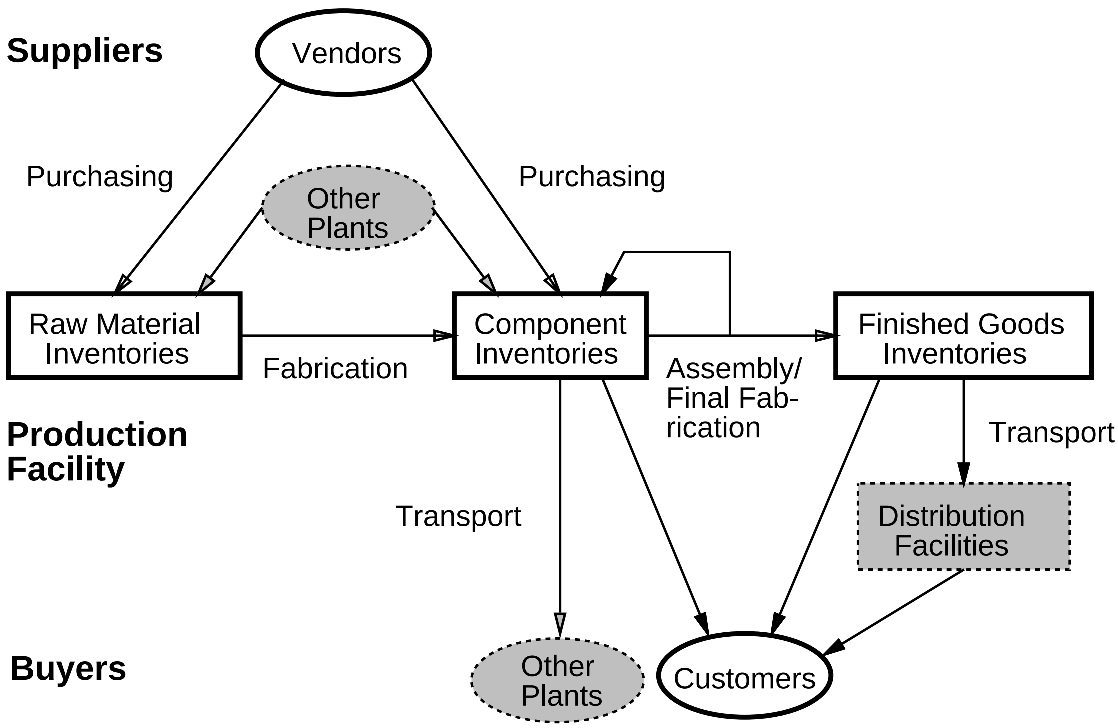

Figure I-1: Material Flow Through a Production Facility

may purchase or manufacture, be it a product, a component, or a raw material. A *component* is an item that goes into (becomes part of) another item during manufacturing. A *product item* is an item that the firm sells to customers. It may be an *end item*, that is not also used as a component of some other item, or it may be a component, such as those items sold to service end items. *Finished goods* are end items ready to ship. *Assemblies* are items that is made by assembling component parts together. A *processed item* is the output of a *fabrication* process, which is any process other than assembly, such as forging, molding, milling, cutting, baking, etc. *Raw material* is the input to a fabrication process, and is generally an extracted material, bought in bulk, such as wood, tubing, steel, plastic pellets, flour, etc.

Any material in a production facility that is not in a component inventory or a finished goods inventory is called *work-in-process* or *WIP*. WIP that is not actually being worked on at any moment, usually because it is waiting for a machine to be processed on, is said to be in a *WIP queue* or a *WIP buffer*.

Smaller manufacturers differ from larger manufacturers in the scope of operations they directly control. For example, large firms tend to have multiple production facilities, sometimes in different countries, which may be suppliers of raw materials or components to a given facility, or recipients of components from that facility. Some large firms also own distribution facilities, such as warehouses, and a fleet of trucks to transport goods from one facility to another. Conversely, the finished goods produced by a small firm may involve no assembly processes, or no fabrication processes. In this report, we are not concerned with firms that own multiple facilities.

The simplicity of Figure I-1 somewhat belies the underlying complexity of material flow. Even for smaller firms, there are likely to be many vendors, many raw materials, many components, many end items, many inventories, many production processes, and many orders per day, all of which need to be coordinated so that the right quantities of items are bought and made at the right times to make the right quantities of products available at the right times to satisfy sales demands. The exact numbers for smaller firms are smaller, of course -- dozens (or fewer) to hundreds, typically, compared to thousands and tens of thousands (or more) for a large firm.

Also not shown in Figure I-1 are all the types and flows of information that are needed to operate a production facility. For example, every manufactured item is made from certain component materials, and information on the types and quantities of components, specified in an item's *bill of materials*, or BOM, is required to either make or buy the components. Every manufactured item is produced by some technical process, comprising a sequence of operations, called an item's *process plan* or *routing*. Specifications of routings are required not only to actually make the corresponding items, but to schedule the assignment of equipment and workers to perform the operations. Moving backward from customers to vendors, many other types of information are generated and consulted: customer orders, invoices, work orders, standard cost sheets, stock records, shop schedules, purchase orders, vendor lists, shipping tickets, etc. The types and flows of information required by a smaller firm is identical to that of a larger firm, although not necessarily the types and flows of records. For an SME, the information and processing tend to be less formal (at the extreme, not even written down), and the number of pieces of information ("transaction volume") is proportionally lower.

I.2 Production Management and Manufacturing Performance

Coordinating stocks and flows of materials with sales, production, and purchasing activities through the use of stocks and flows of information is the province of production management. In the literature, this term has many synonyms, including:

- manufacturing planning and control (MPC)
- production planning and control (PPC),
- production and inventory management (PIM)
- production and operations management (POM)
- production and inventory control (PIC)

Of these, MPC and PPC are most descriptive of the kinds of work that is supported by production management technology. To achieve coordination, production management is centrally concerned with planning and controlling the major aspects of a production facility -- the layout, workforce, inventory, production schedule, and shop floor operations. It deals with all the activities shown as arrows in Figure I-1, from raw material acquisition to processing orders for completed products. It also deals with all the information flows that support these activities. The concerns of production management contrast with the more technical side of manufacturing, such as production equipment design, site engineering, process planning, process control, and so on, although the boundary is sometimes fuzzy.

Informally, the planning part of production management is concerned with getting ready to make things and formulating plans for how things are to be done once one is ready. Planning decisions are made for a span of time to cover all the requirements that need to be fulfilled at different points in the manufacturing cycle for items. A few of the decisions made during planning are:

- How much of what types of raw materials should be ordered, and when?
- When should the production of different types of components be started, and how many of each type should be made?
- Should new people be hired, or new equipment bought, to accommodate future production needs?
- How large a batch (usually called a *lot*) of each sort of item should be made at one time?
- How much time should be allowed for the production of a given lot?
- How should the shop floor be laid out, and how should different lots of items be routed through it most efficiently?
- Which specific shop resources should be allocated to performing the various operations in the process plan for a particular lot?

Production control is concerned with executing plans, tracking status, maintaining documentation, and deciding what to do when things can’t be done according to the original plan. Control decisions include:

- When should shipment of a customer order be promised?
- How should existing inventory be allocated to new orders?
- How should shop floor operation be directed and monitored?
- How much documentation should there be, of what kinds, in what form (electronic or paper), and how should it be generated?
- What should be done if a machine breaks down or a vendor delivery is late?

Planning and control overlap when plans leave certain choices open, to be made during execution. For example, the assignment of a particular worker or particular machine to an operation might not be planned in advance but instead decided on the fly. Conversely, plans can be made for contingencies, like breakdowns and late deliveries.

Overlaid on the dichotomy of planning and control is the dichotomy between inventory and capacity. All firms who don’t defer all material purchases until a customer order is placed necessarily hold some inventory of raw materials, components, finished goods, or combinations thereof. They do this to meet anticipated demand more quickly and/or dependably than if they did not have the inventory. Consequently all of these firms have to decide what quantity of each type of item they should have at each point in time, and how material flows should be managed to yield those quantities at those times. Then they must execute the plan, allocate actual material to particular orders, keep track of stock levels, and make adjustments to compensate for contingencies. These are the inventory planning and control problems, respectively.

The other side of the coin is capacity planning and control. Shop capacity is measured in terms of available hours of shop resources, which, at the lowest level of detail, are individual workers, pieces of equipment, particular tools, areas of floor space, and everything else required to carry out production processes. For planning purposes, resources can also be grouped into aggregates, such as different kinds of equipment and labor, or functionally-defined *workcenters*, such as injection molding, component-x assembly, frame welding, etc. The planning decisions to be made are (1) determining how much capacity is required over time to actually produce the manufactured items that the inventory plan calls for, (2) deciding how capacity in place should be allocated over time to the various operations in production processes that use them, and (3) deciding what to do if there is a mismatch between in-place capacity and the needs of planned production, either at certain times, or over the whole time frame planned. The capacity control problem is similar to the inventory control.

Inventory and capacity are complementary constraints on overall shop output. The amount of capacity available constrains the rate at which new inventory can be built up, and the total volume that can be produced in a given time period. Availability of inventory is a prerequisite to applying available capacity. Consequently, inventory and capacity plans should interlock.

Different (but related) plans for inventory, capacity, sales and production are made at four different levels of granularity, shown in Figure I-2. From top to bottom these are:[11]

1. *aggregate* plans, made for sales, production, and inventory of the different product <u>types</u> that a firm sells, e.g. electric drills and power saws. Aggregate plans cover a span of time -- the *planning horizon* -- that includes at least one selling cycle (e.g., one year), and usually more than one;

2. *master* plans, made for sales, production, and inventory of the different product <u>items</u> that the firm actually makes, e.g. 1/4", 3/8", and 1/2" drills. These plans have a shorter horizon, but still cover at least one selling cycle;

3. *tactical* plans, made for producing and purchasing the components that go into the product items, their components, and so on, down to the level of ultimate raw material inputs. Tactical plans are made for a horizon that is at least as long as the longest complete purchasing + manufacturing cycle;

4. *detailed* plans, made for allocating specific shop resources and item stock to specific process operations at specific times, and for allocating specific purchases to specific vendors.

Capacity allocation plans are also made at the tactical, master, and aggregate levels. At the higher levels, resources are grouped into larger and larger aggregates of capacity. Firms that don't have to worry about seasonal differences in demand, and who forecast sales at the product item level, generally don't make aggregate plans.

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[11]The terminology in the literature varies here. For example, most of what is here called the tactical level is called the "engine" in (Vollmann *et al.*, 1988), and what is here called the detailed level is there part of the "back end".

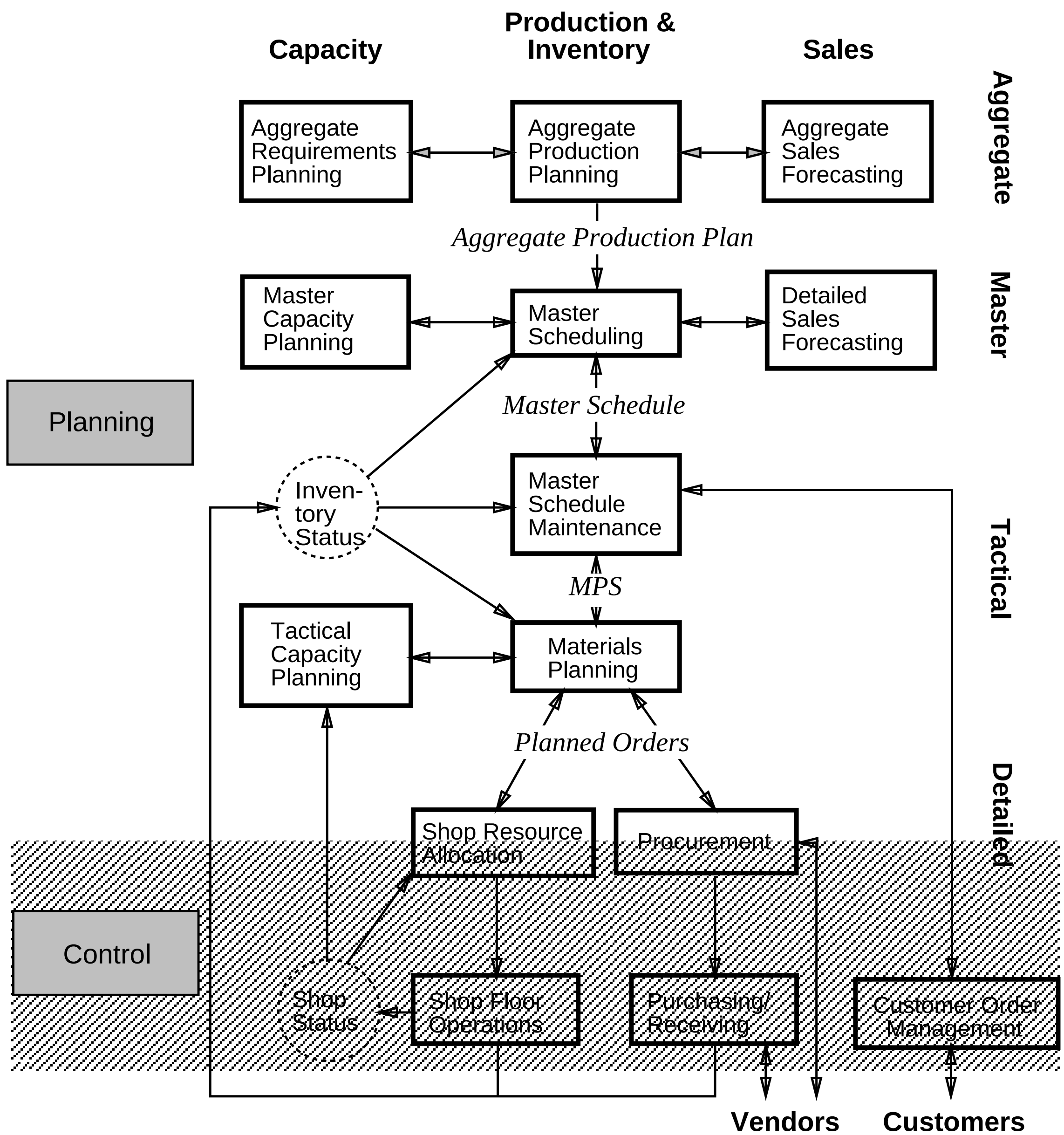

Figure I-2: Production Planning and Control Hierarchy

Depending on the product and the market, firms pursue one of several strategies to plan production at the master level. At one extreme is the *make-to-stock* (MTS) strategy in which everything is done before the sale is made. Finished products are stored in inventory and sales are made out of inventory stock. Everything bought ready-made, off the shelf, was once made to stock. Since this includes virtually all consumer products, MTS production scheduling is the predominant mode in terms of product volumes. At the other extreme, nothing is done before the sale is made, normally because the exact nature of the product is too unpredictable before the customer orders it. This style of production is sometimes called *one-off manufacturing* because it is typically used by firms who custom build one unit of a product per order, such as ship builders.

Between these extremes there are any number of variations. In all cases there is some degree of product customization, some amount of delay while the product is being manufactured, and the manufacturer holds some raw material or component inventories in anticipation of orders. The generic term covering all strategies other than make-to-stock is *make-to-order* (MTO). To some extent, firms can mix MTS and MTO strategies for different products. It is not uncommon, for instance, for a firm to use MTS for its most popular products and some version of MTO for the rest.

All plans made in production management are *time-phased*, which means that they specify planned volumes of items to produce or purchase during each period of a span of time, called the *planning horizon*. The main output of aggregate planning is called the *aggregate production plan*, or simply the *production plan*. It specifies planned volumes of output by product type for each period in the aggregate planning horizon. These periods are typically months or quarters. The main output of master planning is called the *master schedule*. It specifies the sales plan, production volume, inventory actually allocated to customer orders, and projected inventory balance by end item for each period in the master planning horizon. Master schedule periods are typically weeks or months. The term *master production schedule* (MPS) is used to refer to planned production of end items by period.

The main output of tactical planning is a set of orders to the shop for lots of components to be made, and to the purchasing department for lots of components and raw materials to be bought. The time at which a lot is supposed by received into stock is called its *due-date*. Periods at the tactical level are typically days or weeks. Taking the shop orders as input, the main output of detailed planning is a shop resource allocation plan, for a horizon of hours or days, and purchasing commitments. The allocation plan may be expressed simply as a prioritization of operations -- which ones should be worked on first. This is called a *dispatch list*. Or, it may be expressed in terms of blocks of time on each resource that are to be allocated to different operations. This sort of plan is called a *finite loading*, a *finite capacity schedule*, a *Gantt chart*, or sometimes just a *schedule*.

Production management decisions are important for two reasons. First, every firm must routinely make them, if only informally. Every manufacturer must purchase quantities of materials at different times, schedule operations, make promises to customers, and so on. Second, these decisions have consequences which affect the firm's *performance*.

The most important measures of a manufacturing firm's performance are the financial ones, just as for any other kind of business: revenue, earnings, growth, market share. The manufacturing function affects these measures directly via its contribution to costs, and its potential for increasing revenues. The major costs affected by production management decisions are those related to inventory (cost of storage and commitment of working capital), operations (cost of labor and equipment utilization), quality assurance (cost of inspection, rework, and scrap), and administration (overhead cost incurred for record keeping, planning, clerical, and supervisory functions). Revenue is affected by the rate of output the plant produces per period (the *throughput*). If there is more demand for product than a plant can supply over a period of time, then some revenue is foregone. If plant output is increased under these conditions, revenue will be increased.

Production management can affect a firm’s performance indirectly as well. For example, if delivery promises are made judiciously and production is well-coordinated with the promises, *delivery dependability* (percent of orders shipped when promised) will be high. When customers get their orders on time, they are more disposed to remain customers, which affects the revenue stream, and the firm won’t have to pay lateness penalties, which affects costs. Good production management decisions will lower *manufacturing cycle time* (also called *manufacturing lead time*), which is the average time it takes to make items not held in stock. Cycle time affects the response time to custom orders and to orders that have to be backlogged, and response time, in turn, is almost always an important factor in winning bids. Over the long run, a firm that gains a solid reputation for lower costs, high dependability, and quick response will win new customers, which results in growth. Finally, if a firm’s performance comes to be consistently better than its competitors, it acquires a competitive advantage that should eventually translate into increased market share.

Appendix II. MRP I, Closed-Loop MRP, and MRP II

"MRP" is used to refer to three different planning concepts, corresponding to three stages in the development of modern MRP II systems: MRP I, closed-loop MRP, and MRP II. MRP I is part of closed-loop MRP, which is part of MRP II.

II.1 MRP I

MRP I is sometimes called "little MRP", "MRP logic", or just "MRP". At base, it is an algorithm for calculating the quantities, need dates, and order release dates for all the component items required to manufacture a given quantity of parent items by a certain date, taking into account the projected inventories of all items and the times to be allowed to manufacture or purchase components. The total quantity of an item that needs to available by a certain date is called the item's *gross requirement* for that date. The date itself is called the *need date*.

II.1.1 The MRP Algorithm

The main ideas behind the algorithm are that one doesn't need to produce what one expects to have on hand, and one should not receive or complete manufacture of component stock until just before it is needed to assemble into parent stock. The algorithm itself involves a loop over two steps that schedule work and purchases so these conditions are met. Suppose one has a gross requirement for a parent item, P:

> *Gross-to-net calculation.* Subtract the gross requirement for P from its projected inventory balance. If the balance falls below the *safety stock* level (minimal allowable balance) for P, then a *net requirement* for P exists on its need date, in the amount of the difference. This is the quantity of P that must be scheduled for manufacture, because it can't be taken from inventory.

The term "date" may suggest that requirements are kept by day, but this is not necessary. Sometimes a period of a week is used, sometimes a period of a month, sometimes something else. The periods MRP plans for are called *time buckets*.

The amounts of time allowed to either manufacture or purchase items are referred to as *lead times*. These are the amounts of time expected to elapse between the release of an *order* to the shop or to the purchasing department and the completion of manufacture or receipt of purchase.[12] Total manufacturing lead time is the sum of the lead times for each operation in the process routing for an item. The lead time for each operation is made up of:

- *move time*, the time expected to move material from one workcenter to another;
- *queue time*, the time material is expected to spend waiting to be worked on;
- *setup time*, the time expected to set up the workcenter (change tools, affix jigs, etc.) to perform the operation;
- *run time*, the time expected to actually perform the operation given the number of items in the lot (*lot size*) being worked on;

A *lot sizing* policy is the method used to determine the lot size for a given item.

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[12]This usage of the term "lead time" should not be confused with "delivery lead time" or "manufacturing lead time", both of which are the average of *actual* process durations (flowtimes), not *expected* durations (Kanet 1982).

The second step of MRP determines how many items to order and when, given a net requirement.

> *Lead time offsetting and lot sizing.* Apply the lot sizing policy for P to determine the size of the lot to make or buy. The projected inventory balance for the need date is then this lot size minus the net requirement (since the net will be used up to satisfy the gross requirement). Subtract P's lead time from its need date, yielding its *order release date* and create a *planned order* for one lot of P to release on that date.

Now we have an order for one lot of P whose completion will satisfy the net requirement.

If P is a manufactured part, it will have components (identified in P's BOM) that also need to be bought, made, or taken from inventory. By design, MRP schedules all component lots for a parent lot to be available at the start of manufacture of the parent. Hence all component need dates are the same as the release date for the parent order. The quantity of each component needed is just the quantity contained in one P, multiplied by P's lot size. The result is the gross requirement of each component needed to make the lot of Ps.

> *Loop.* For each gross component requirement, go back to the gross-to-net calculation with the need date just established. If there are requirements for the same component derived from other parents, sum them up before netting.

When all of the loops have been completed, the end result is a set of time-phased planned orders derived from the required quantity and need date of the original parent. This process is called the *bill of materials explosion* because it steps down through the components of the parent, the manufactured components of these components, their manufactured components, and so on, until it has reached all the purchased items at each level. When the process is applied to the requirements for product items shown in each period of the master production schedule, all the time-phased orders for all the items that need to bought or made during the planning horizon will be determined. These orders constitute a production plan and a purchasing plan for components that is exactly coordinated with the production schedule for product items.

The control parameters to MRP are the bucket sizes, update frequency, planning horizon, safety stocks, lead time, and lot sizing policies. MRP methodology does not prescribe what these should be, except that they be fixed for the entire plan. In some systems today,[13] formulas can be used to make the lead time a function of the chosen lot size. The traditional practice[14] in setting control parameters has been to:

- use weekly buckets and weekly update frequency;
- use a planning horizon that is long enough to make blanket procurement arrangements with suppliers and subcontractors for approximate quantities of material and work -- a span of three months to a year, typically;
- use sufficient safety stocks to compensate for variances from plan, such as many more customer orders than forecast, lots that must be scrapped, equipment breakdowns, absenteeism, and deliveries from vendors that are short, late, or of unacceptable quality;
- use lead times with a queueing component that is 90% of the total;
- use lot sizes that are either equal to net requirements, or are fairly large to avoid setup

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[13]by which we will mean modern MRP II systems, which include the basic MRP I procedure

[14]presented in textbooks such as (Vollmann *et al.* 1988) and (Fogarty *et al.* 1991) and confirmed in the case study literature

costs,[15] or are standard quantities for purchased items, such as a gross or a carload.

If safety stocks are not used, and variances from plan are common, inventory shortages will inevitably develop that will prevent production of product items in time to meet customer orders. If lead time allowances are too short, it will be impossible to meet production due-dates because the shop will not be able to complete the work assigned to it in the time allowed.

II.1.2 MRP Production Control

In most firms, revisions to plans are the norm rather than the exception. New information comes in, improvements to products are made, customers change their minds. Revisions affecting production plans stem from engineering changes to products or process plans, revisions to sales forecasts, and changes that customers make to their orders before production starts. MRP prescribes several techniques for controlling the impact of change on the flow of production, such as the use of "time fences" and "firm planned orders" to freeze the schedule in a principled way. In addition, MRP systems provide a capability for recommending changes to planned orders that will accommodate changes made in BOMs, MPS requirements, standard lead times, etc. During the explosion process, the system not only reads in the requirements, BOMs, and other planning data, but also all the orders that it previously created. By comparing newly generated orders to the old ones, recommendations for revisions can be reported, such as shifting the timing, changing the quantity, and cancellation. These recommendations are nontrivial since one change in an end item requirement, for example, will produce a coordinated set of recommended revisions to component orders at all levels of the product structure.

Textbooks on MRP also emphasizes the idea that variances from plan are the norm, to be expected, and a fact of life. Variances differ from the changes mentioned in the last paragraph because they are discovered during plan execution, and hence affect orders that have already been released to the shop, called *open orders*. Consequently, there is much less time to take corrective action, and much less freedom as to what action to take. Examples of variances include the problems with forecasts, vendors, equipment, and scrap cited above plus discovered inaccuracies in inventory records, and customers who change their mind after production of their orders has begun.

Given a production environment in which variances are endemic, it is crucial to be able identify all the open orders that are affected. MRP systems help production managers do this in two ways. First, they analyze open orders in the same way as planned orders, and make recommendations of a similar sort. Now however, the recommendations point to current shop activities which need to be given higher priority (*expedited*), put off until later (*de-expedited*), or abandoned. Making such recommendations accurately involves considerable computation and in general is impossible without a computer. Not only are there vertical dependencies between components and parents to consider but also dependencies between components and their siblings, cousins, and other more remotely related lots up and down the product structure.

A second kind of help that most systems provide is a way to cross reference component lots to the

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[15]the larger the lot, the more time people and equipment will be busy actually processing material, and the more units that setup cost can be amortized over

parent lots they depend on, and sometimes to the original customer order(s) associated with the requirement for product items. This is called *pegging* and it too is generally impossible without a computer, since any given lot may contain component items needed for more than one parent lot, each of which may itself contain component items for several grandparents, and so on all the way up to many original customer orders.

II.2 Closed-Loop MRP

One of the shortcomings of MRP I systems was that there was no software for planning and controlling the master schedule in the same way that MRP logic was used to plan and control production plans for components. Another was that there was no tool for determining whether the master production schedule was *feasible*, i.e., whether the shop could finish enough product items to meet each time-phased requirement, given shop capacity. Without such a tool, sales departments tended to add unplanned demand to the MPS as sales opportunities arose. This then "inflated" the MPS beyond the point of feasibility. Closed-loop MRP systems were developed to remedy these shortcomings.

II.2.1 Master Schedule Planning and Control

Master schedule planning is the process of translating a time-phased aggregate production plan for product types into a time-phased production plan for product item lots -- the MPS -- taking current inventories and scheduled production of product items into account. The major innovation here was the realization that BOM records could be used to encode the decomposition of a product type "parent" into product item "components" simply by specifying the component quantities as fractions, rather than multiples, of the parent quantity. The fractions represent a forecast of the ratio between product item sales and total sales of the encompassing product group. So, if sales of drills in March are forecasted to be 10,000 units, and the ratio forecast for 1/4" drills is 12% of the total, the item forecast for 1/4" drills is 1,200 units. This, then, is the gross requirement for 1/4" drills in March. Applying MRP gross-to-net calculations to all such gross requirements yields the MPS.

Master schedule control is the process of allocating product item inventory and/or production output to actual customer orders. A minor innovation in this area was the addition of *available to promise* logic. This keeps track of the quantity of inventory and scheduled output that is not yet allocated. Given a properly maintained (and feasible) master schedule, an order taker can use this information to quote accurate quantities and ship dates to customers. The software for both master schedule planning and master schedule control in a closed-loop MRP system is bundled together in a *master production scheduling* module.

II.2.2 Capacity Planning

When sales are projected to increase over time, it is not always clear from experience how much increase in workload the shop can handle, and which specific resources will be affected most critically. Similarly, when sales are projected to decrease or change mix volumes, it is not always clear which resources will be affected most and in what time periods. The first objective of capacity planning is to answer these questions.

The way this is done in closed-loop MRP is first to compute a projection of the workload implied by a given time-phased production plan. This yields the number of hours of each resource that appear to be needed in each period of the planning horizon. If all equipment in the shop is manned, the hours used are typically standard labor hours, since one can get an estimate of the labor requirements at the same time. The workload projection is then compared to an estimate of capacity -- the resource hours expected to be available in each period -- to determine whether there is enough projected capacity to accommodate the projected workload. The result is displayed on a *load report*.

The second objective of capacity planning is to make changes in plans to improve the profile of capacity utilization. If the load report shows overloads in certain periods, one response is to increase capacity, e.g., by planning overtime work for those periods. Similarly, for underloads, one can plan undertime or layoffs. Another possibility, is to try to juggle the assignment of shop resources to use underloaded resources to relieve the pressure on overloaded ones. Finally, one can try to negotiate changes in the production plan that produced the projected workload in the first place. In general, this can ripple back to changes in the MPS, which may require changing the sales expectations from which the MPS was derived. This is what is meant by "closing the loop".

Closed-loop MRP systems provide two software tools for making workload projections, one to be used at the master planning level and one at the tactical level. For both levels, hours available on individual resources are aggregated into workcenter hours per period.[16] At the master level, a *rough cut* capacity analysis is prescribed in which current component inventory and shop load are ignored. In practice, resources that are never overloaded are also ignored. The production plan that is input at this level is the MPS. There are three standard methods for converting this into a workload projection. All of them involve multiplying MPS quantities by factors that yield hours required in each planning period for each workcenter. The most detailed method, *load profiling*, associates time offsets with the factors to time-phase the workloads projected. For example, if a lot of 100 of item 7 is to be assembled in period 4, and this takes .2 hours on workcenter A per assembly, and .3 hours on workcenter B is required to complete one kind of component for item 7 in the period just before assembly, and .1 hours on workcenter A is required to complete other components for item 7 before assembly, then the workload projected for the whole lot of 100 item 7's would be 20 hours on workcenter A in period 4, 30 hours on workcenter B in period 3, and 10 hours on workcenter A in period 3. The total load on each workcenter is the sum of the loads derived in this way.

At the tactical level, the workload projection tool is called CRP (for *capacity requirements planning*). CRP takes as input the set of all shop orders produced by MRP, both planned and open, and the routing for each item ordered. The current status of all open orders is also read in, both to establish current workcenter load and to exclude from projected workload those initial operations on material that have already been completed. CRP applies the load profiling method to these data to produce a workload projection. For each remaining operation in the routing for each order, the order's lot size is multiplied by the operation's unit run time to yield total run time. This is then added to the setup time to yield the total time the operation's workcenter will be busy working on this operation. That amount of work is then

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[16]or some other measure of capacity such as tons of stock producible per period

added to workcenter load in the period that is offset from the order release date by the time taken by all preceding operations plus the queue time and move time of the operation in question. Finally, a load report is generated. By using MRP orders to project workload, the effects of existing component inventory and component lot sizes are taken into account.

All the decision loops involved in closed-loop MRP are shown explicitly in Figure II-1. At the master

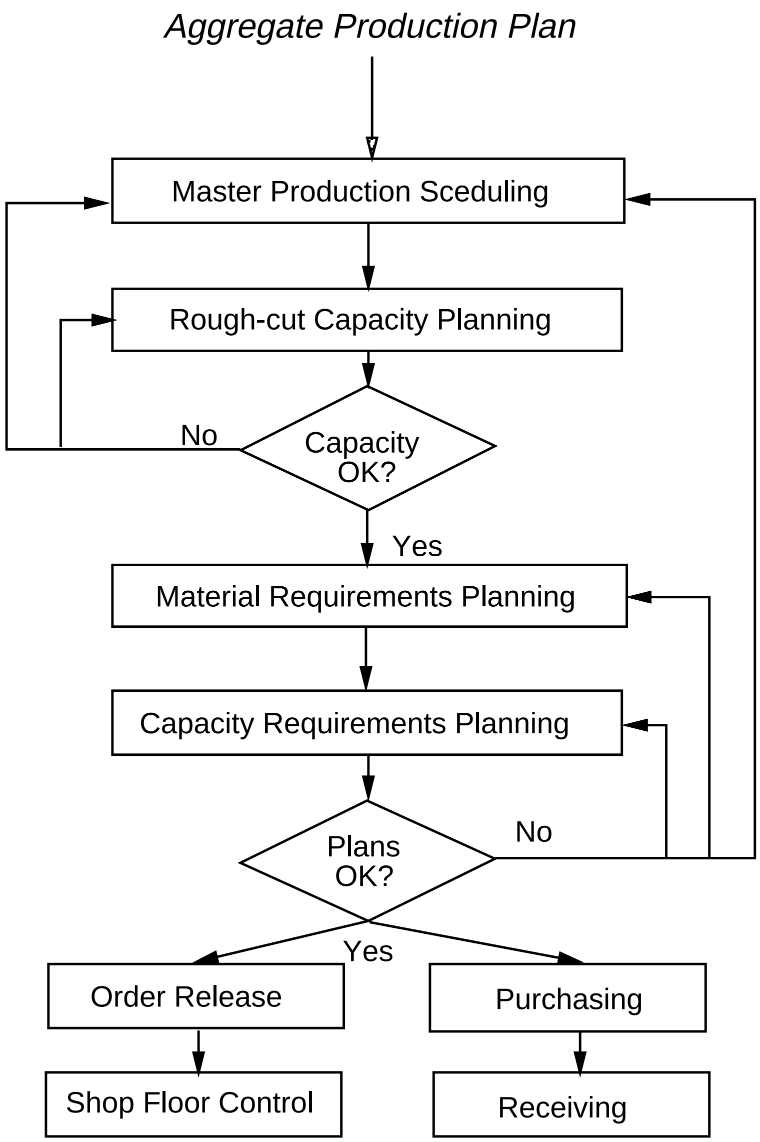

Figure II-1: Closed-Loop MRP

planning level, plans are made for a longer time horizon, but with much less detail. At the tactical level, much more detail is considered, but with a shorter horizon. The MRP technique used in both master production scheduling and material requirements planning is often called ’infinite capacity scheduling’ because it does not explicitly consider the workload on the shop implied by the schedules it generates. The only way shop capacity enters into a fixed lead time schedule is through the allowed queue times. Ignoring implied workload is equivalent to assuming that the shop has infinite capacity for executing any plan it gets, as long as the plan respects the lead times.

But this assumption does not hold for every plan, so planners need to use the workload projection tools to test it. Inherently, this is meant to be an iterative process in which a schedule is generated, the workload is projected, a comparison is made to capacities, changes are made, and the process repeats. At the master planning level, fairly large changes in plan can be tried, such as deciding to buy a component rather than make it, or deciding to hire more people to staff more shifts.

When the MPS satisfies the rough-cut test, it is passed on to material requirements planning and CRP for more detailed analysis, planning, and feasibility testing. If problems show up here, options are more limited, but there are still possibilities for using different routings, overtime and undertime, hiring part-time workers, and so on. If no option for adjusting capacity at either level is sufficient, the only thing left to do is to revise the MPS and try again.

II.2.3 Shop Resource Allocation

The MRP methodology does not prescribe any methods for allocating resources to operations on the shop floor. It allows shop foremen complete freedom to schedule labor and equipment as they see fit, within the bounds of the order release and due-dates. The technique that is traditionally used is to construct *dispatch lists* which specify the sequence in which operations are to be performed on individual resources. These lists are based on dispatch rules, which tell which operation should have priority over others when a resource can be assigned to any one of them. It is recommeded, but not prescribed, that the priorities be based on order due-dates, so that orders with nearer due dates have their operations performed first. In the MRP literature, *priority planning* means assigning due-dates to shop and purchase orders by means of the MRP I algorithm.

II.3 MRP II

MRP II is an extension of closed-loop MRP that provides the capability to translate manufacturing plans and orders into dollars and documentation. The concept was first put forth by Oliver Wight (Wight 1981), who revised the acronym to stand for "manufacturing resource planning" in order to denote an extension in scope beyond just materials planning. From a software standpoint, a *resource requirements planning* module is included that projects the financial impact of the aggregate production plan, and also a number of accounting and clerical modules that work off of the data already present in a closed-loop MRP system. MRP II emphasizes the idea of a common, integrated database for the firm, which the manufacturing, sales, accounting, finance, and marketing functions all use. Online responses and printed reports generated from this database are intended to form a full manufacturing information system. Finally, a simulation capability is included in MRP II so that trial plans can be formally separated from final, approved, authorized plans.

A number of benefits obtained by five of the most progressive early users of MRP II are described in (Melnyk and Gonzalez 1985). Although the sizes of these firms are not given, they would appear to be LEs. All five firms cited reductions in manufacturing inventories, fewer stockouts, and improved delivery. Two firms cited improvements in materials coordination during new product introduction. These sorts of improvements would all come from the use of MRP I and the closed-loop planning embedded in MRP II. Examples of benefits stemming from the simulation and financial resource projections, that might be applicable to larger SMEs, are as follows, quoting from the article:

> [In one firm,] manufacturing managers were able to show marketing that it was necessary to smooth the sales plan so that manufacturing could level its labor requirements. With MRP II, the effects of different master production schedules could be demonstrated in terms of sales and manufacturing capacity. In another firm, marketing actively participated in smoothing the MPS by negotiating orders in the backlog with its customers. ...
>
> In firm E, the finance department calculated the inventory investment what would put the firm in the best tax position at year's end. By using MRP II's simulation and data conversion capabilities (i.e., translating manufacturing's numbers into financial terms), manufacturing determined how best to manage inventory to meet finance's goal....
>
> The sales manager in Firm A had an opportunity to land a large contract. Before accepting it he called manufacturing, which then evaluated the order in terms of capacity requirements. It was found that the order could not be accepted given the current load. Sales and manufacturing analyzed the load and by rescheduling part of it were able to accept the order.....
>
> Using the "what if" simulation capability of MRP II, management can evaluate the potential effect of strikes on corporate resources such as capacity and cash. ... An example was observed in Firm A, whose main production facility, located in the Midwest, is organized by a strong international union.... A year before the last strike, management considered how best to meet customer deliveries should a strike occur. MRP II was used to identify strike-induced capacity shortages and to schedule vendors to make up projected capacity shortfalls. Management created a strike contingency plan. During the 13-week strike, the company met all its commitments -- not one delivery was late.

These examples highlight the central innovation of MRP II: that a production management database, plus the closed-loop MRP modules, plus a financial resource projection module, plus a simulation capability can function as a support tool for making planning decisions at several different planning levels.

II.4 Current Commercial Software Systems

All commercial systems today that include MRP I are generically called "MRP II" systems (CPI 1993). Virtually all of them are also closed-loop MRP systems. The idea that an MRP II system should serve as a manufacturing information database coupled with a production management and control system has been retained, and expanded, but not many systems offer resource requirements planning and rough-cut capacity planning as off-the-shelf modules. Different systems offer different levels of simulation capability at the different planning levels.

II.4.1 Core Modules and Functions

The software architecture of a typical MRP II system that one can buy commercially is shown in Figure II-2 (CPI 1993). The circles denote data, the boxes denote processing modules, and the lines denote data flows. Functions are grouped into modules as follows:

- Master schedule planning and master schedule control functions are contained in the master production scheduling module. This module is used to maintain the master schedule for each product item.
- The material requirements planning module includes the MRP I algorithm and MRP production control functions.
- The capacity requirements planning module is used to project workloads as described above.

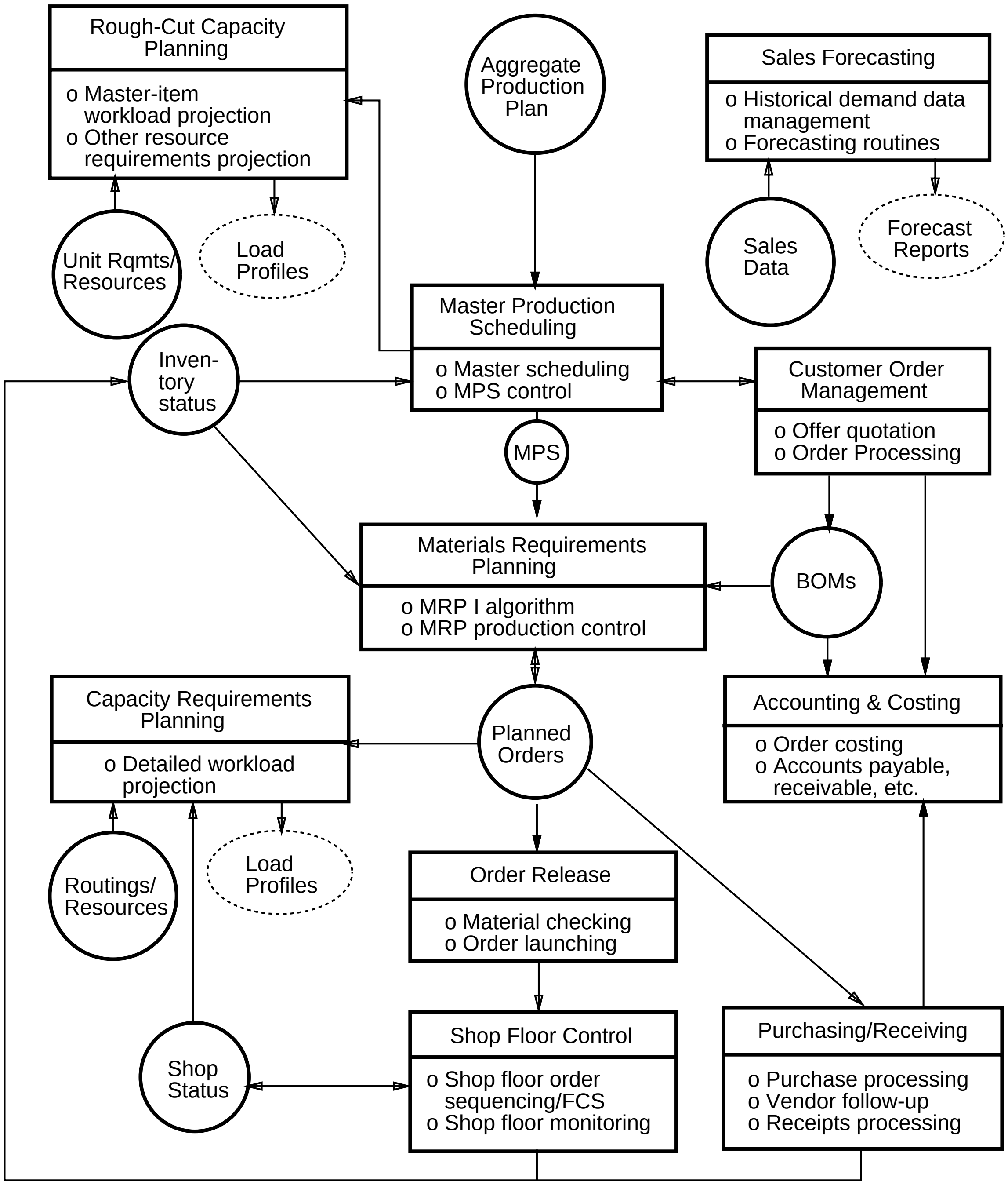

Figure II-2: MRP II Software Architecture

- Order release functions include (a) checking inventory records to verify that material for a releasable shop order is actually in stock; (b) generating transactions against inventory to allocate items to new shop orders; (c) generating the database entry and/or hardcopy that represents an open shop order, including the routing, list of allocated materials, list of special tools required, etc. Order release functions are typically bundled in with either the material requirements planning module or the shop floor control module.

- Purchasing/receiving functions generate and maintain information relating to purchase orders, from the time a requisition is initiated through placement of a purchase order and receipt/inspection of the delivered items.

- Shop floor control functions are used to enter data on the progress of production, to record receipt of inventory from open shop orders, and to generate dispatch lists for workcenters. The majority of MRP II systems provide integral FCS modules for shop floor scheduling.
- The majority of MRP II systems offer a sales forecasting package of functions as an option. More comprehensive and sophisticated packages are also available from third-party vendors.

The integrated nature of MRP II data and processing are nicely illustrated in the customer order management functions. When an order is being taken, prices can be retrieved from the item master file,[17] credit rating and discounts available can be retrieved from a customer file, and inventory availability can be retrieved from the master schedule. Once the order has been accepted and entered, a "picking list" is generated to pick items from inventory for the order, and/or an open shop order is generated to manufacture the items. When the items are ready for shipment, a customer invoice is produced and the order record is updated to reflect items shipped, items backordered, etc. Shipping charges, taxes, and so on, are calculated at this time. A summary sales transaction is then generated to update the accounts receivable file, sales history data for this customer are updated, salesman's commission is posted to the appropriate account, sales tax information is recorded, and a general ledger transaction file may be updated.

For accounting and costing virtually all systems provide one or more of the following functional modules:

- job costing: collects data on the actual cost of a job or lot (including labor, materials, overhead, outside vendor processing), compares this to standard cost data, and reports any variances;
- product costing: sums up the unit cost of a product based on cost elements (for labor, material, overhead, etc.) associated with the BOMs at each level of the product structure;
- accounts receivable: maintains customer account records, which are updated as invoices are created and payments received; handles debit and credit memos, application of finance charges, printing customer statements, etc.;
- accounts payable: performs all the functions associated with recording vendor invoices and paying amounts due, including generation of general ledger transactions, debiting expense accounts, crediting accounts payable, printing vendor checks, updating the check register, etc.
- payroll: calculates payroll information (gross pay, deductions, taxes, etc.), maintains payroll data files, prints paychecks, and posts transactions to general ledger accounts;
- general ledger: produces financial statements at the end of each accounting period including at least a trial balance (all transactions for the period by account number), balance sheet, and income statement.

Each of these modules, as well as the ones listed earlier, generally include facilities for displaying and/or printing several kinds of managerial reports.

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[17] We use the term *file* generically to refer to flat files that some systems maintain, or to tables in a relational database

II.4.2 Core MRP II Data

Finally, all systems include facilities for managing all the static and status data that underlie the functional modules. Static data is that which changes slowly and is generally the same from one planning period to another. At a minimum it includes:

- *item/master data*: item number; descriptive, engineering, and cost data; associated BOM and routing; lot-sizing policy, safety stock, scrap factor, lead time; manufactured vs. purchased; vendor part number; prices;
- *BOM data*: item number; component quantities; engineering change number, effectivity date;
- *routing data*: item number; operations list: sequence number, workcenter, setup time, unit run time, queue time, move time, alternate operation(s), material used;
- *workcenter data*: id; machines included; capacity/period;
- *vendor data*: id; descriptive data; items supplied, prices;
- *customer data*: id; descriptive data; credit limit, sales history.

Status data is that which generally changes from one period to the next. It includes at least:

- *item/inventory data*: quantity on hand, current allocation to shop orders, scheduled receipts to stock, time-phased gross requirements, planned orders, pegging data;
- *master schedule*: time-phased forecast, customer allocation, MPS, scheduled receipts, projected available balance, and available to promise for each product item;
- *open purchase orders*: id; item, quantity, vendor, due-date;
- *open shop orders*: id; item number, quantity, due-date, routing; current operation, operator, workcenter, time in, yield, accumulated cost; children of split orders;
- *open customer orders*: items, quantities, quoted prices, due-date;
- *pick lists*: shop order number, items and quantities issued to orders from inventory.

The main idea to take away from these long lists of modules, functional capabilities, and data types is that the MRP II approach to manufacturing management is inherently complex, irrespective of the size of a firm, because so many different kinds of information are involved. Consequently, installing an MRP II system is a large undertaking and relatively expensive, regardless of the size of a firm.

II.4.3 Additional Features

Besides the core modules and data management facilities just described, nearly all systems offer some subset of the following features, often as a extra-cost options (CPI 1993):

- *Lot traceability*: For some products, such as pharmaceuticals, it is important to keep track of the specific lot that a particular end item was part of when it was manufactured, and to keep track of the customer orders that were satisfied from each lot. This allows a backward trace from customer orders to information about the manufacture of items received, such as date produced, place of manufacture, inspections performed, etc.
- *Bar coding interface*: The use of bar codes and bar code readers provides a relatively cheap, rapid, and accurate means of collecting data on inventory transactions, receipts from vendors, and shop floor operations. Status data accuracy is crucial to MRP II systems since all the modules depend on it. A bar coding interface takes input from commonly-used bar code readers and converts it into a format suitable for updating the relevant MRP system files.
- *EDI interface*: Electronic Data Interchange (EDI) allows customers and suppliers to exchange business information electronically over a standardized EDI network. Examples of

such information include purchase orders, purchase order acknowledgements and amendments, shipping notices, and invoices. An EDI interface translates this information from the internal format of an MRP II system into a standard EDI format and vice versa.

- *Product configurator*: A product configurator provides information regarding allowable combinations of product features and options. It is used to ensure that configuration rules are followed when taking customer orders.
- *Warehouse management*: A warehouse management subsystem automates the clerical functions associated with warehousing, such as the generation of bills of lading, putaway and picking lists, inventory transactions, and so on.
- *Distribution requirements planning*: A application of MRP logic to a hierarchy of distribution facilities. Projected demands and inventory balances at lower level warehouses are used to calculate expected demands on the next higher level warehouses. Projected demands and inventory balances at the highest level warehouses are used to forecast demand on manufacturing plants.
- *Multi-plant operation*: Allows certain system functions to be run on different computers at different locations, and other functions to be run at a single central location.
- *Multi-currency*: Provides automatic conversion of foreign currency values into home currency values, at current exchange rates, for all financial modules, and support for computing value added taxes.

Only a few of these features are likely to be of benefit to the majority of SMEs, notably the bar code and EDI interfaces. However, as a group they indicate the main direction that MRP II development has taken over the last ten years. By including more and more functions within an integrated package, system vendors have begun to emphasize enterprise integration as the main benefit of MRP II, as opposed to its use for planning.

II.5 MRP II Systems for SMEs

It may have once been true that purchase price and computing platform cost were barriers to SME adoption of MRP II. But this is hardly the case today.[18] It is possible to buy a bare bones MRP I system that runs on a PC under DOS/WINDOWS for $995 (E-Z-MRP Lite from Alliance Manufacturing). If that's too much, there are spreadsheet templates available for $744 (from User Solutions, www.usersol.com). If that's still too much, a firm can implement MRP I on a spreadsheet at no cost using published instructions (Sounderpandian 1989).

The lowest price we've seen for a full function closed-loop MRP system is $2,995, and it supports multiple users on a LAN (E-Z-MRP). The MCS-3 system (from S.I. Inc.), advertised as the "lowest priced complete MRP II system on the market", includes a module that performs financial resource projections and sells for $13,500. The lowest priced closed-loop system with a graphical user interface seems to be MMC (Microware Corporation) at $5,000. Each of these systems has an installed base numbering in the hundreds. Other PC platform systems that have been on the market longer (e.g. Fourth Shift and Macola) have tens of thousands of installations. Out of the 208 systems on the market (CPI 1993), 75 run on PC platforms. Within this group we found 27 systems with a version that sells for

[18]Prices in this section were obtained by calling the vendors listed in (CPI 1993).

$20,000 or less and which can be installed by the user without additional consulting and training charges. Minimal PC platform cost today would run about the same as the software cost.

It must be mentioned at this point that the small MRP system market is worlds apart from the large system market. For one thing, almost all sales of large systems today are made to replace old systems whose implementation technology has been outdated (Teresko 1994). The technology used in the new systems includes relational databases, graphic interfaces, client/server distributed processing, and 4th generation implementation languages. While all of these technologies are also available in smaller systems (although usually not all together in the same system), a larger proportion of low-end systems are sold to first-time buyers. Secondly, all large systems are sold bundled with consulting and installation services that can cost more than the purchase price of the software. Small system buyers usually balk at large service fees (Greene 1995). Thirdly, large MRP II systems are being sold today primarily on their capabilities as control and information systems, rather than as manufacturing planning systems. Emphasis is placed on integrating with legacy systems, network connections with suppliers and customers, customizable screen formats, real-time data collection, customer order-entry and service support, and other ways to automate clerical and administrative functions (Parker 1984). The longer the optional feature list, the better. Small systems are still sold based on standard MRP II functionality.

II.6 Problems with MRP Methods

Despite the high levels of MRP adoption in most industrialized countries, and apparent benefits users derive, the overall efficacy of the "MRP approach" has been criticized by several authors along a several dimensions. For instance, an inevitable consequence of specifying long lead times with a high queue time component is that WIP inventory is larger than if the queueing component were less -- 10 times larger if the queue time is 90% of the total (Kanet 1988). But it is very difficult to separate the shortcomings of MRP tools and methodology from the shortcomings of traditional production management practices, because the two are so closely intertwined. There is no "law of MRP" that prescribes that the queueing allowance should be so large. Moreover, it is very difficult to tell how much the tools and methodology affect the practices. E.g. the fact that implied WIP cost is not included on standard MRP reports makes it easy to disregard when evaluating plans.

Other criticisms of MRP related to the tools and methodology include the following:

1. Built-in MRP lot-sizing algorithms are myopic. Production management textbooks present a number of sophisticated methods to try to minimize unit cost as a function of both setup costs and inventory holding costs together. Most MRP systems today provide software that implements the majority of these methods. The problem with using them is that the lot size chosen for any given item has an impact on the lot sizes of all components at lower levels in the product structure, but there are setup and holding costs at these lower levels that are completely ignored (Fogarty *et al.* 1991).

2. Projecting workloads based on preset queue times is inherently inaccurate. The times at which operations are actually performed will vary widely from the times predicted. Queueing delays between operations will be distributed in unpredictable ways depending on the shop queues that actually arise. Consequently the loads shown on load reports are likely to be wrong. (Kanet 1982; Higgins *et al.* 1991).

3. Aggregating resources into groups for planning at one level can hide large overloads on member resources at the next level down. For example, suppose group A consists of machine A1, which can mill 10 widgets per period, and machine A2, which can mill 90 per period. The group capacity for work is 100 per period. However, if most of the work at the individual resource level actually requires A1, then any workload much over 10 widgets per period will result in overload, even though higher level capacity analysis indicated feasibility. In a study reported in (Bakke *et al.* 1993), aggregate workload projection masked overloads of 120% to 150% on several member resources. See also (Barker 1994).

4. Neither the rough-cut capacity planning tool nor the capacity requirements planning tool actually generates any plans. The tools themselves do not suggest which problems one should work on first, do not propose any options, and do not recommend any options over others. Moreover, there is nothing in the MRP methodology that assures convergence on a "good" final production schedule, only a feasible one.

5. Passing the CRP test doesn't prove feasibility. The MRP methodology includes compensation for errors in the aggregate by prescribing lower level analysis to verify a higher level analysis. In particular, CRP is a lower level check on MPS feasibility after rough cut analysis. However, this idea is not extended to the detailed level. There is no shop-floor-level feasibility assessment at planning time. Hence, if resources are aggregated at the tactical planning level and heavily loaded, it is not until execution time, on the shop floor, that underlying problems are actually detected.

6. The consequences of overload are doubly devastating. First, of course, work on the overloaded resources will be delayed. In the Bakke study, simulation of the aggregate plan, thought to be completely feasible, at the member resource level showed that orders would actually be late by more than a month (an average of 23 work days). Second, expected work at downstream resources will not arrive as planned, causing these resources to be under-utilized.

Exacerbating this effect is the fact that near overload conditions in queueing systems have an exponential impact on average flowtimes. For instance, given unsynchronized work arrivals, and non-constant processing times, increasing shop resource utilization from 80% to 90% *doubles* average flowtime. Going to 95% utilization doubles it again (see (Kanet 1982) for details in an MRP context).

7. Overload detection at execution time is too late. First, there is not very much scheduling flexibility left, in the context of all the other ongoing work. Second, the costs of handling discovered overloads are considerable. Overtime, subcontracting, and part-time hires have to be arranged on very short notice, which is more costly than capacity adjustments that could have been made at the tactical or master planning levels (Bakke *et al.* 1993). Part of the need for expediting and expeditors stems from late overload detection. The consequences of not responding to overloads are, of course, missed customer delivery dates, uncoordinated flows of components to an assembly, delayed assembling, and extra WIP.

8. The MRP approach assumes that variances from plan are a normal fact of life to be dealt with, not a condition to be eliminated. The success of JIT systems has shown this assumption to be false in many cases.

9. Better and/or computerized scheduling at execution time cannot eliminate overloads arising from a truly infeasible MPS. This is a truism.

10. Better and/or computerized scheduling at execution time has no direct bottom-line benefit given a feasible MRP plan in a stable environment. Under these conditions, WIP cost is a fixed multiple of lead time. Execution-time shop floor scheduling will affect resource utilization patterns and actual flowtimes, but not the time material spends in the shop. Hence, if resource costs are fixed (e.g., the shop owns the equipment and workers are full-time), there is no benefit for either higher resource utilizations or earlier job completion (Goldratt 1986).

This statement is actually weaker than it looks because all the qualifications are essential. First, there are clear *managerial* benefits to be gained from the early visibility of future loading and completion times produced by scheduling at execution time. Second, *indirect* benefits may also obtain from execution-time allocation of machines that are more suitable to an operation for engineering or quality reasons. Third, there may also be *cost-accounting* reasons to assign certain workers and machines to certain jobs.

More importantly, a truly feasible MRP plan (one that passes CRP with fully disaggregated resources) will have enough lead time slack in it that there will be no resource overloads. Incorporating this much detail in CRP analysis is rare in practice. Also very rare in traditional practice is a stable environment, i.e. an environment in which there is no need for dynamic rescheduling due to breakdowns, scrap, late deliveries, etc.

11. Some kinds of execution-time flexibility can destroy the validity of workload projections. In particular, the common practice of setup batching seems beneficial, but produces larger lots than planned, which increases the run time of downstream operations, which can cause unpredicted fluctuations between overload and idleness. In the Bakke study, this frequently led to a combination of overtime and undertime work at the same workcenter in the same week!

12. Simplified process models hide opportunities for improvement. It is sometimes desirable to split or join lots in order to expedite an order, achieve higher utilization of resources, or reduce queues. For example, two successive operations on a lot may be performed in less time than the sum of the two lead times if part of the lot is transferred to the location of the second operation for immediate processing while the remainder is completing the first operation. Two lots are often temporarily joined into one when they both require the same setup on a machine; this saves one setup time. But, because MRP schedules are established using routings that ignore these possibilities, opportunities for WIP reduction through lead time reduction, and for increase capacity utilization, are not visible at the tactical planning level. (Kanet 1988)

13. The prescribed closed-loop process takes so much effort that planners inflate lead times to avoid the loops. Given a proposed MPS, it takes three tools and two load profile reviews, at a minimum, to verify that the schedule is feasible. For an LE with thousands of item inventories and hundreds of workcenters, performing these reviews is complex and time-consuming. Going through the sequence again is not a pleasant prospect. To avoid it, planners include extra lead time to spread the workload out of more periods (Kanet 1988). This indeed reduces the apparent capacity needed in each period, but adds to WIP cost.

14. There is no tool to support order promising based on available capacity as there is to support order promising based on available inventory. All firms that make to order are to some extent selling their capacity to perform future work as opposed to inventory that they have already made. An essential question that has to be answered for every order, then, is when can the product be delivered? No MRP tool answers this question directly, and going through the planning loops with different proposed due-dates is not viable (Hendry and Kingsman 1989).

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