Integrating Enterprise Resource Planning and Lean Manufacturing at an Automotive Components Supplier

by

JAMES SCOTT BALL

B.S. Mechanical Engineering, United States Military Academy, 1992

Submitted to the Department of Mechanical Engineering
and the Sloan School of Management
in Partial Fulfillment of The Requirements for the Degrees of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING
and
MASTER OF SCIENCE IN MANAGEMENT

in Conjunction with the
Leaders for Manufacturing Program

at the
Massachusetts Institute of Technology
June 2000

Signature of Author ______________________
Department of Mechanical Engineering
Sloan School of Management
May 5, 2000

Certified by ______________________
Professor David S. Cochran, Thesis Advisor
Department of Mechanical Engineering

Certified by ______________________
Professor Sandy D. Jap, Thesis Advisor
Sloan School of Management

Accepted by ______________________
Professor Ain A. Sonin, Chairman, Committee on Graduate Students
Department of Mechanical Engineering

Accepted by ______________________
Margaret Andrews, Executive Director of the MBA Program
Sloan School of Management

Integrating Enterprise Resource Planning and Lean Manufacturing at an Automotive Components Supplier

by

JAMES SCOTT BALL

Submitted to the Department of Mechanical Engineering and the Sloan School of Management on May 5, 2000 in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Management
and
Master of Science in Mechanical Engineering

Abstract

This thesis details a study of Enterprise Information System Strategy at Visteon, Ford Motor Company's automotive components subsidiary. Like many manufacturers, Visteon is attempting to replace numerous legacy Information Systems with Enterprise Resource Planning (ERP) software. Concurrently, Visteon is rapidly implementing Lean Manufacturing production methods in order to reduce costs, streamline operations, and improve competitiveness. This document outlines an integration framework for combining ERP and Lean Manufacturing.

The focus of this research is to identify a means of integrating the planning aspects of ERP with the execution of a Lean Linked-Cell Manufacturing System (L-CMS). Current ERP systems use an MRPII engine to perform centralized production planning and materials management. Conversely, a Lean Manufacturing execution system utilizes kanban loops and shop floor smoothing heuristics to concurrently perform decentralized production and materials control. This research outlines a framework for employing a relatively new tool, Advanced Planning and Scheduling (APS) software, as a decision support and planning system for a L-CMS execution system.

In addition to the integration framework, this document also details a qualitative and quantitative evaluation of both APS and MRPII planning systems in support of a Lean Manufacturing execution system. The qualitative analysis defines a theoretical ideal information system and then compares the 2 competing applications to this ideal. The quantitative analysis uses a discrete events computer simulation to model and compare the operational characteristics of the two Information Systems.

Thesis Supervisors:
Professor David S. Cochran, Department of Mechanical Engineering
Professor Sandy D. Jap, Sloan School of Management
Tim Evavold, Visteon (Ford Motor Company)

Acknowledgement

I would like to thank Ford Motor Company and Visteon for sponsoring this work and for their continued support of the Leaders for Manufacturing Program. A special acknowledgement goes out to my supervisor, Tim Evavold, for his help, coaching, and guidance throughout the development of this research.

I greatly acknowledge the support and resources made available through the MIT Leaders for Manufacturing Program, a partnership between MIT and major US manufacturing companies. I would also like to thank my thesis advisors, Professor David Cochran and Professor Sandy Jap for their help, advice, and insightful guidance.

I would also like to thank the LFM class of 2000 for a great two years of learning and camaraderie. In particular, I would like to thank the group whose internship was located in Detroit, Abizer Gaslightwalla, Rob Giammatteo, and Matt Bromberg.

I would like to thank my parents and family for their support and encouragement over the years. I would not be in the position I am today without their continued guidance and mentorship.

Most importantly, I thank my wife Wanda who has supported, challenged, and encouraged me throughout my academic and professional career.

Table of Contents

Table of Figures

Table of Tables

1 Overview

1.1 Introduction

The automotive components industry has undergone a metamorphosis over the past few years. With industry consolidation and fierce price competition, the remaining suppliers are viciously competing in a race to develop a complete product portfolio for their customers. Original Equipment Manufacturers (OEMs) are leveraging this new market competitiveness to demand more out of their supply base in order to increase their own competitiveness by decreasing lead times and moving to a direct sales channel facilitated by the internet.

In addition to the consolidation, growth, and new customer requirements, component suppliers are attempting to integrate a new production methodology into their business in order to ensure their future competitiveness. Dubbed "lean production" by the Massachusetts Institute of Technology International Motor Vehicle Program, the new concepts are dramatically different from the mass production manufacturing systems which are prevalent throughout the entire domestic automotive supply chain [Womack, et al, 1990, 13].

The convergence of many of the industry dynamics described above takes place in the corporate Information Technology (IT) department. The IT shop is responsible for providing the processes and information systems to support the new customer requirements and new manufacturing processes. During this value chain transformation over the past few years, the automotive component supplier's IT organization has also undergone significant change. Previously, the departments developed and maintained proprietary information systems using internal resources. Although this approach fulfilled very specific requirements, it is becoming increasingly difficult and expensive to maintain and upgrade these individual systems. The new "best practice" sweeping the industry is to replace these so-called legacy systems with packaged software provided by enterprise software vendors. Automotive component supplier's IT departments now spend the majority of their time and resources choosing, configuring, installing, customizing, maintaining, and upgrading vendor provided software.

This study focuses on enterprise level information system strategy at a Tier-1 Automotive Components Supplier. Visteon Automotive Components is a wholly owned subsidiary of Ford Motor Company. Visteon produces automotive components for Ford's Vehicle Operations (final assembly) and Powertrain divisions. Visteon is currently comprised of 5 divisions, 80 plants and 78,000 employees in over 20 countries. Since its inception in the fall of 1997, the subsidiary has worked aggressively to seek non-Ford customers for its integrated automotive components in an attempt to distance itself from its corporate parent. Although the spin-off has not been executed, the subsidiary has been preparing itself for independence for the past three years. To support their independence and new customer requirements, Visteon is replacing many of its legacy information systems with an Enterprise Resource Planning (ERP) software package from the German software powerhouse SAP. The research for this thesis was conducted during the author's six-month internship as a member of the ERP implementation team.

This documents details the attributes of a Manufacturing Information System which complements and supports lean manufacturing. The focus of the research was on production planning and materials management, which are the two key functional differences between a mass production manufacturing system and a lean production manufacturing system. Although many of the aspects of this thesis are directed at the specifics of the automotive industry, the general architecture and systems level approach should be fairly universal.

The study concludes with three main points:

1) MRP was designed to support a Mass Production System Design and therefore is not appropriate for a Lean Production System Design.
2) The Manufacturing Planning System needs to be functionally independent from the Manufacturing Execution System.
3) Manufacturing Information Systems require both a Database Transaction System and a Memory Resident Decision Support System.

1.2 Motivation

The goal of this thesis is to provide a theoretical framework for integrating the high level ERP System strategy with the low level lean manufacturing production system strategy. The author entered the Visteon IT organization six months after the initiation of the SAP implementation project and thus the decision to install SAP had already been made. The SAP project (Project Vista) initially focused on non-manufacturing processes involving customer service, finance, and accounting. The thesis research began while the IT staff was in the process of deciding how to replace Visteon's legacy MRPII system, Centralized Manufacturing

Management System (CMMS), which currently handles all of Visteon's manufacturing transactions.

CMMS is a legacy system developed by Ford to automate the transactions involved in the company's Mass Production methods. The main motivation for replacing CMMS is that the Information System could not sustain Visteon's anticipated future growth. As Visteon was a vertically integrated subsidiary of the Ford Motor Company, CMMS was designed to service only one customer (Ford). Therefore, limitations in the software functionality made it very difficult to perform the customer service functions necessary to support Visteon's future customer base. In addition to supporting sales growth, the ERP system had to fulfill the following requirements:

- Replace several Ford legacy systems (finance, accounting, sales, part number databases, etc) to reduce IT system maintenance costs
- Provide data separation and security for customer design data
- Support the Ford Production System (FPS- Ford's lean manufacturing implementation methodology)

As a member of the Plan, Manufacture, and Deliver (PMD) subteam of the SAP implementation, the author was assigned the task of refining and evaluating two proposed Information System architecture designs outlined by the PMD team leader.

- The first design was the "stock" SAP R/3 architecture which utilizes an integrated MRPII planning and scheduling engine.
- The second design called for the use of Advanced Planning and Scheduling (APS) software as the planning and scheduling engine for the ERP transaction system.

Although the team had invested a fair amount of time researching both systems, the company faced several uncertainties with the APS configuration. While performing due diligence on the design, the PMD team was able to find very few examples of manufacturers utilizing a system architecture similar to the APS-ERP architecture. Although several companies are using APS in an Finite Capacity Scheduling role, the team was unable to find an example of APS used as a planning tool to support lean manufacturing. This perception was re-enforced by feedback the PMD team leader received at several industry conferences.

Despite the difficulty involved with researching similar examples of the proposed design, the potential rewards seemed promising. Marketing literature provided by software vendors claimed astronomical customer success stories. Although these successes were quite convincing, the team had not refined the information system design enough to quantify the system impact. The author's assignment was threefold:

- Define an "ideal" planning system (with or without a computer) to support lean manufacturing and compare the two competing designs to this ideal
- Refine the APS configuration
- Develop a quantitative comparison of the two systems

1.3 Thesis Scope

An Enterprise Resource Planning (ERP) System is a very complex software program. The latest version of SAP R/3 consists of over 8000 configuration tables. This thesis does not address the technical details of the computer hardware or software configuration. Similarly, detailed mathematical proofs of the proposed production system were not included to avoid the complexity of operations focused scheduling theory. The scope of the thesis is therefore focused on the managerial strategies and business implications of the entire production system as related to manufacturing. Specifically, the document is focused on the Production Planning (PP) and Materials Management (MM) aspects of the production system design. Additionally, the thesis does not detail the impact of product architecture, cell layout or machine tool design. The research assumes that Visteon's FPS efforts will result in a Lean, Linked-Cell Manufacturing System (L-CMS) and therefore the author focused his research on business strategy and information system design to support the L-CMS [Black, 91]. Lastly, a detailed financial analysis model was not developed to support the business case for the production system design. To do so would have required extensive data analysis on inventory flow and manufacturing processes involving thousands of products in 80 plants.

1.4 Reader's Guide to the Thesis and Overview of Remaining Chapters

The thesis is broken down into three parts. The first two chapters outline background information for the assignment and further defines the scope of the problem addressed. Chapter 3 outlines the functionality of an ideal Manufacturing Information System. Chapters 4 and 5 address the detailed Information System design and its subsequent evaluation. Chapter 6 reviews the managerial issues involved and makes recommendations for further research on the Information System tradeoffs.

Overview of Remaining Chapters:

Chapter 2 discusses several facets of the industry dynamics and business environment which Visteon faces. In addition, the chapter outlines the evolution of manufacturing software.

Chapter 3 provides the reader with an overview of Production Planning and Materials Management in an MRP system and a lean manufacturing system. Readers familiar with both Manufacturing System Designs may want to focus on the section that details the ideal system configuration.

Chapter 4 details the specifics of the proposed ERP design that utilizes an APS planning engine and then compares this design and MRPII to the ideal system described in Chapter 3.

Chapter 5 describes the computer model developed to quantify the system comparison. A discrete event simulation package was used to model the production environment and a simple computer program was used to model the two different IT configurations (MRPII and APS).

Chapter 6 addresses many of the managerial issues, project risks and strategic implications of the system design.

1.5 Literature Review

A literature review of journals, books, past theses, and on-line databases was conducted continuously throughout the internship and thesis development. Although the author found numerous articles and books written on both manufacturing software and lean manufacturing, little material on lean information systems was available. The subject and keyword searches include: lean manufacturing, Toyota Production System, MRP, ERP, MRPII, APS, production scheduling, production planning, production smoothing, materials management, simulation and e-commerce. The results are grouped into the following categories

1) Lean Manufacturing and Supply Chain Topics
2) Manufacturing Software Topics: MRP, MRPII, ERP, and APS
3) Operations Research Publications and Textbooks
4) Simulation Topics

1.5.1 Lean Manufacturing and Supply Chain Topics

1.5.1.1 Lean Manufacturing

There is no shortage on lean manufacturing literature. There is very little on lean IT systems, however. The best material the author found on lean information systems was contained in Monden's book on the Toyota production system. Although Monden attempts to describe the technical architecture of the system quite extensively, additional detail on the Actual Performance subsystem and the planning subsystem would have been of great help [Monden, 1998, 292]. Specifically, detail on the communication processes used to refine the monthly production forecast sent from Toyota to its suppliers. Womac's *Lean Thinking* made reference to the use MRP for forecasting and supplier communications [Womack et al, 1996]. A paper by Benton and Shin highlighted some of the current research of integrating JIT and MRP [Benton & Shin, 1998]. Professor David Cochran's Doctoral Dissertation provided an outline for defining and designing lean production systems [Cochran, 1994]. Kent Bowen's article on the DNA of the Toyota Production System highlighted some cultural learning issues associated with TPS [Bowen, 1999]. Shigeo Shingo provides an excellent analysis of load leveling and the importance of continuous improvement [Shingo, 1989]. Lastly, re-reading Ohono's book provided new clues as to how the culture evolved over 50 years at Toyota [Ohno, 1988].

1.5.1.2 Supply Chain

Many of the concepts and models developed in Professor Charley Fine's book *Clockspeed* were also influential [Fine, 1999]. Specifically, Fine addresses the dynamics of industry oscillation between vertical and horizontal organization and integral and modular product architecture. This model helped explain the auto industry's shift away from vertical integration as well as the movement to a modular product architecture [Miller, 2000].

1.5.2 Manufacturing Software Topics: MRP, MRPII, ERP, and APS

As with lean manufacturing, numerous papers, books, articles, and marketing material was available on manufacturing software. Some of the most useful material came out of APICS and Operations Research journals. The Vollman text *Manufacturing Planning and Control Systems* was used to study MRP in great depth [Vollman et al, 1997].

One of the most useful papers in regards to my subject was a paper written by Professor Jeff Liker from the University of Michigan. This paper provides a high-level framework of how APS can be used as a planning system in conjunction with a lean manufacturing execution system [Liker, 1999]. Chapter four of this document extends Liker's framework and provides more detail as to how the planning subsystem interacts with the manufacturing execution subsystem.

1.5.3 Operations Research Publications and Textbooks

The production scheduling, smoothing, and materials management literature search resulted largely in Operations Research (OR) type literature. The author made reference to the bibliography of several OR textbooks to accelerate this search. The textbook that proved most useful was Hopp and Spearman's *Factory Physics*. *Factory Physics* outlines a very useful pull production planning framework which was studied extensively. The MRP-C concept from the book was used to help define the Functional Requirements (FRs) of the ideal IT system.

Scheduling is a very mathematically complex topic. As such, the literature on the subject is very dense, written primarily by mathematicians for mathematicians. The two topics that continuously appeared were the minimum makespan job shop problem and flow time minimization in a multiple machine flow shop. Due to its complexity, dynamic scheduling of multiple machines is classified as Non-Polynomial, hard (NP-hard). An NP-hard problem is currently extremely difficult to optimize due to the exponential number of combinations. The author did not find any of the scheduling literature particularly useful except to clarify that scheduling and sequencing is a difficult subject and that simple system designs are more robust.

The production smoothing algorithm in chapter five is borrowed from the paper by Cruickshanks, Drescher, and Graves. This algorithm uses inventory status, forecasts, and capacity rates to determine an optimal smoothing sequence [Cruickshanks et al, 1984].

Materials Management (MM) literature was less extensive and difficult to separate from production planning and scheduling. Most of the MM papers and books revolved around end item/retail inventory management and purchasing that was of limited value to this thesis. The literature most useful came from lean manufacturing and MRP books [Monden, 1998], [Sipper, 1997], [Bollmann, 1997] and [Proud, 1999].

1.5.4 Simulation Topics

Most simulation literature deals with a very specific usage of simulation (very low level evaluations) and the mechanics of how to do it. The simulation package used for this research was a relatively simple, visually oriented Microsoft Windows application (Simul8). Useful information was obtained from the software vendor's web site (www.simul8.com) as well as the Ford Simulation Help desk. A web keyword search for "simulation" revealed a vast amount of user group listings containing C source code and random number libraries which were not useful. This thesis utilizes the simulation modeling procedure outlined in Harrell's book *Simulation Made Easy* [Harrell, 1995]. In addition, the author reviewed past LFM theses that used simulation in some form. Two of the more successful uses of simulation were [Kippel, 98] and [Myron, 96].

2 Automotive Components Business Environment

This chapter outlines the competitive environment of the automobile industry and provides a backdrop to help delineate the impact of Visteon's Information Technology decisions. The goal of the first section is to 1) identify the sources of power in the automotive value chain and then 2) point out the impact of the evolving value chain on the component suppliers. The last section provides a quick synopsis of manufacturing software evolution and the automotive manufacturer's IT department.

2.1 Automotive Industry Dynamics

2.1.1 Automotive Industry Drivers

As tier 1 suppliers to the very large OEMs, automotive component suppliers currently have little weight to leverage against their customers. Individual contracts can equate to hundreds of millions of dollars, and thus the OEMs demand and receive excellent customer service. Domestic industry policies often include the provision of customer service clauses into supplier contracts. With some plants earning up to $30,000 per minute, there is a very strong cultural emphasis on ensuring enough component inventory is on hand to prevent an OEM assembly plant shutdown. A geographically distributed supply base complicates the matter as there can be weeks of component inventory in route between Tier 1s and the OEMs. With these dynamics in mind, this section outlines two drivers in the OEM market and then demonstrates how these drivers impact the component suppliers. The two key drivers in the automotive industry are ***the Direct Sales Channel and Increased Demand for Financial Performance.***

2.1.1.1 Evolution of the Direct Sales Channel.

In an attempt to get closer to the customer, OEMs are beginning to explore use of the Internet as a means to better meet customer needs. The advantages of the direct sales channel are easy to identify: a reduction in the current 60+ days of channel inventory, less obsolescence costs, reduction in incentive plans, and increased customer satisfaction are just a few advantages of the direct model. Suffice to say, the success of Dell's direct model has set a new standard for make to order manufacturing [Dell, 1999, 21]. Dell can assemble a computer to a specific customer order and have it delivered within three days. In the automotive industry, a custom order requires at least 21 days. Even though current state franchise laws prohibit the manufacturers from selling directly to the consumer, Forrester research predicts that the Internet will in some way influence over half of the 16 million cars sold in the US in 2003 [McQuivey, 1999]. A recent HBR article notes that unless OEMs begin to offer configurable choices on line, infomediaries could potentially insert themselves into the value chain and reduce the manufacturer's power [Slywotzky, 2000, 5]. CarsDirect.com and Cars.com are working to do just this. OEMs are not taking these threats lying down however. Ford has signed agreements with *Yahoo*, *Microsoft Carpoint*, and *Priceline.com* while GM has formed an agreement with *AOL* in addition to launching its own new division, e-GM, to focus on the opportunity [Bloomberg, 2000]. Regardless of the marketing hype and franchise laws, the OEMs will exert much less control over this yet defined sales channel.

<u>Effect of the Direct Sales Channel on Component Suppliers</u>

- **Reduced forecasting horizon and order to delivery lead-time.** A direct sales channel means that the majority of orders flowing through the manufacturing system will be make to order (MTO) instead of build to forecast. In a MTO environment, order to delivery speed will be an important factor influencing customer satisfaction. A recent ComputerWorld article quoted Ford stating that it hopes to deliver on the 3-day car by 2004 [Ulfelder, 2000]. Component suppliers will need to redesign their production systems to meet these new customer requirements.
- **Increased volume and mix volatility**. OEMs who respond to customer orders over the internet will retain less control over the order stream (mix volatility). Additionally, customer demand will not be buffered by 60 days of dealer inventory and thus increased volume volatility will result. Assemblers and suppliers will need to adapt their production system to prepare for this in order to smooth and level the demand as much as possible.
- **Increased ILVS and JIT requirements.** ILVS (In-Line Vehicle Sequencing – the delivery of components in the same order as the final assembly production sequence) is an important facet of TPS. For a complete review of ILVS, refer to [Moeller, 1997, 15]. Inferring from previous lessons in the Auto and Computer industry, increased JIT requirements results in the transfer of mix and volume variability backwards onto the supply base.

2.1.1.2 Increased Demand for Financial Performance.

The Internet is not just altering the sales channel; it is changing the expectations of financial performance as well. MIT Professor Charley Fine points out that the decreasing cost of information processing and transmission has caused the pace of every industry to increase [Fine, 1999, 27]. The auto industry is certainly no exception. As of late, OEMs have struggled to increase their stock valuations despite record years of profitability and sales. In an attempt to increase their Return on Assets (ROA), the two remaining domestic OEMs have planned to spin off their component manufacturers. The spin offs will simultaneously increase competition in the supply base and reduce the OEM's operating assets. In an another attempt to reduce final assembly labor and product development costs as well as decrease time to market, OEMs are pushing an increasing amount of design work out into the supply base and requiring entire integrated component assemblies from their suppliers. Component suppliers will therefore provide entire integrated "modular" systems configured to customer order. For example, Delphi Automotive recently won an Excellence in Logistics award from Transportation & Distribution magazine for its innovative supply system that delivers fully assembled modular cockpits to Mercedes-Benz U.S. International's (MBUSI) assembly plant in Tuscaloosa, Alabama, just-in-time and ILVS [PR Newswire, 1999].

Effect of Financial Performance on Component Supplier

- **Spin-off.** The spin-off of the suppliers has sparked a race for market share and industry consolidation in an attempt to create a "one stop shop" for integrated system modules.
- **Modularity.** Automotive suppliers are increasingly becoming systems integrators as well as individual component fabricators. Configured modules result in very complex supply chains and component suppliers will need to develop competencies around supply chain management much the way the OEM assemblers have.
- **Decreased Product Development Cycles and Product Lifecycles.** The time pressures on the OEMs directly translate to the component suppliers.

2.1.2 Supply Chain Evolution

The above discussion has outlined several shifting dynamics within the automotive supply chain. The new distribution channel and financial pressure exerted on the OEMs has caused them to search for new ways of decreasing product development and order-to-delivery time. This time compression results in a need for a more horizontal industry structure and an increasingly modular product architecture. A modular product architecture for an automobile means that contracts for entire subsystems will be awarded for both the design and manufactured supply. For example, an OEM will award contracts for a vehicle's entire fuel system instead of individual fuel components. Modularity results in design efficiencies as well as manufacturing efficiencies as module suppliers can reuse designs and tooling for individual components. Fine points out that this shifting industry structure and product architecture is a natural business cycle and several industries have gone through similar oscillations [Fine, 1999, 46]. While the OEMs are evolving into a horizontal/modular structure, the newly empowered component suppliers are evolving into a vertically integrated industry that produces a more integral product architecture. The industry is already experiencing a rapid consolidation to help facilitate this integrality [Miller, 1998]. Supply Chain evolution is not a minor point to consider. Companies must actively seek their niche in the value chain and work to create processes, technology, expertise, and a culture to defends their niche [Vasilash, 1998].

2.1.3 Automotive Component Supplier Target Competencies

Given the component industry drivers and supply chain evolution outlined above, this section outlines target competencies automotive component suppliers must master to be successful. Many of these competencies span departmental boundaries in the organization and thus require multiple dimension concurrent engineering between product development, manufacturing operations, marketing and sales, and purchasing/supply chain management. The key to developing these competencies is to identify the sweet spot in the value chain and then reinforce success by developing metrics, processes and projects that will drive the organization to the goal [Hamel & Prahalad, 1987].

2.1.3.1 Target Competency 1: Velocity

Given the make to order environment, successful companies in this space will design their entire production system around time compression. Processes must be streamlined, bureaucracy reduced, and authority and autonomy pushed down in the corporate hierarchy. Specifically, time must be compressed in the following functions:

- Order to Deliver Time
- Product Development Time
- Manufacturing Process Development Time
- RFQ Response Time
- Supplier and Customer Communications Time

2.1.3.2 Target Competency 2: Manage product and process transitions

Fortunes are made and lost during transitions. Michael Dell notes "looking for value shifts is probably the most important dimension of leadership" [Magretta, 1998, 84]. The most difficult task facing component suppliers is to manage the organizational and product architecture transitions and drive the company to the point in the value chain where they can gain a competitive advantage. To do this, companies must develop organizational metrics for their lean manufacturing implementation and Information Technology projects to help management guide them in the correct direction.

2.1.3.3 Target Competency 3: Intelligent and Rapid Request for Quote (RFQ) Response

Three-dimensional concurrent engineering is the intersection of supply chain design, product development engineering, and manufacturing system engineering. With decreasing OEM product development cycles, component suppliers need to understand their costs and existing plant capabilities extremely well so as to quickly and intelligently respond to customer RFQ requests. OEM B2B electronic commerce eMarketplaces only reinforce this requirement as communications inefficiencies are removed from existing business processes. Intelligence means that only profitable or strategic project quotes emerge from this difficult process. To do this, companies must develop three-dimensional concurrent engineering decision support Information Systems that span multiple departments to help with this process.

2.1.3.4 Target Competency 4: Assemble to Order (ATO)

Decreasing order to delivery times and high component configuration complexity requires product architecture, manufacturing processes, and information technology that support ATO. Very complex configuration will require a customer order before production and thus the companies with the shortest manufacturing lead times will have a significant competitive advantage. Supplier plants that deliver configured subassemblies JIT will begin to resemble OEM assembly plants. Many supplier assembly operations will need to relocate near OEM assembly plants in order to decrease transport time. All supplier plant manufacturing processes and fabrication operations must efficiently feed JIT component assembly processes. Component suppliers must manage the internal and external supply chain very effectively to support ATO.

2.1.3.5 Target Competency 5: Integrate New Products and Customers

Markets are awarding automotive component suppliers with relatively high price to earnings ratios in anticipation of operational economies of scale. Component suppliers must respond by leveraging existing equipment, technology, and people. Increasing volume and mix volatility means that plants must design Production Systems that are flexible enough to respond to this stochastic environment.

2.2 Manufacturing Software

2.2.1 Automotive Manufacturing Software

Information Technology is not a foreign concept to the automotive industry. With incredibly high fixed costs, car companies have spent billions upon billions in software to keep their factories running as efficiently as possible. With unbelievable scale, very specific requirements, and an immature manufacturing software industry, car companies were forced to develop their own internal systems. Until recently, automotive IT departments consisted of hundreds of software engineers and outside contractors.

A maturing software market and the increasing power of desktop computers have changed the financial dynamics of the automotive IT department. Current batch oriented legacy systems which run on mainframe computers are very expensive to maintain and very difficult to modify. Like most other manufacturing industries, automotive suppliers are exiting the software development business and focusing on implementing packaged software supplied by software vendors and technology consulting companies.

2.2.1.1 Project Vista — Visteon's SAP implementation Project.

Visteon's decision to install SAP is representative of how companies are transitioning away from legacy software systems. In 1997 Visteon decided to replace their legacy MRPII system CMMS with packaged ERP software. To put the CMMS replacement decision in context, CMMS was custom developed by Ford over a period of 10+ years in an attempt to digitize the company's mass production methods. Although the time and cost investment of the information system is significant, the real impact is the processes and culture that have evolved from the workflows embedded in the software. Each day, thousands of production employees get a printout of their production schedule and material requirements while management receives daily reports to evaluate production efficiency.

2.2.2 MRP to ERP: The Evolution of Manufacturing Software

MRP (Material Requirements Planning) evolved out of the adoption of computers to solve inventory management problems in the early 1960s. The main originator of MRP was Joseph Orlicky of IBM who published his collection of notes on the subject in 1974. Orlicky's development of the MRP algorithm was a significant advance over previous order point systems for two reasons:

- MRP separates independent demand from dependent demand in a production system
- MRP time phasing approach provides an excellent planning mechanism

The adoption of MRP systems by manufacturing companies was extremely successful in part thanks to the American Production and Inventory Control society's "MRP Crusade." Although MRP was an advancement over current practices, Orlicky himself identified two main shortcomings of the system: **Fixed lead times and infinite capacity**. Despite these system shortcomings, the development of MRP was a significant accomplishment for another reason: very efficient use of computer memory. In the early 1970s, Random Access Memory was extremely expensive. The MRP algorithm is well tuned to work under this constraint. [Orlicky, 1974, 40]

MRPII (Material Resource Planning) was the logical extension to MRP. MRPII "closed the loop" on MRP by incorporating Capacity Requirements Planning (CRP) which takes the MRP output and determines if the schedule is realistic [Wight, 52]. In addition to the feedback loops, MRPII included functionality for purchasing, marketing, finance, engineering, and shop floor control. MRPII systems were also widely accepted, by 1989, thousands of US companies supported a $1.2 billion MRP market [Hopp and Spearman, 1996, 173]. Despite the validity of the claim that CRP fixed the infinite capacity problem, CRP still suffers from the fundamental problem of assuming fixed lead times. For an excellent review of MRP, MRPII and CRP, see Thomas Vollman's excellent text on Manufacturing Planning and Control Systems [Vollman, et al, 1997]. Please note: the term MRP and MRPII are used interchangeably in this thesis. In most cases, MRP refers to the original MRP algorithm, MRPII describes the entire "closed-loop" computer application. Also note, MRPII is an ERP subsystem and this thesis references the term in that context.

FCS. A further evolution of manufacturing scheduling systems was the Finite Capacity Scheduler (FCS). A finite capacity scheduler takes the output of the MRPII system and attempts to create a detailed schedule which fits into existing plant capacity. Although FCS systems are only a "bolt on" to an MRPII system, they do represent an advancement in algorithm design and computer system architecture.

ERP (Enterprise Resource Planning) is yet a further extension of the original MRP system both in technical evolution and functionality. An ERP system is a technical evolution because it utilizes modern relational database management systems, fourth-generation languages, and client-server architecture. Functional enhancements include increased financial features, distribution planning, human resource management, and strategic planning. In short, an ERP system is the application which handles enterprise wide planning and business transactions. Current generations continue to use MRPII as the Production Planning and Materials Management engine. The worldwide ERP market is enormous. The market is lead by German powerhouse SAP which reported revenue of over $5 billion in 1999.

2.2.3 APS

Advanced Planning and Scheduling (APS) is a new concept in manufacturing software that builds upon some of FCS's technical advances in software architecture and algorithm design. In short, APS is the combination of advanced algorithms and memory-resident processing. As opposed to a transaction system which must serve thousands of users concurrently, most APS systems run on servers with huge amounts of memory and serve only a few users running a single model at a time. Many APS software vendors note that APS algorithms can simultaneously account for material availability and machine capacity and therefore are superior to MRPII algorithms [Layden, 1999]. A recent AMR article reported that many ERP vendors are in the process of replacing their MRP planning engines with APS [Bermudez, 1998].

One note on APS: As with MRP/MRPII/ERP, APS can have multiple meanings. For this thesis, APS is considered a general term which represents constraint-based, memory resident, manufacturing scheduling software. The term APS can also be used to describe Supply Chain Management and logistical optimization tools, but this thesis will not consider APSs' use in that context.

2.2.4 Chapter Summary

This chapter outlines the dynamics of the automotive components industry and the evolution of manufacturing software. Both markets are evolving rapidly and the component suppliers will need to make significant strategic decisions on how they will employ software to support their manufacturing processes. The supply chain automotive component suppliers face is also evolving rapidly and the future of the industry seems to be shifting towards consolidation. The chapter also presents target competencies component suppliers will need in order to successfully compete in the evolving make to order automobile marketplace. The next three chapters are a technical analysis of the manufacturing software decision outlined above.

3 Production System Design: Production Planning and Materials Management

This chapter details the operational aspects of the Production System Design (PSD), specifically that of the Manufacturing Planning and Control (MPC) and Manufacturing Execution System (MES). To begin, the first section defines a useful framework which is used throughout the remainder of the thesis. The second section then briefly outline the evolution of MRP-Mass and lean manufacturing in order to point out some of the cultural artifacts of both systems. The third section conducts an in-depth look at two operational processes in both system designs: Production Planning (PP) and Materials Management (MM). Lastly, the final section defines an ideal hybrid solution which draws on the strengths of both MRP and lean manufacturing

3.1 Production System Design

A Production System (PS) is an enterprise view of a manufacturing company and involves all processes necessary to support the task of converting raw material into physical products for customers. Production System Design (PSD) is the physical design of the enterprise system. A Manufacturing System (MS) is the sub-process of the PS that converts material and information into products for consumption [Black, 1991, 17]. Similarly, Manufacturing System Design (MSD) is the physical design of the Manufacturing System. A Manufacturing System (MS) is a complex arrangement of physical objects characterized by measurable parameters which may be used to control the system performance [Cochran, 1994, 41]. Physical objects include people, machines, material, energy, and information. Measurable parameters include production rates, quality rates, unit cost, customer satisfaction, and on time delivery percentage. Figure 3-1 outlines several functions of the PS.

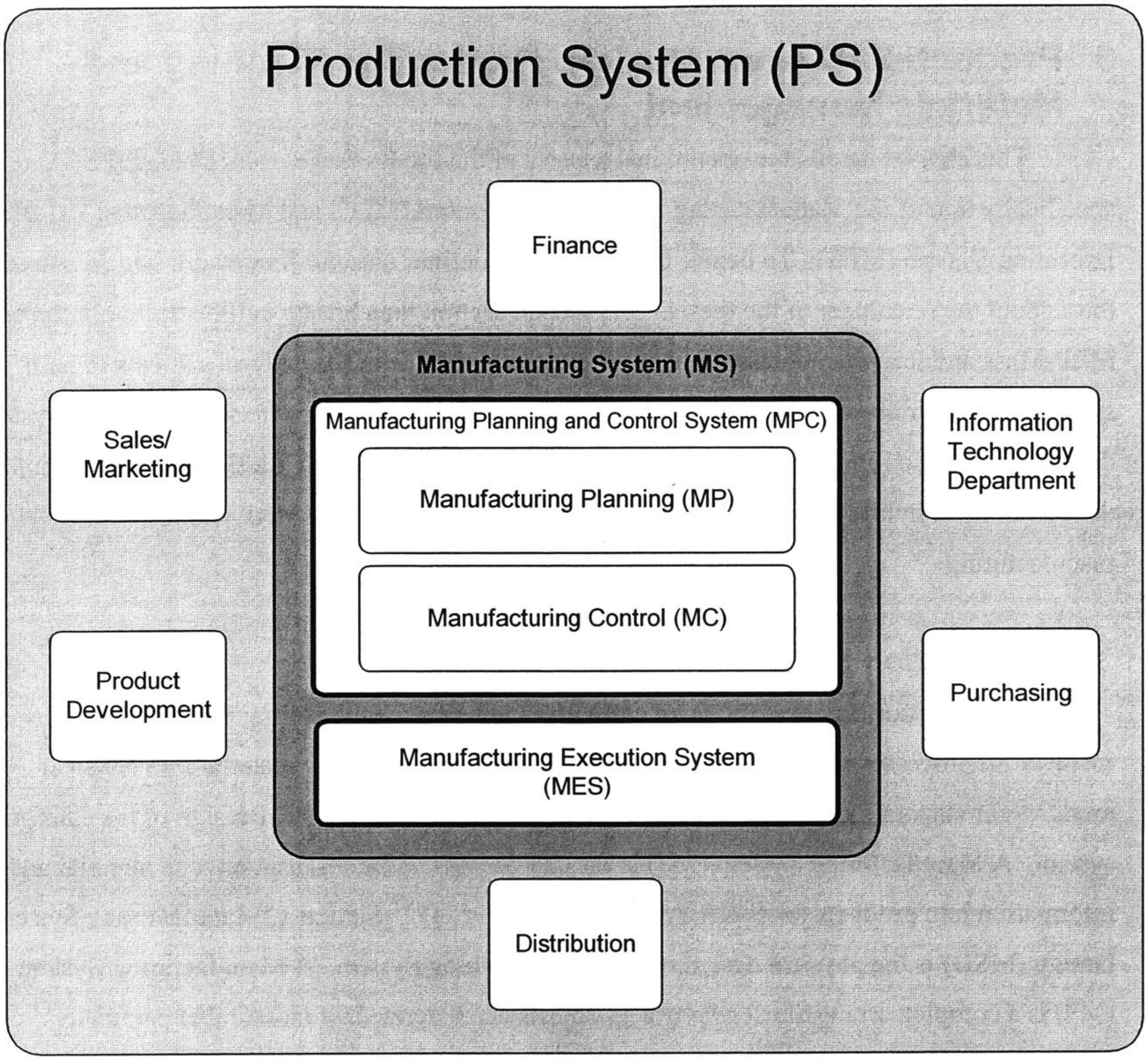


Figure 3-1 Enterprise View of a Production System

In a manufacturing company, all company processes and departments support the Manufacturing System (MS) as the MS is the function that adds value to the product which benefits the customer. A MS interacts with suppliers and customers in the supply chain as depicted in figure 3-2.

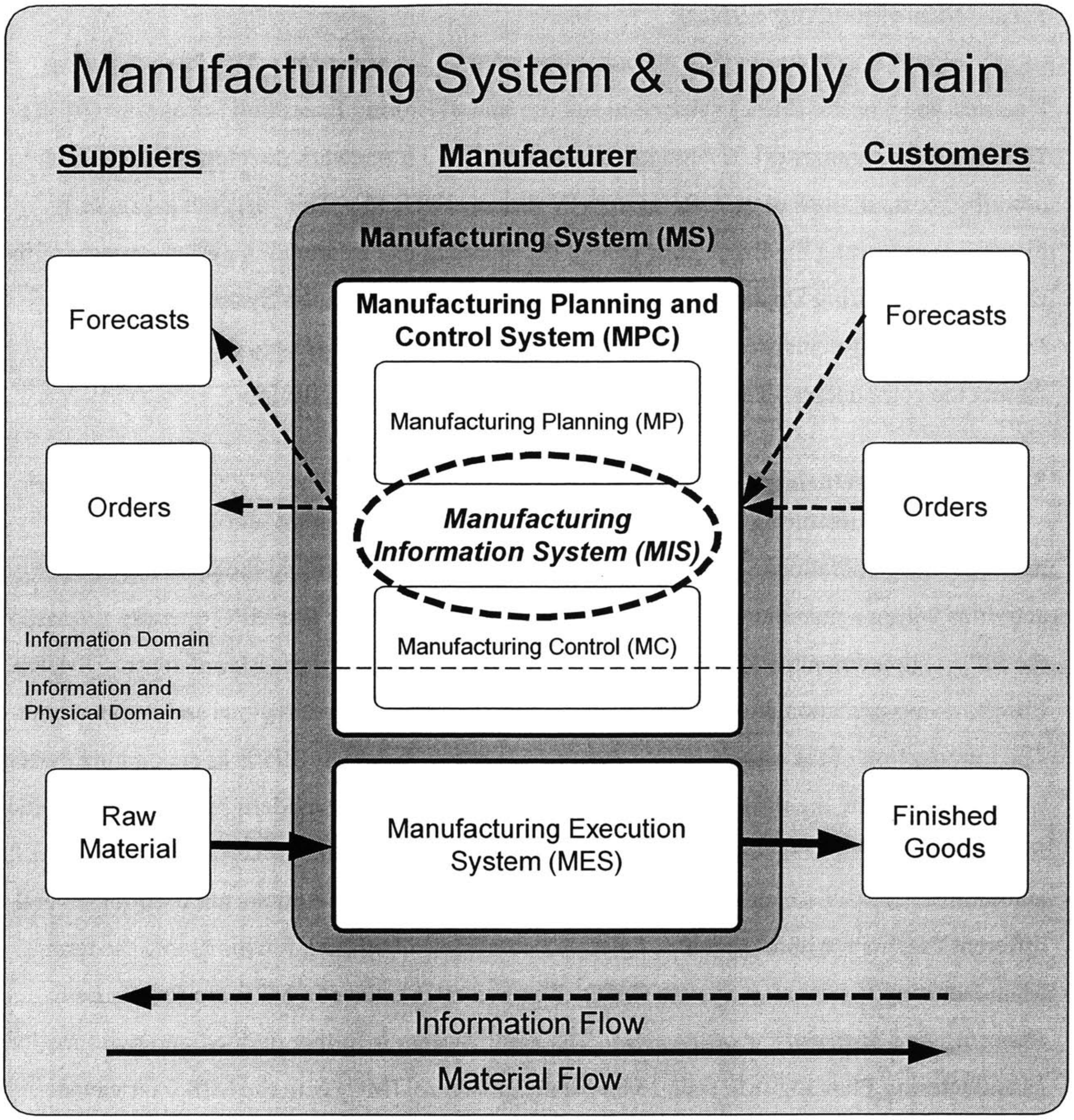


Figure 3-2 Manufacturing Planning and Control System

As shown in figure 3-2, the MS operates in both the information and physical domain and converts forecasts, orders and raw material into finished goods for channel customers. Additionally, the MS communicates planning and order information to suppliers. Figure 3.2 is a general depiction of the MS process and is loosely based on an MRP MPC. This thesis further defines the MPC framework and adapts it as necessary in future sections. One key aspect of an MS is that information flows in the opposite direction of material.

3.1.1 Manufacturing System

Figure 3-2 above also identifies the two subsystems of the MS: The Manufacturing Planning and Control (MPC) subsystem and the Manufacturing Execution Subsystem (MES). This theoretical framework is a modification of the MPC framework developed by Vollman to describe the operations of an MRP system [Vollman, 1997, 15]. This research is primarily directed at extending the framework around the planning and information system aspects of the entire Manufacturing System to include the Manufacturing Execution System. Note: Manufacturing Systems are very complex, dynamic organisms; it is very difficult to easily dissect the components. The following is a simplistic MS decomposition.

3.1.1.1 Manufacturing Planning and Control System (MPC)

The Manufacturing Planning and Control System (MPC) plans and controls manufacturing operations. MPC is a generic framework for describing the planning and control activities within a manufacturing organization [Vollman, 1997]. The MPC operates primarily in the information domain and facilitates all information activities for the Manufacturing System. Prior to computer automation, the MPC activities were paper based, tedious and cumbersome. The introduction of the computer into this process began in the late 1950s as accounting systems were extended into the manufacturing realm [Orlicky, 1974]. All modern MPCs contain some form of computer system to assist in information processing and this is certainly the case for the automotive industry which is heavily computerized. Although computers are used for several different functions within the MPS, figure 3-2 combines all of these functions into the term Manufacturing Information System (MIS). The two main tasks of a MPC are ***Production Planning and Materials Management.*** The MPC System is further divided into two functions: Manufacturing Planning (MP) and Manufacturing Control (MC) with the MIS interleaved between the two.

3.1.1.1.1 Manufacturing Planning (MP) Function

This function facilitates all aspects of manufacturing planning. MP resides only in the information domain and serves as the central point of contact for all supporting activities (finance, accounting, sales, etc.) which interact with the MS. MP is performed at the area, plant and enterprise level. The MP function is most often centralized and involves many different aspects of the MS to include capacity planning, workforce sizing, and manufacturing performance evaluation. As the MS is an abstract conglomerations of concepts and processes which occur in a manufacturing company, the planning system can either be centralized, decentralized or a hybrid; computer automated, non-computer automated, or a hybrid. MP resides strictly in the information domain, that is no physical assets other than information are necessary to perform the task.

3.1.1.1.2 Manufacturing Information System (MIS)

The Manufacturing Information System (MIS) is the computer information system (or collection of computer systems) which support the MP and MC functions. The MIS facilitates information processing and communication between all supporting activities and thus acts as a central repository for all manufacturing information. In the domestic automotive industry, the MIS is the part of the MPC that receives input from customers in the form of forecasts and orders via Electronic Data Interchange (EDI), processes the information, and then communicates forecasts and orders to suppliers via EDI. The MIS is the main link between the MP and MC functions as it takes the customers input, calculates the production parameters and schedules, and then communicates the output to MC. The Manufacturing Information System is not computer automation for the shop floor (also known as Computer Integrated Manufacturing–CIM), it only performs calculations and facilitates communication between MP and MC, suppliers and customers.

3.1.1.1.3 Manufacturing Control (MC) Function

MC is the subsystem of the MS that uses the information from the MIS to control manufacturing execution. This system is also known as shop floor control. MC occurs at the area level and below but it is primarily concerned with intra-cell materials movement. MC is responsible for ensuring that the correct quantity and mix of parts with the right quality is delivered to the customer at the correct time. Once a production plan is released onto the shop floor, the MC is responsible for completing the production. The MC resides in both the information and physical domain. The MC operates in the information domain due to its reliance on production information in the form of schedules and customer orders. The MC also operates in the information domain as it uses the status of physical production equipment and personnel to control the flow of material through the MS. The MC must be robust to any type of demand volatility or production problems so as to ensure MES stability.

3.1.1.2 Manufacturing Execution System (MES)

MES is the subsystem of the MS that converts raw material and energy into physical products for consumption. The MES consists of people, machines, material, energy, and information. The MES is controlled by the MC function of the MPC. As with the MC, the MES resides in both the physical domain and the information domain. One important domain note is that the physical domain also contains information, all materials in a MS are information points (location, status, quantity, quality, etc.) and thus the physical domain will consequently be referred to as the physical and information domain.

3.1.2 Production Hierarchy

In addition to outlining a framework associated with the MS, the concept of a Production Hierarchy would also prove useful. The term Enterprise Resource Planning (ERP) is a difficult concept to grasp and therefore the production hierarchy is a useful framework to define the information system scope. The production hierarchy is the modular decomposition of a Manufacturing Company (Enterprise). A Enterprise consists of Plants (Factories) > Areas > Cells > Stations > Machines. The following two figures depict the production hierarchy.

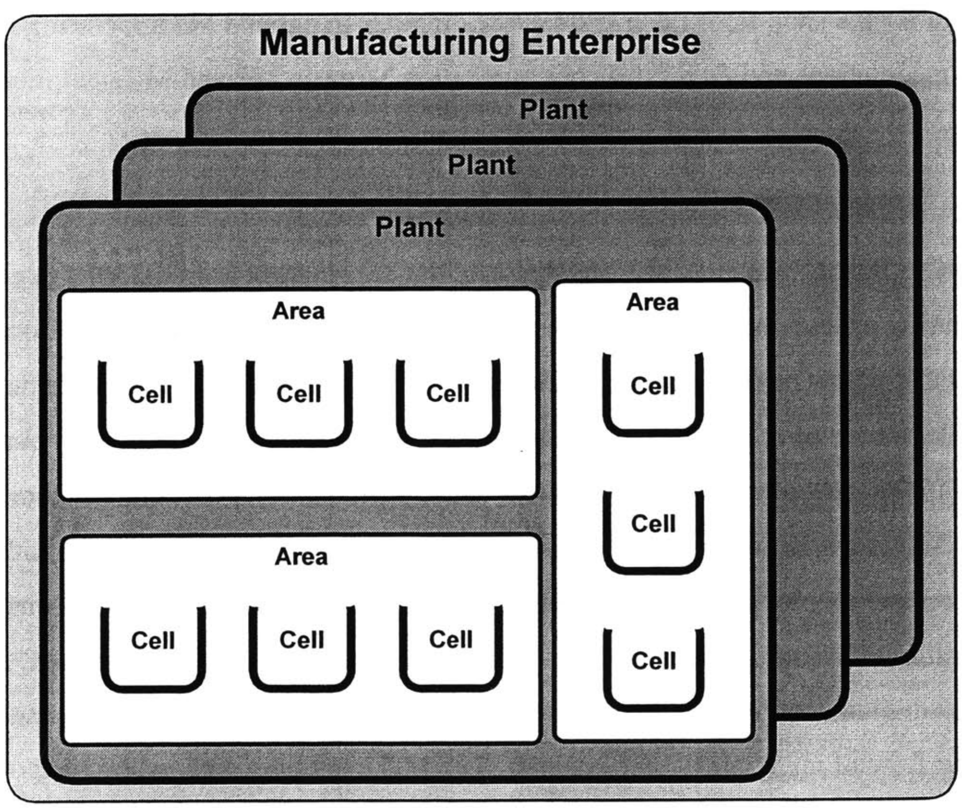


Figure 3-3 Production Hierarchy Level 1

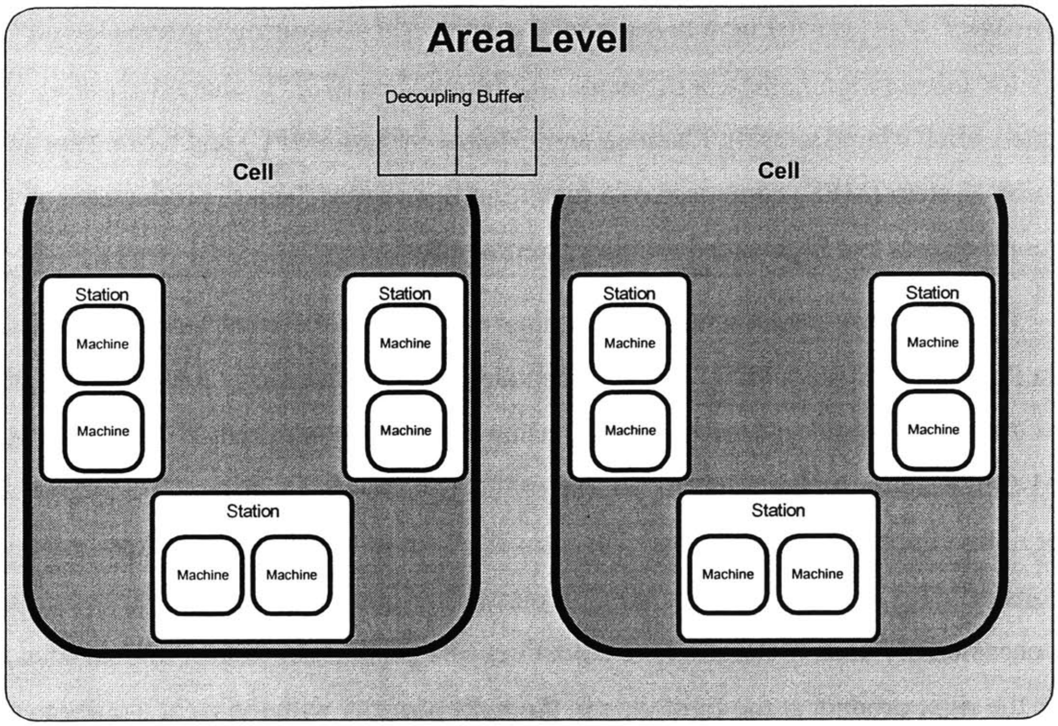


Figure 3-4 Production Hierarchy Level 2

This research focuses on the information system requirements necessary at the Production Hierarchy Level 1, thus the Manufacturing Information System (MIS) at the Enterprise Level. Put another way, the MIS is the subsystem of ERP that performs planning for manufacturing operations at the cell level and above. The users of such a system include all managers above the area level. Therefore, the planning granularity of the MIS does not extend below the cell level, thus the lowest level of production planning in an ERP system is at the inter-cell level. Thus, this thesis focuses on production planning and control at the cell level and above.

3.2 Evolution of MRP and Lean Manufacturing

The above discussion attempts to provide a framework to help identify the information processing aspects of a Manufacturing System (MS) and such dissection is essential to understand the manufacturing information requirements of an ERP System. Before launching into the design elements of the MIS, it is valuable to first discuss the evolution of the two Manufacturing System Designs (MSDs) under consideration: MRP/Mass and JIT/L-CMS.

Although the term MRP typically refers to a Manufacturing Information System (MIS), the term MRP-Mass is used here to describe the entire Manufacturing System Design (MSD) and not just the information system component. An MRP/Mass MSD is characterized by an integrated MRP Manufacturing Planning and Control System (MPC) and a Manufacturing Execution System (MES) composed of a functionally arranged "mass" production job shop that feeds components to a high-speed moving assembly line.

The term "lean manufacturing" describes a number of different facets embodied in the Toyota Production System PSD. To help standardize the terminology for this thesis, the term JIT/L-CMS will be used to describe a MSD using a Kanban controlled, JIT MPC and a Lean, Linked-Cell Manufacturing System (L-CMS) MES [Black, 1991]. Figure 3-5 below helps further define the terminology. Note: The term JIT does not completely address many of the functions of MRP as outlined in the MPC framework of figure 3-1 and 3-2 for two reasons: 1) JIT is occasionally used to describe the objectives of a production control system (that is, to deliver the right product at the right time in the right quantity with the right quality to the customer) and 2) Later in this chapter, the MPC framework will be slightly modified to better describe the lean manufacturing model.

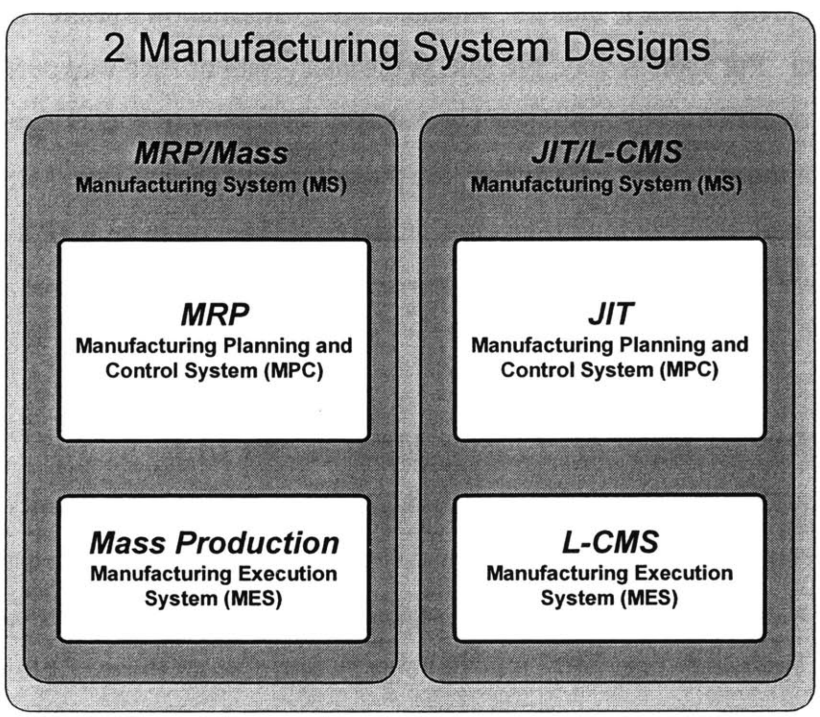


Figure 3-5 Manufacturing System Designs

The previous chapter noted that Visteon, like other automotive component manufactures, is adopting lean production techniques. Visteon's current MSD is very much a MRP-Mass system as described above (MRP MPC with a job shop feeding a mass production assembly line). The transition to a JIT/L-CMS MSD is not easily achieved however. Many manufacturing companies have found that the culture that evolved around the MRP/Mass MSD have created significant institutional inertia. Although there volumes of literature lauding lean manufacturing and criticizing MRP, the next section briefly outline a few historical and cultural points associated with the two Manufacturing System Designs. Note: since this thesis deals primarily with the MPC design, emphasis will be placed on only the aspects of the MSD that apply to the MPC (ie, MRP and JIT) and not on unrelated MSD functions.

3.2.1 MRP/Mass Manufacturing System Design (MSD)

MRP was originally developed to replace the inefficiencies of order-point systems in a job shop production environment during the early 1960s [Orlicky, 1974]. The job shop MRP met was characterized by monthly production schedules, 3 inventory turns per year, and lead times of 6-8 weeks [Latamore, 1999]. These functionally arranged job shops can have thousands of flow-path combinations for individual batches of parts to traverse. Therefore, it was very difficult to keep track of WIP and customer orders. MRP provided a technical solution to matching work in process inventory to customer orders. Prior to MRP, order point systems (Order Point (OP), Order Quantity (OQ)) were adopted to help rationalize the manufacturing system inventory flow. Order point systems attempt to take advantages of the economical advantages of very large batch sizes and consequently resulted in large piles of slow-moving inventory. MRP effectively centralized the planning of an entire factory in an attempt to match sub-assembly production and purchase material ordering with the scheduled delivery of the final product. In fact, the main strength of MRP is that it separates dependent demand from independent demand and provides an intra and inter-company communications medium [Karmarkar, 1989]. Centralized planning requires that all employees are subservient to the production schedule, any disruption or divergence from the schedule creates system instability and chaos. The limits of MRP surfaced quickly once companies became accustomed to its nuances. This thesis assumes that readers will be relatively familiar with the workings of an

MRP system. For an in-depth analysis of MRP, please refer to Vollman [Vollman, 1997]. Section 3-3 will cover the strengths and weaknesses of MRP in great detail.

Despite MRP's shortcomings, American manufacturer's faith in the technology was very persistent. The 1960s computers from which MRP evolved were very anemic compared to today's machines. The expense of processing power and RAM necessitated the use of batch driven software algorithms which read small bits of data into memory, process it, and then write the results out to magnetic media. In this light, the MRP transaction algorithms are incredibly efficient. As processing power increased and RAM expense decreased, MRP software vendors poured endless patches and fixes into their systems in an attempt to deal with the shortcomings outlined above. To this day, many manufactures continue to plow millions of dollars into their MRP systems in an attempt to find the holy grail of a perfect system. As manufacturing competitiveness increases though, companies are facing decreasing order-to-delivery times, decreasing product lifecycles, and increasing customer demand volatility. The current status of the MRP crusade is that many companies are unsatisfied with their very complex manufacturing information systems and are looking to lean manufacturing to help them gain a competitive advantage [Hopp & Spearman, 1996].

Cultural Impact of the MRP/Mass MSD

- Centralized Production Planning and Materials Management
- Adherence to Production Schedule is a key management performance metric
- Direct labor based accounting systems
- Faith that the next MRP version will solve the current problems
- Continued expansion of the functionally arranged job shop
- Removal of any responsibility for lead-time reduction from the shop floor
- Incentive to increase lead times to prevent process variability from impacting product delivery times
- Bounds the expectations of the Manufacturing Execution System by fixing lead times and scrap rates
- No embedded emphasis on improving system performance

3.2.2 Lean Manufacturing (JIT/L-CMS) Manufacturing System Design (MSD)

Lean manufacturing evolved out of Toyota's Taiichi Ohno's relentless pursuit of waste reduction. Faced with a tight capital market and overpowering competition from the American industrial complex following WWII, Ohno focused his engineering efforts on reducing throughput time and increasing labor productivity through establishment of a flow system in the machine shop [Ohno, 1988, 10]. The Toyota Production System (TPS) is built upon two pillars:

- Just in Time
- Jidoka (autonomous automation-not advancing a defect)

These two simple concepts enable a culture focused around continuous improvement. By separating the individual machine operator from the machine, (autonomation) Toyota was able to develop a team based approach to problem solving. Lean production systems are characterized by a "pull" information system that replenishes decoupling buffers upon use. A fixed (standard) amount of inventory is held in the decoupling buffers at all times. The decoupling buffers are therefore, in effect, Standard Work in Progress (SWIP) [Black, 1991]. Production supervisors who own buffer stocks (SWIP) immediately identify with Little's Law: decreasing SWIP decreases lead-time. In addition, they can identify that any manufacturing process variation that creates a disturbance in lead times (and thus the need for SWIP) is also undesirable. The resultant effect is that a pull system, by design, reinforces a culture of continuous improvement around lead-time and SWIP reduction [Karmarkar, 1989, 6].

While the American machine shops continued to develop faster, more complicated multi-purpose production machines, Toyota focused on building simple, slower machine tools which performed only a single task. TPS considers all excess WIP as waste and works very diligently on reducing the production variability that causes the waste [Monden, 1998]. Harvard Business School Professor Kent Bowen has studied Toyota for several years and his analysis concludes that the production system success is not based on the operational tools of lean manufacturing, but rather on the culture that it nurtures [Spear & Bowen, 1999]. This culture is supported by four simple rules that he identified.

Four Rules of the Toyota Production System:

1) All work shall be highly specified as to content, sequence, timing and outcome.
2) Every customer-supplier connection must be direct, and there must be an unambiguous yes-or-no way to send requests and receive responses.
3) The pathway for every product and service must be simple and direct.
4) Any improvement must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible level in the organization

The cultural aspect of continuous improvement is an important facet of TPS, but culture is a result of human social behavior evolution over time in a given environment. In a manufacturing setting, people are organized around the process of converting raw material into products for consumption. *The design of the manufacturing system must precede the culture.* Therefore, a manufacturing organization's culture is a function of the Manufacturing System Design (MSD) and not vice-versa. As described in the previous paragraph, a JIT/L-CMS MSD utilizes SWIP to decouple flow from variations in the work cells. The MSD operates as a closed-loop feedback control system where the SWIP is the set point. By design, SWIP is a form of direct visual feedback for the operators of the work cells. This visual system provides immediate feedback to the workers in the cell to let them know what to build, how many to build, and if they are ahead or behind. Additionally, supervisors can easily identify imbalances in material flow or production problems by the shortage or pile-up of materials on the plant floor. With an understanding of the flow of materials, workers can perform scientific experiments on processes to determine if and when SWIP can be removed from the system [Shingo, 1989, 26]. Thus, the continuous improvement, scientifically oriented culture Bowen describes resulted from the Manufacturing System Design (MSD) and not the discovery of four operating rules [Cochran, 2000].

The topic of company culture is a very difficult subject that is beyond the scope of this thesis. The main point to draw from this section is that an MRP/Mass organization focuses on using technology, centralized production planning, and individual engineering prowess to solve production challenges. Lean manufactures on the other hand focus on team-based, scientific problem solving, waste reduction, continuous improvement, and decentralized material and production planning to solve the same problems.

Cultural Impact of Lean Manufacturing (JIT/L-CMS MSD)

- JIT demands continuous improvement in batch and run sizes, setup times, lead times, scrap rates, cost variations, and quality [Huq, 94, 2].
- Separation of the man-machine interface through autonomation enables the development of a multi-function workforce [Monden, 1988, 166].
- WIP levels and kanban counts represent physical stocks of material. Stocks are a robust control parameter on which to focus continuous improvement efforts. By contrast, MRP systems attempt to focus on improving the rates at which work is released into the system. Because rates are time dependent, they are a more difficult parameter to measure and control [Hopp & Spearman, 1996].

- Direct customer-producer relationships facilitate immediate communication about quality control
- A kanban controlled manufacturing system responds to customer orders from the next sequential process and the overall system is less dependent on a customer demand forecast. Therefore, the JIT/L-CMS MSD is incapable of stockpiling Finished Goods or WIP to "hedge" against forecast imperfections that occurs in an MRP/Mass environment.

3.3 MRP and Lean Manufacturing Production Planning and Materials Management

Production Planning (PP) is the hierarchical process of matching a manufacturing company's production supply with customer demand. Production planning occurs on several levels and each level corresponds to a different time window. Strategic Planning involves capital equipment acquisition, long-term capacity planning, manufacturing process development and facilities location over a period of about 1/2-10+ years. Tactical Planning (few weeks to 1 year) involves production line design, material routings, and plant loadings. Operational Planning involves master production scheduling, purchasing decisions/supplier forecasts, and workforce sizing. Manufacturing Control and Execution (1 hour to 1 week) involves production sequencing, material flow control, machine setup decisions, and shop floor execution scheduling. Mirroring the MPC-MES framework outlined in section 3.1, this research concentrates on Operational and Execution Level Production Planning. Figure 3-6 graphically depicts the timeframe and activities of production and materials planning.

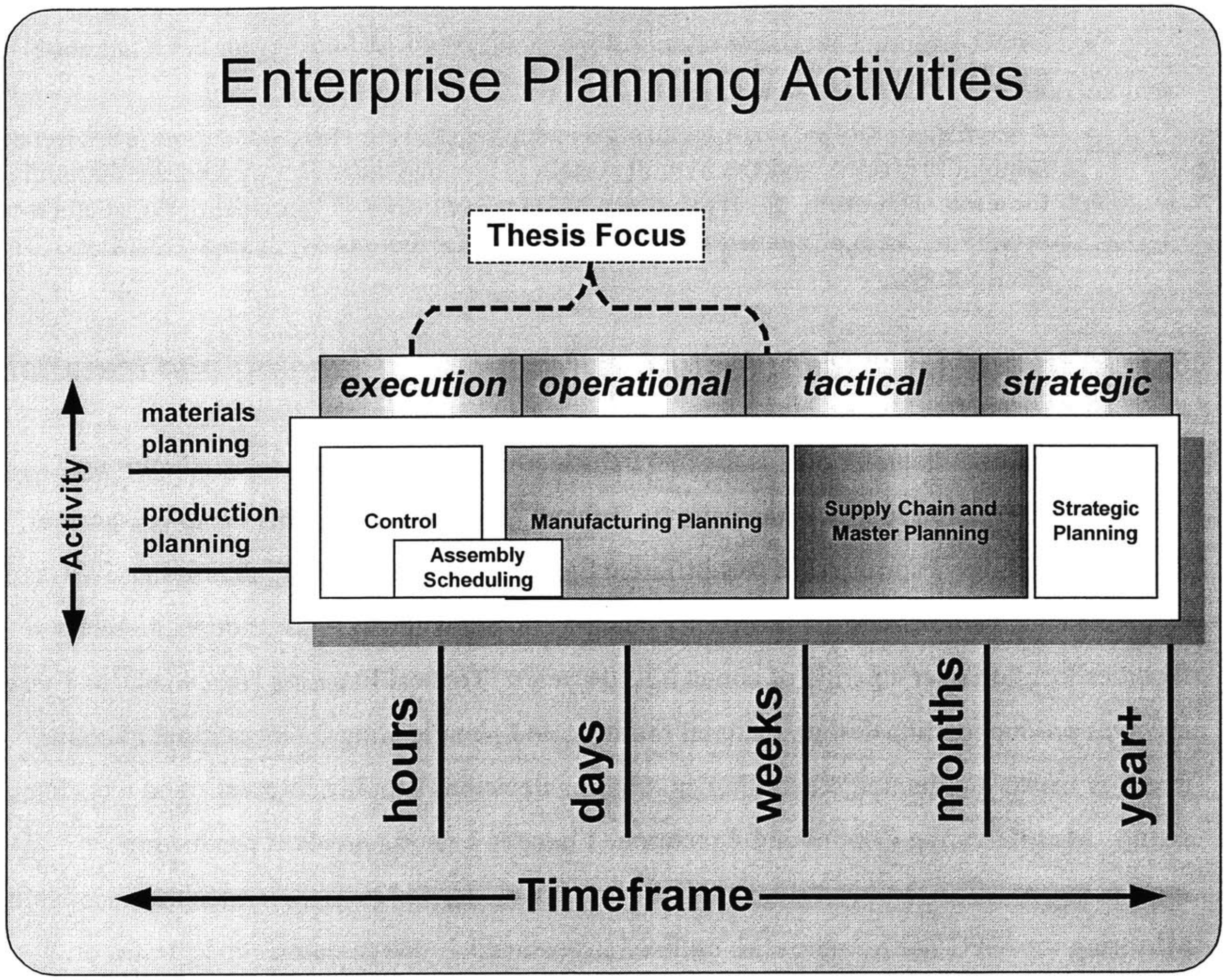
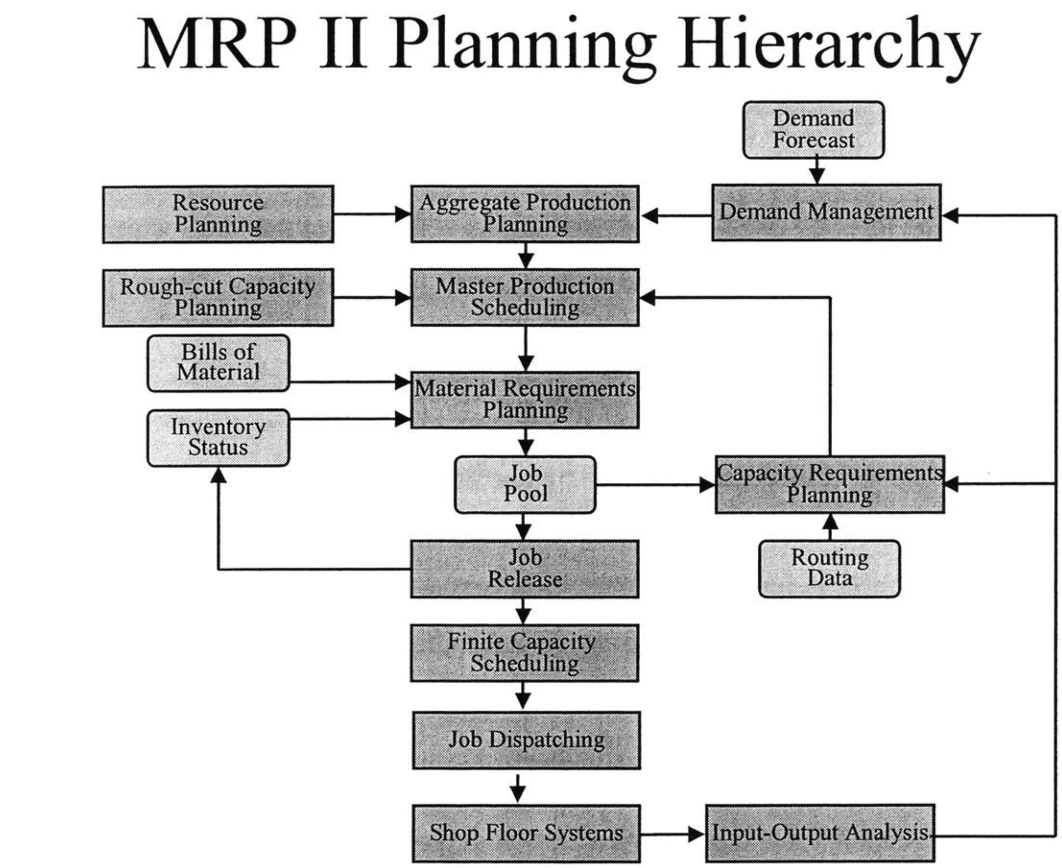


Figure 3-6 Production Planning Hierarchy

Materials Management (MM) is the ordering, receiving, and accounting for all materials involved in the manufacturing system. "Materials" include all purchase parts, sub assemblies, and Work in Process (WIP) inventory. In the Automotive industry, supplier contracts often last for the duration of a vehicle platform. This means that once the purchasing department has set up the contract, the MPC communicates forecasts for material requirement via EDI links to suppliers. Material release is controlled by a number of different mechanisms, EDI, Vendor-Managed Inventory, and Kanban are a few examples. Because of this contract driven, centrally controlled setup, MM planning is performed by the MPC, MM execution and control is facilitated by either the MPC or manual systems. Since MM and PP are very intertwined processes, this section does not attempt to scrutinize the difference but rather looks at both processes simultaneously.

3.3.1 MRP Production Planning and Materials Management

MRP provides an excellent mechanism for developing production schedules to fulfill anticipated demand. In a comparison of JIT and MRP, Professor Uday Karmarkar points out that MRP systems "inherently aim to be a JIT system" [Karmarkar, 1989, 3]. MRP systems were a great advance over Order Point, Order Quantity systems in that an entire plant could plan for increases or decreases in demand via the MRP forecast and Bill of Material (BOM) explosion. Despite MRP's best intentions, the MRP MPC system suffers from many design flaws which result in manufacturing system instability. This section first outlines the MRP planning hierarchy and then covers the system strengths and weaknesses. Figure 3-7 is a graphical representation of the MRP planning process.



Source: Manufacturing Planning and Control Systems, Vollmann, 1997]

Figure 3-7 MRPII Planning Hierarchy

3.3.1.1 Planning Sequence

The Overall Planning Sequence in an MRPII MPC is the logical stepwise traversal of figure 3-7. Each process produces a data file which is subsequently processed by the next module. On a macro scale, an MRP system takes a demand forecast and then creates a time phased production schedule for every subassembly and purchase part on the BOM. The schedules are communicated to the shop floor system in the form of a work order for each batch of parts in each department. Comparing figure 3-7 to figure 3-2, "Shop Floor Systems" is synonymous with MC.

3.3.1.1.1 Demand Forecast

An MRP system is completely dependent on an accurate demand forecast. If the forecast is not completely accurate, any changes made to the forecast cascade through the system during the next MRP BOM explosion run. The forecast is especially important for communications with suppliers who have long lead times. In the auto industry, most supplier communications occurs over EDI links to the supply base. As with any supply chain communication system, any disturbances in the forecast result in wild oscillations at the end of the "bull whip." Since MRP is completely dependent on forecasts and system instability results from changing the forecast, it is important for the input forecast data to be as correct as possible.

3.3.1.1.2 Master Production Scheduling (MPS)

From the demand forecast, the MPS creates a time phased final assembly production schedule which meets the required demand. The MPS uses input from Rough Cut Capacity Planning (RCCP) at this point to identify any production capacity shortfalls. If any shortfalls exist, the system attempts to schedule production ahead of the due date. This is known as build ahead.

3.3.1.1.3 Material Requirements Planning (MRP)

MRP takes the MPS and performs a "BOM explosion" to create a time-phased schedule for all purchase parts and sub assemblies. A BOM explosion is the level by level gross to net material calculations performed by the MRP algorithm. At this point, system capacity is not considered and lead times and batch sizes are assumed to be a fixed input to the system. Chapter 2 of Vollman provides an excellent description of the MRP algorithm [Vollman, 1997, 13].

3.3.1.1.4 Capacity Requirements Planning (CRP)

The next major phase of MRP takes the schedule output from the BOM explosion and determines if this schedule is feasible or not based on the given production system capacity. Due to the huge amount of data processing required, CRP is a fairly course measure of system capacity which does not account for setup times or arrival sequence. The algorithm just determines if it is possible to produce the required amount of work in the given time bucket. Thus, CRP assumes fixed lead times as well. Because CRP cannot shift around production schedules in the MRP output without causing disruption further down in the BOM, CRP only reports capacity shortfalls and then MRP must be rerun to correct for the shortfalls [Hopp, 1996, 487]. Optimal sequencing and scheduling is very mathematically challenging and the MRP-CRP algorithm does not even attempt to perform such, it simply dumps the demand into a time bucket and lets the user sort out the detailed sequence. Supplier material releases are ordered based on the schedule output of the MRP-CRP. Although many of the MRP shortcomings can be traced back to the iterative MRP-CRP process, this thesis does not attempt to attribute cause to an individual sub-feature of the MPC system but rather it assesses the shortcoming of the entire MPC system as a whole. Note: the term "MRP run" or "MRP-CRP output" refer to the iterative computer processing of the MRP and CRP modules.

3.3.1.1.5 Finite Capacity Scheduling (FCS)

Finite Capacity Scheduling (FCS) takes the file output from the MRP-CRP run and attempts to fit it into existing capacity. FCS tries to fix any problems which may have been created by MRP-CRP's inability to optimally sequence production. FCS is typically only run for a short production time frame, only for the period of time between MRP runs. FCS accounts for setup times, changeovers, machine maintenance, and any shop floor status changes. As noted above, optimal sequencing is an incredibly difficult task which takes the form of an Non-Polynomial (NP-hard) mathematical optimization problem. See [Mattfeld, 1996], [Sipper & Bulfin, 1997, 445] and [Muth, 1963] for a discussion of the finite capacity sequencing problem.

3.3.1.2 MRP Manufacturing Production and Control (MPC)

3.3.1.2.1 Manufacturing Planning (MP)

In an MRP system, the entire MPC is centralized and all production is controlled by schedules which order production in anticipated customer demand. If the system works as planned, the final product is assembled Just in Time to meet the forecasted due date. As shown in figure 3-8, the MPC for an MRP system is tightly integrated (As illustrated by arrow thickness). The MSE is dependent on the schedules produced by MP and MP is dependent on MES information (WIP and Production Counts) to perform central production planning via BOM explosion. Supplier material releases are also an output of the MP. Please note that Manufacturing Planning (MRP BOM explosion) is run at predetermined intervals based on a selected time bucket. For example, an "MRP run" is completed weekly in most manufacturing companies at the discretion of the master production scheduler. As will be identified in the "shortcomings" section, the time delay between the capture of production data and the regeneration of the next production schedule is the critical design flaw of the MRP MPC.

3.3.1.2.2 Manufacturing Control (MC)

In an MRP system, the MIS does not initiate or control production; it only provides the Manufacturing Control (MC) function with the schedule output from the MP. MC then initiates and controls production by ordering the MES to produce a quantity of a certain part (batch). The MC is not an automated process, but rather requires human judgment in the form of the area production manager. Area managers use the scheduled batch due dates from the MIS to help determine what product to produce and when to initiate production. Since MP does not attempt to produce a schedule for exact production control, area managers use their own judgment as to when to initiate production. FCS is MRP's attempt at automating the MC, but it suffers from many of the same problems identified above. Often, shop floor control is heavily influenced by "expediting" customer orders in order to meet shipping requirements. Expediting makes the area manager's job even more difficult as component parts may or may not be available to initiate production. Additionally, since production schedules are created based on customer forecasts, any deviation from the forecast result in an "expedition." As more and more schedules fall into disruption, shop floor performance degrades as machine run lengths are interrupted to facilitate the schedule changes. Eventually, MRP must be re-run to catch all of the net expediting changes. The end result is that an MRP MPC is not robust to demand or production variability and the resultant expediting reinforcing feedback loop creates further instability. Figure 3-8 depicts the information and material flows of an MRP MPC as described above.

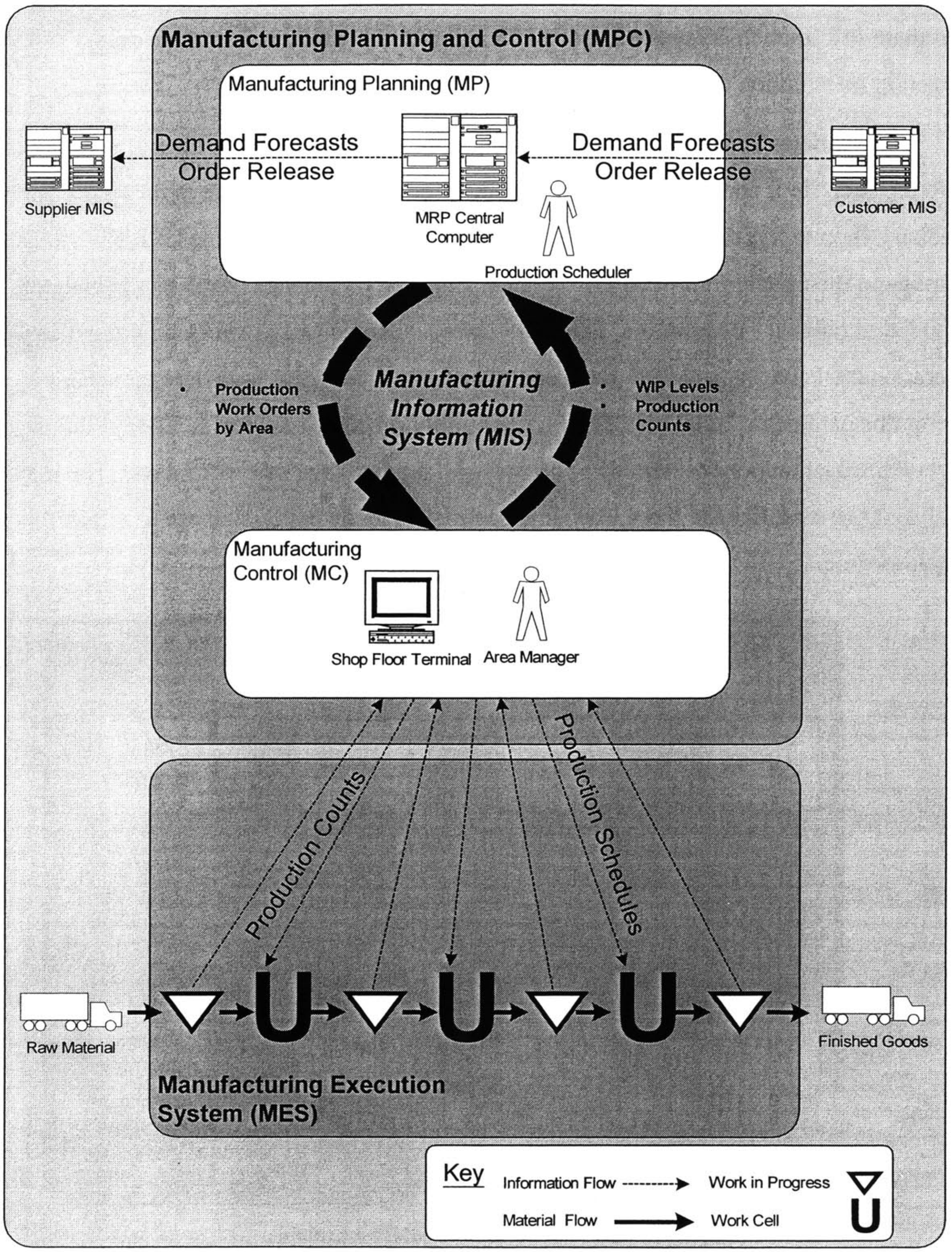


Figure 3-8 MRP MPC

3.3.1.3 MRP Shortcomings

3.3.1.3.1 Information Delays

Information delays represent the most fatal design flaw of MRP. Delays that occur between the MP and MES create system instability and initiate the expediting cycle. There are two main information delays embedded within MRP: parameter information delays and problem detection information delays.

Parameter Information Delays: This is the delay between the time of production release onto the shop floor and the measurement of the production output. The input/output analysis feedback loop in figure 3.7 shows that this function compares the planned schedule to the actual output and then sets the demand management and CRP parameters based on the realized production output. For example, figure 3-9 shows a component part requiring three consecutive operations (OP 10, 20, and 30). Each operation has a fixed MRP lead-time parameter of 10 days. Using this parameter, MRP creates a final assembly schedule based on a 30-day lead-time. After several production periods, the MES, on average, produces the part in 25 days. The input/output analysis then modifies the fixed lead-time parameters in the MRP database to reflect this new 25-day lead-time.

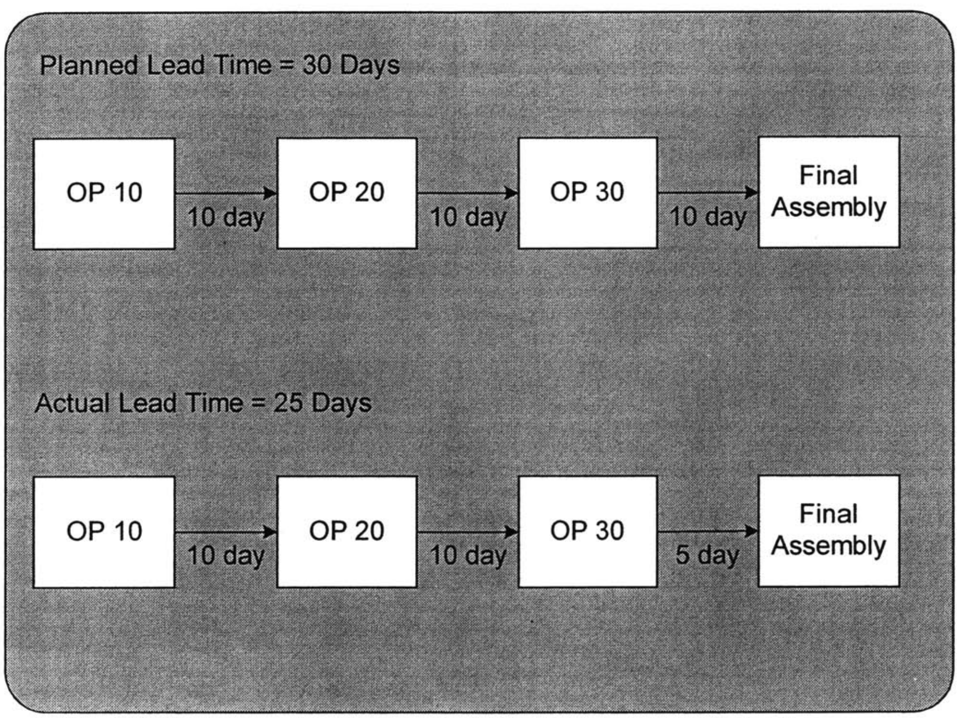


Figure 3-9 Fixed Lead Time Example

The new lead-time also changes the rate at which work can be released onto the shop floor, so the demand management parameters are also modified. Hopp and Spearman point out that the manufacturing lead-time is actually a function of the shop floor loading at any particular point in time which is a function of the rate at which work is released onto the shop floor [Hopp & Spearman, 1996]. With the new lead time parameter, work is released onto the floor too quickly, Final Assembly orders become starved for parts, and the input/output analysis consequently recommends to change the lead time for OP 30 back to 5 days. Thus, the information delay associated with the fixed lead-time MRP algorithm chases its tail and is inherently unstable.

Figure 3.10 depicts the impact of parameter information delays. This WIP graph is the output of a systems dynamics model developed to quantify the effects of manufacturing planning system instability. Figure 3.10 show the resultant instability with a step change of 10% in the customer demand rate. The graph shows the model output of three different simulations with one parameter changed, the parameter being the reaction time it takes to change the WIP levels based on the status of production operations. This "inventory adjustment period" is analogous to the lead-time parameters in MRP. If the system changes the parameters too quickly, system instability results. If the system changes the parameter too slowly, the production system cannot keep up with the customer demand rate in time. Thus, because MRP attempts to control the rate at which work is released onto the shop floor and does not account for the shop floor loading, the information delay associated with the slow input/output feedback loop causes system instability.

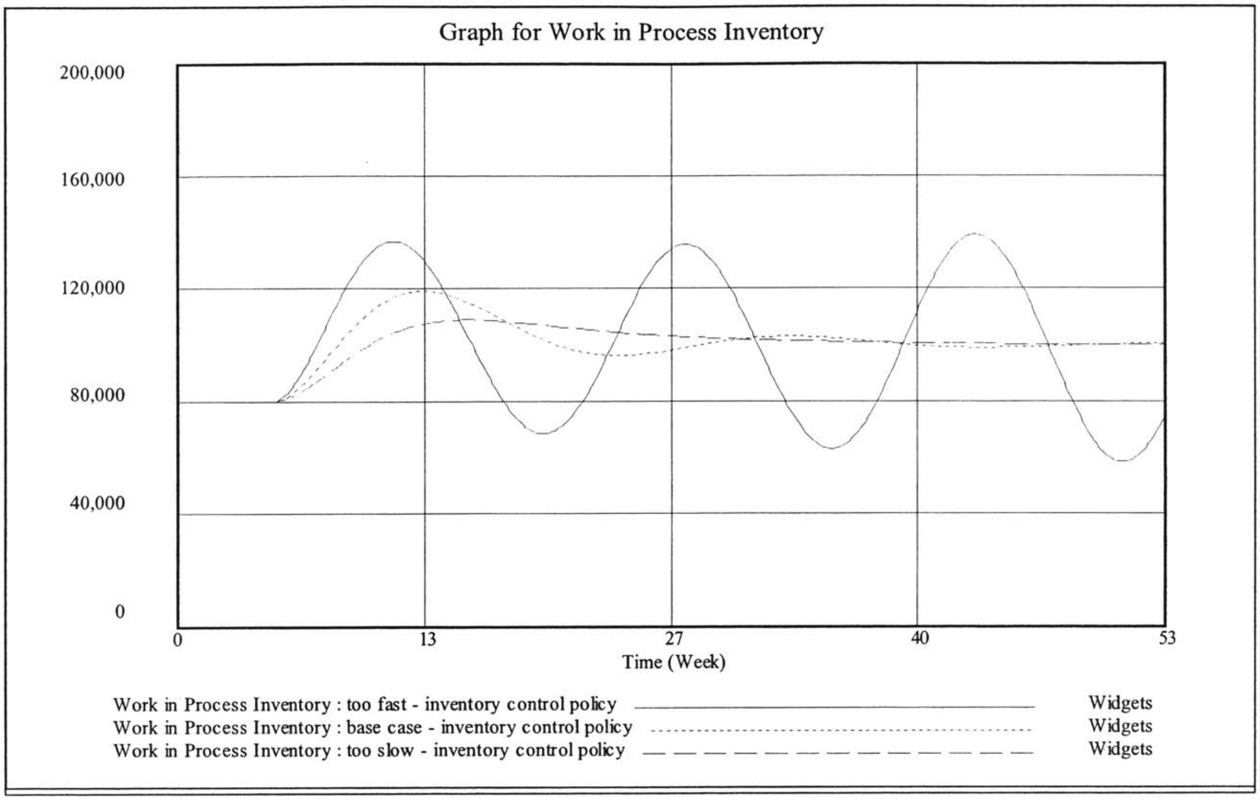


Figure 3-10 MRP Information Delay Example

Problem Detection Information Delays: This delay is the time between when a schedule is output in MRP and the time when the next schedule is produced. Because any type of variability in production or raw material quality can upset the MRP schedule, the area manager begins to expedite orders to fix the problem. As described in the preceding section, expediting kicks off the vicious cycle that creates further Manufacturing System instability. In essence, the re-planning delay creates Manufacturing System instability.

3.3.1.3.2 Fixed Lead Times

To create the time-phased production schedule, MRP assumes that the lead times for production processes are fixed and then releases work into the system based on these lead times. With an understanding of queuing theory, it is easy to identify that the amount of work currently in the system determines the lead time of new work released into the system. Therefore lead times are definitely not deterministic. Because lead times can sometimes be longer than what was quoted, there is a strong incentive to inflate the lead times to cover the worst case scenario so that downstream operations are not starved as a result of an improperly quoted lead time. [Huq, 1994, 3]

3.3.1.3.3 Fixed Run (Batch) Sizes

MRP uses a pre-determined fixed run size (batch size) to perform the BOM explosion. These batch sizes are usually a function of efficient machine setup and run sizes. Therefore, if only 1 part is needed and the batch size is 500, a run of 500 is ordered and then 499 components remain as unused WIP. Since run size is a system parameter, there is no incentive for the shop floor to reduce the run size and reduce the delays associated with a part waiting until the preceding batch is completed.

3.3.1.3.4 Nervousness

Dynamic forecasts, improper cycle counts, fixed batch sizes, and missed due dates cause MRP production schedules to fluctuate between MRP runs. For example, after the first MRP run, a work cell is required to build 100 of part A for delivery in three weeks. The next MRP run (completed one week after the first MRP run) then reschedules the work center to build 75 of part A for delivery in two weeks. The third run reschedules the quantity for 125 for delivery within a week. This schedule instability is system considered nervousness. See [Nahmias, 1997, 364] and [Vollman, 1997, 462].

3.3.1.3.5 Infinite Capacity

The MRP BOM explosion assumes that all work centers can make the requisite amount of components per period. This assumption is completely invalid and CRP and FCS are not able to fix the problem. A second problem is that MRP does not provide the factory floor with notification that they are not keeping up with the pace of demand, it only reports late shipments at the end of the time bucket. See [Orlicky, 1974, 46] for a description of the purpose of MRP. He points out that MRP is capacity-insensitive. See [Hopp, 1996, 486] for a description of the two types of schedule infeasibility produced by MRP.

3.3.1.3.6 No Attempt to Smooth or Level Production

MRP produces a Master Production Schedule (MPS) to meet the forecast. The time-phasing approach of the MRP algorithm is incapable of performing production smoothing because all demand data is lumped into the time bucket at which it is due. Production smoothing takes the due dates and "smoothes" the demand over several periods in order to prevent production spikes, building ahead as necessary. Because of the time-phasing approach to production scheduling, MRP cannot compress the lead times of Final Assembly because the component parts may not be available unless all lead times are planned. Also, since MRP is insensitive to production mix, it is also incapable of leveling the final assembly sequence.

3.3.1.3.7 Dependence on WIP Data

One critical input into the MRP is the shop floor inventory status. *Without **detailed, accurate** WIP data the system cannot perform the Gross to Net calculation (BOM explosion).* Therefore, the entire plant floor must be "wired" to facilitate "cycle counting" which is a non-value adding process. In addition, the information delays between BOM explosions also impose significant limitations on the MC when production disturbances occur. Since each production area is indirectly linked through the Manufacturing Planning (MP) function, Manufacturing Control (MC) must use manual intervention in the form of expediting orders to overcome the information delays and system nervousness.

3.3.1.4 MRP Advantages

3.3.1.4.1 Provides an intra and inter company communications medium

MRP is a natural hub for inter-functional communications and data management. The solution provides a central database through which interaction with the MIS yields instantaneous intra-company communications. Also inter-company communications through EDI to the supply base [Karmarkar, 1989, 8].

3.3.1.4.2 Time phased planning hierarchy for matching demand with supply

Time phasing is a very attractive concept that allows production planner to produce ONLY what is needed for final assembly. Thus, the system provides an excellent planning hierarchy which facilitate many intra company processes like demand management, forecasting, sales quoting, accounting, and financial consolidation. Another disadvantage of MRP is that the excellent planning hierarchy does not extend to an excellent execution system. The computer solution is unable to plan for uncertainties due to quality fallout, production disruptions, and unforecasted demand and thus the system is unable to keep its promises.

3.3.1.4.3 Separates dependent demand from independent demand

Order Point, Order Quantity (OP, OQ) is incapable of separating independent demand (demand for final product which occurs outside of the system) from dependent demand (demand internal to the MS, from one process to the next) variability. When the two demands are aggregated (when all production is planned in isolation) the resultant variability is much greater than each of the individual demands. The higher variability results in a much higher than necessary safety stock. MRP completely separates these two demands, which ensures that unnecessary inter-process safety stock is not held [Hopp, 1996, 106]. Despite this good intention, in actual practice inflated planned lead times replace the safety stock.

3.3.1.4.4 Provides a means for dealing with demand volatility through forecasting

Through forecasting fluctuations in end item demand, the system automatically incorporates this demand volatility into the production schedules and then propagates it throughout the entire system and out into the supply chain via EDI.

3.3.1.4.5 Inventory Database

MRP provides a means of tracking all inventory (RM, WIP, and FG) and therefore the database can be used to estimate lead times for new orders. This database can be used to facilitate other company functions such as cost accounting, finance, HR planning, etc. The extension of manufacturing data into enterprise level data is exactly how ERP extends MRP. Ideally, a central data repository eliminates the need for redundant IT systems and thus the entire enterprise can run off of one concurrent database.

3.3.2 Lean Manufacturing Production Planning and Materials Management

As identified in the discussion from 3.2.2, a JIT/L-CMS Manufacturing System Design enables a culture of continuous improvement focused on reducing lead times and production variability. The visual feedback Standard Work in Progress (SWIP) inventory control provides excellent production feedback for the manufacturing workers. Combined with low inventory levels and excellent operational characteristics, JIT seems to be sold as the panacea that could cure many production evils [Hopp & Spearman, 1996, 179]. Despite the operational efficiency which can be achieved through Lean, Linked-Cell Manufacturing, the approach does have its drawbacks. The following figure explores the benefits and drawbacks of lean manufacturing following a brief description of the enterprise level planning process.

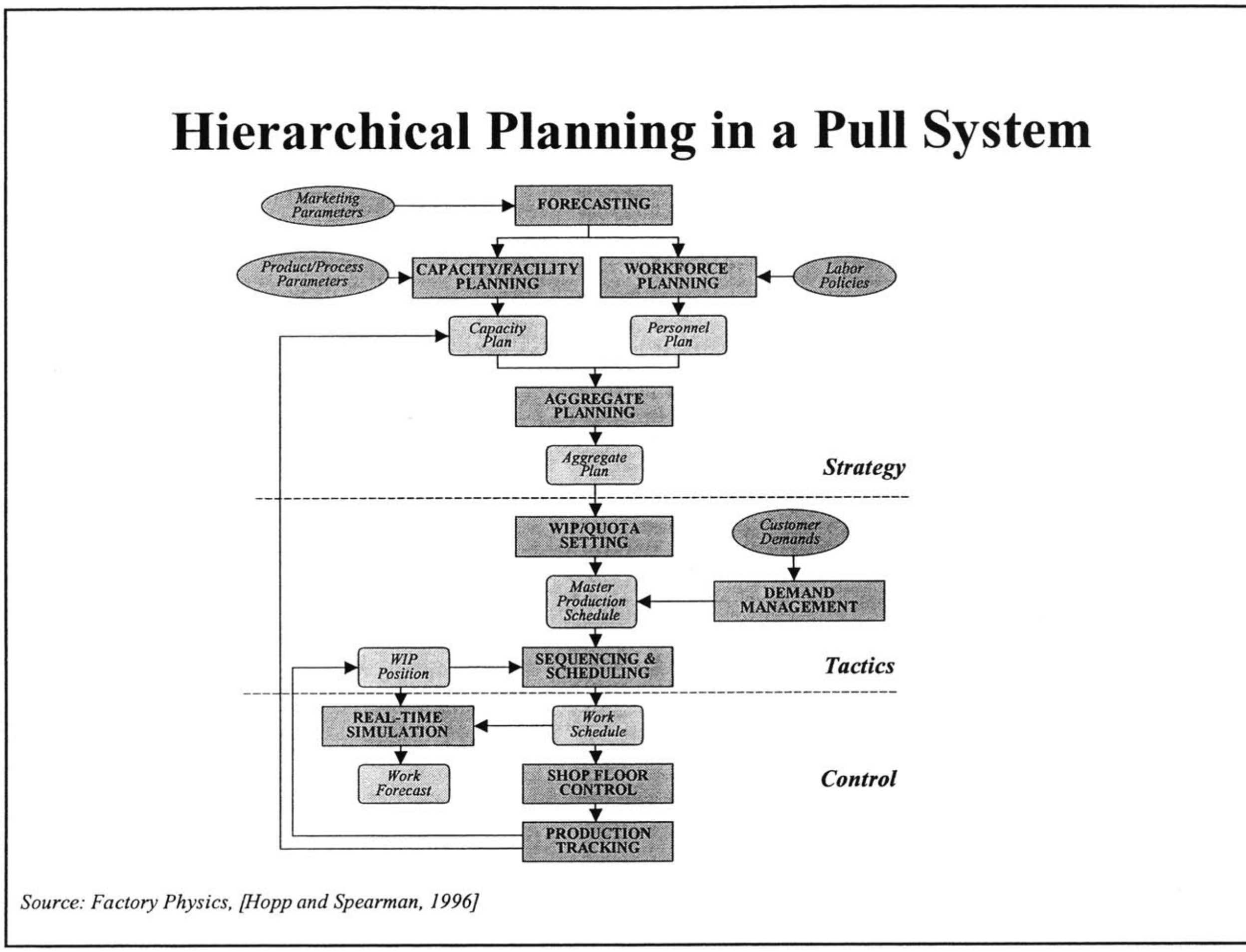


Figure 3-11 Hierarchical Pull Planning Framework

3.3.2.1 Planning Sequence

A pull planning system is similar to the MRP planning in that the process is a hierarchal flow that takes the demand forecast to help set production parameters like workforce size and cell capacity. The main difference between the two planning processes is that an MRP MPC uses the demand forecast to create a schedule for shop floor control whereas a JIT MPC uses actual customer demand signals to create the final assembly sequence. Comparing figure 3-11 to figure 3-2, "Shop Floor Control" is synonymous with Manufacturing Control and Execution.

Many of the concepts presented in this section were taken from multiple chapters in Monden's book on the Toyota Production System. Monden describes the dealer order entry information system through which dealer forecasts and orders are used for capacity planning and final assembly sequencing [Monden, 1998]. Although Toyota has excellent information systems which are used to optimally sequence final assembly, many JIT implementations do not posses Toyota's level of computer sophistication to perform both production leveling and smoothing. Furthermore, Monden describes Toyota's use of MRP for planning purposes and supplier communications and thus some sort of hybrid planning process must be possible [Monden, 1998]. Many scholars have identified the planning difficulties associated with JIT [Karmarkar, 1989], [Huq & Huq, 1994] and [Hopp & Spearman, 1996]. Since an off-the-shelf computer package for JIT planning does not exist, many JIT implementations in practice are not facilitated by a centralized computer planning system [Benton & Shin, 1998]. Without a computer planning system, no central database is available to provide data for other company functions. Similarly, intra-company and inter-company communications must be performed by other methods. The following sections outline a stepwise traversal of the production planning framework of figure 3-11 [Hopp & Spearman, 1996].

3.3.2.1.1 Forecasting

As in MRP, demand forecasting must be completed to determine capacity requirements in the plant. The forecast then needs to be communicated throughout the supply base so that suppliers whose lead-time is longer than the order to delivery time for the end product can be notified. Monden notes that for Toyota, forecasts are sent in 30-day and 10-day increments. The 10-day forecasts are guidelines that are "fine tuned" +/- 10% by kanban. Fine tuning means that suppliers should not produce exactly to the forecast, but exactly to the kanban signal which may be +/- 10% of the forecast. Thus, Toyota inherently provides an incentive for suppliers to reduce their replenishment cycle time within the time interval of successive the kanban circle. Monden also notes that the +/- 10% is a very rigid standard, deviations outside of 10% may not be filled as adequate supplier capacity may not be available [Monden, 1997, 76].

3.3.2.1.2 WIP/Quota Setting

Once the aggregate schedule is produced through high-level production planning, the end item build schedules are broken down to determine the Takt Time of each subsequent production process. From this Takt Time, kanban card quantities and Standard Work in Progress (SWIP) sizes are calculated. Note that SWIP/kanban card sizing is based on demand forecasts.

3.3.2.1.3 Demand Management

A JIT L-CMS Manufacturing Systems must be built upon a smoothed demand stream that prevents production peaks [Karmarkar, 1989]. The demand management module of figure 3.11 provides for the production smoothing by only creating a feasible final assembly order sequence. Feasibility means that the order stream is within the capacity constraints of the Final Assembly process. Monden points out that Toyota works with its dealer network to continuously refine and smooth the final assembly production flow [Monden, 1998]. Additionally, the demand management module also "levels" final assembly in that the mix of cars to be produced is optimally sequenced so as to prevent a "surge" in any component configuration. Level production smoothes the demand for parts through the manufacturing system and reduces the amount of inventory that must be maintained to meet customer demand. A level, smoothed demand pattern also dramatically reduces volatility in the supply chain. By focusing the smoothing efforts on the final assembly sequence, the smoothed sequence is then cascaded backward throughout the supply chain via kanban flow. Please note that Demand Management occurs after WIP/Quota setting. The insight being SWIP and kanban quantities are set via forecasted demand while quantity control occurs on the shop floor in real time with real customer orders.

3.3.2.1.4 Sequencing and Scheduling

To schedule and sequence the shop floor, Toyota employs Heijunka (Japanese for load smoothing) which seeks to minimize the tradeoff between setup times and run sizes. Through heijunka, Toyota is able to provide a mechanism for decentralized shop floor control [Liker, 1999]. Additionally, a Heijunka box illustrates how setup time reduction can reduce WIP. One study on JIT in a job shop points out that without a load leveling system, inventory and due date performance can be poor [Huq & Huq, 1994]. Sequencing and scheduling can be either a computer automated or a non-computer automated process.

3.3.2.2 Lean Manufacturing/JIT Manufacturing Planning and Control System (MPC)

In a lean manufacturing/JIT Manufacturing Planning and Control System (MPC), much of the planning and all of the control is decentralized and not dictated by a central schedule. Production is initiated by the local demand of the next server [Benton & Shin, 1998, 416]. Without computer automation, the pull production process relies on simple, decentralized shop floor heuristics to fulfill the master production schedule. Figure 3-12 depicts a MPC for a Tier 1 automotive components supplier. Customer demand does not flow through Manufacturing Planning (MP), but rather directly to the shop floor via customer pull signals. Ideally, these pull signals are leveled and balanced by the customer or the demand management system. As identified above, Toyota performs supply chain leveling via the vehicle final assembly sequence.

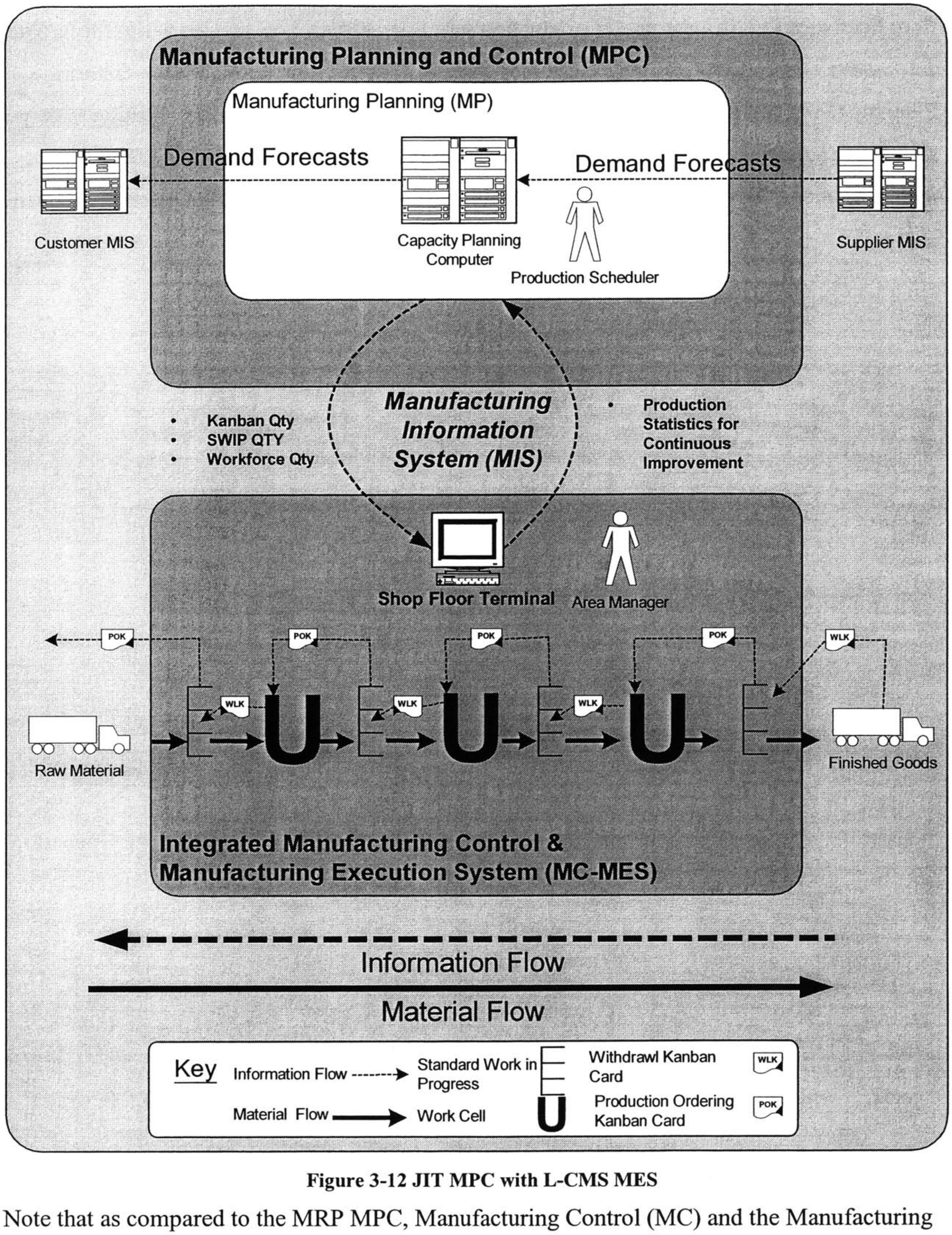


Figure 3-12 JIT MPC with L-CMS MES

Note that as compared to the MRP MPC, Manufacturing Control (MC) and the Manufacturing Execution System (MES) are completely integrated while the Manufacturing Planning (MP) function is uncoupled from the MC. Also, most of the human judgment in the MC is eliminated;

production control is based on demand signals from the next operation via kanban. Kanban cards at the MC-MES level also control supplier material releases and thus material is only brought into the plant as needed. The previous discussion prompts a slight modification of the MPC model to adapt to the integrated MC-MES as described above. Therefore, although JIT primarily describes the manufacturing control portion of the JIT-MPC, the term JIT will continue to be used to describe the MP aspects of the MPC. Additionally, since the Manufacturing Information System (MIS) is only used to communicate information to the shop floor, the Manufacturing Planning (MP) functions will be combined with MIS to create the term MP-MIS. Although not as clean as before, the modified MPC framework is depicted in figure 3-13.

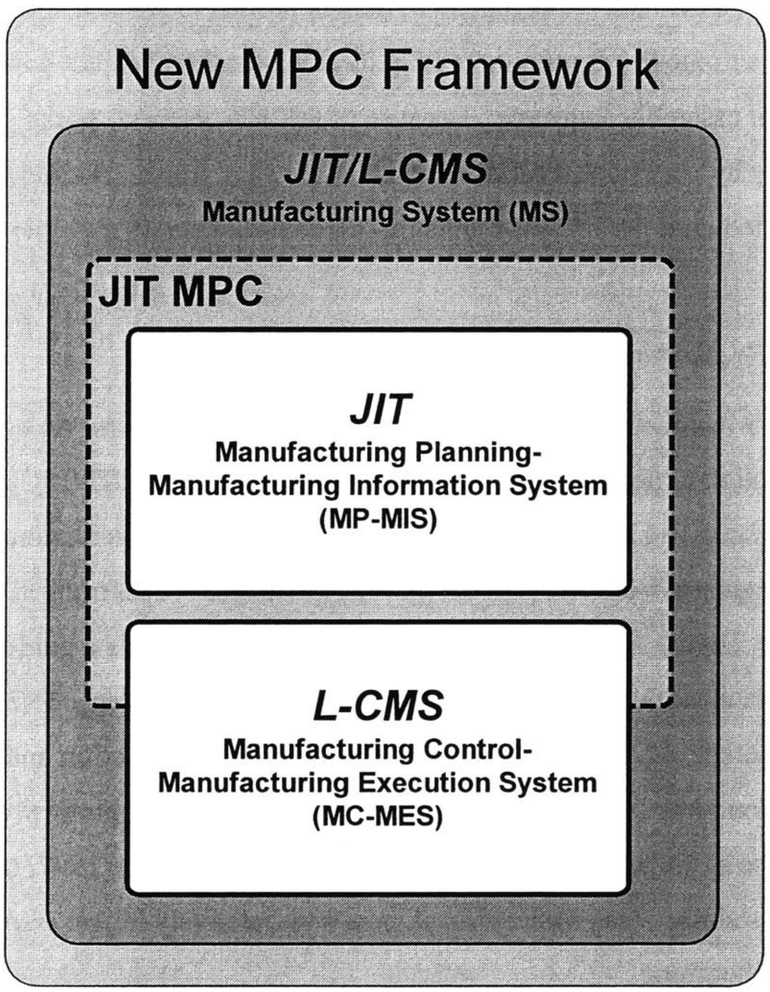


Figure 3-13 Lean Manufacturing MPC

The chief takeaway from figure 3-12 and 3-13 is that the Manufacturing Planning (MP) function uses forecasts to set operational parameters for the shop floor (MC-MES) and then decentralized shop floor control builds to actual customer demand. ***The planning system does***

not require continuous information feeds from the shop floor to control what the shop floor produces and thus there are no information delays—just direct connections between suppliers and customers. The only feedback loop from the shop floor is in the form of production statistics that help refine the planning sequence and support continuous improvement efforts.

3.3.2.3 Lean Manufacturing Shortcomings

3.3.2.3.1 Manufacturing Execution System Requires Smooth Demand

A JIT/L-CMS Manufacturing System requires a smoothed, level demand stream in order to operate effectively. Monden goes so far as to consider uneven periods of demand "waste." To correct for this, a demand management system is needed to smooth and optimally level demand. For an automotive components supplier, the best arrangement possible is for the OEM to level their final assembly sequence. Because of this requirement, a lean system "punishes" demand volatility by very poor response outside of planned limits. A sudden surge in demand will not be satisfied until the limited number of cards can circulate multiple times [Karmarkar, 1989, 8].

3.3.2.3.2 Long Re-planning Cycles

Most JIT Manufacturing Planning and Control (MPC) systems do not have end-to-end computer automation to perform the steps outlined in figure 3.11. JIT/L-CMS Manufacturing Systems are characterized by both centralized and decentralized calculations for kanban quantities and Standard Work in Progress (SWIP) quantities. A centralized kanban master planner is used at Toyota for monthly re-planning and this system is a guide for the area managers who are most familiar with the system operations [Monden, 1997, 293]. Monden also points out that there is a system tradeoff between smoothing production and continuously refining production plans. While an hourly-refined production plan may produce exact customer demand, it may be at the expense of a smoothed schedule [Monden, 1997, 64]. Therefore, in order to achieve stability, lean systems work best with relatively longer re-planning cycles that facilitate better smoothing.

3.3.2.3.3 Kanban is Reactive

Because of the longer re-planning cycle and emphasis placed on smoothing, it is difficult to continuously convert forecast updates to system operational parameters. Consequently, it is very difficult to communicate end-item demand volatility. It is definitely not at the "push of a button" like MRP.

3.3.2.3.4 Difficult to Quote Due Dates for non-forecasted orders

Again, due to the lack of end-to-end computer automation, longer re-planning cycles, and lack of a shop floor feedback loop, it can be difficult to quote order lead times for non-forecasted production orders. A non-forecasted order does not have adequate SWIP buffers between the manufacturing cells and thus special kanbans must be circulated to produce the non-standard part. The awkwardness of integrating repair part demand into the system is a good example of the difficulty in quoting lead-times, there simply is no information system to perform this task. A further difficulty lies in identifying any capacity shortfall for shared resources since BOMs and computerized routings are not an integral part of the MPC system.

3.3.2.3.5 SWIP must contain some infrequently used components

This shortcoming is similar to the previous point. In a repetitive manufacturing environment, downstream processes pull components from SWIP which is then refilled by upstream processes. Since production is initiated by consumption, some SWIP must always be in the system. Infrequently used components are not well suited to this production environment as they must be held in SWIP but rarely used. Workarounds must be made for these low volume components, as their stagnation is wasteful. This shortcoming is more of an issue for non-repetitive manufacturing and service parts for products no longer in production.

3.3.2.3.6 Demands Continuous Improvement

Employee motivation and management support are key factors in the success of a lean manufacturing implementation and without either, the Manufacturing System Design will never achieve its full potential. Some manufacturing literature suggests that the success of lean manufacturing is not achieved by the planning and control techniques, but by continuous improvement efforts [Benton & Shin, 1998, 415]. Please note: continuous improvement is also listed as a benefit below.

3.3.2.4 Lean Manufacturing Advantages

3.3.2.4.1 Small Run Sizes

In order to run a pull production system, the lead times of upstream processes must be minimized with single piece flow cells so as to fulfill downstream requirements in reaction to customer orders. In order to accomplish this objective, run sizes and setup times must be minimized or the resultant SWIP quantities may overflow from the shop floor. Therefore, small run sizes are needed to minimize SWIP as mandated by factory floor-space constraints.

3.3.2.4.2 WIP CAP

Hopp and Spearman point out that an MRP system is basically an open queuing network which feeds work into the system without regard to the shop floor status. By comparison, a pull system acts as a closed queuing network with the number of kanban cards limiting the WIP on the shop floor. The WIP cap prevents the system from overloading [Hopp & Spearman, 1996].

3.3.2.4.3 Quick Order Response

With low WIP levels, short setup times, and small run sizes produced by single-piece flow, a Lean Linked-Cell Manufacturing System (L-CMS) quickly responds to marketplace withdrawals. This quick response means that the manufacturing system is less dependent on short-term forecasts. With this MSD, short-term forecasts are most necessary for special orders or components from long lead-time suppliers who cannot respond to kanban signals. Long-term forecasts are used for capacity and workforce planning. Refer to figure 3-12 for a depiction of the use of demand forecasts.

3.3.2.4.4 Supports Assemble to Order (ATO) and In Line Vehicle Sequencing (ILVS)

A kanban controlled JIT MPC System supports a final assembly, Assemble to Order (ATO) environment very well in that all configuration options are pulled from an upstream SWIP and assembled JIT. Since upstream SWIP is continuously restocked based on consumption, the automotive components supplier final assembly sequence can be ordered in the same sequence as the OEM final assembly sequence (ILVS). This process does depend on a 100% reliable final assembly process which has no quality loss.

3.3.2.4.5 Demands Continuous Improvement

Continuous improvement is listed both as a shortcoming and an advantage. Increased manufacturing competition demands continuous improvement. Lean production systems provide an excellent mechanism for sustaining continuous improvement efforts around variation and lead-time reduction.

3.4 An Ideal, Hybrid MPC System for Production Planning and Materials Management

From the previous discussion, it is clear that both MRP and Lean Manufacturing/JIT have advantages and disadvantages. What seems unclear is how to achieve the benefits of both. Benton and Shin point out that a relatively new research trend is to explore the possibility of a hybrid MRP-JIT system. A hybrid MPC system embodies the planning elements of MRP and the execution elements of lean manufacturing. It uses MRP's long term capacity planning and centralized data as well as JIT's agility in daily production control [Benton & Shin, 1998, 424]. A hybrid system nurtures the culture of continuous improvement (lead time reduction, small batch sizes, setup time reduction, employee involvement) and does not bound the expectations of the Manufacturing Execution System (MES) with allowable scrap rates or fixed lead times.

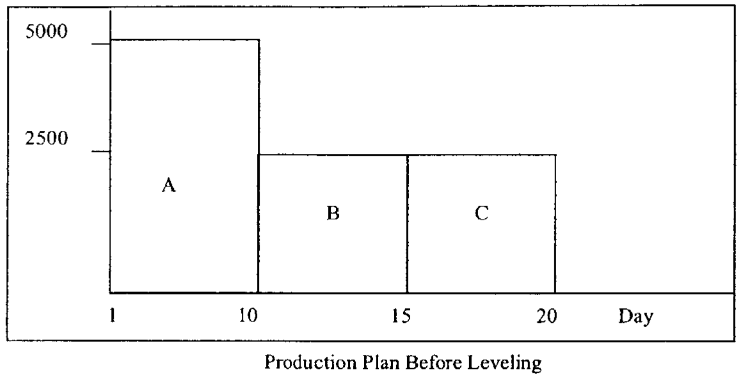
To contemplate such a system, it is beneficial to refer to the elements of the MPC outlined in figure 3-2. A hybrid system embodies the uncoupled design of a JIT MPC and L-CMS MES (figure 3-12) while also providing a centralized database which acts as a hub for intra-company and inter-company communication and data management. In short, the ideal design uncouples the Manufacturing Planning (MP) function from the Manufacturing Control and Manufacturing Execution System (MC-MES) while providing computer automation and database management support for other company functions. The Manufacturing Information System (MIS) automates all of the MP functions and communicates the requirements to the MC for decision support purposes. Thus, the ideal system integrates ERP with Lean Manufacturing (Lean-ERP).

3.4.1 Ideal Manufacturing Planning (MP)

MP provides a hierarchal planning process for support of the L-CMS Manufacturing Control and Execution System (MC-MES). The Manufacturing Information System (MIS) is an integral part of the MP function -- the MIS provides an automation framework for the Pull Planning hierarchy of figure 3-11 above. The ideal MP function performs the following functions.

3.4.1.1 Dynamically Smooth and Level Demand and Schedule Final Assembly

The MP smoothes and levels the incoming demand stream and optimally sequences and schedules the final assembly operation. Thus the final assembly operation is scheduled via the MPC and all material and components are withdrawn from upstream SWIP. This operation can be scheduled ILVS as necessary. Figure 3-14 below depicts the difference between a non leveled and a leveled production sequence. The second schedule below places less demand pressure on upstream operations as the demand for components is spread out over the entire day. Thus, all shipments are completed on time and upstream operations can refill SWIP with a predictable frequency. Additionally, if the process can run concurrently as new demand enters the IT system, the final assembly operation would have the maximum lead time available to complete the production requirements.



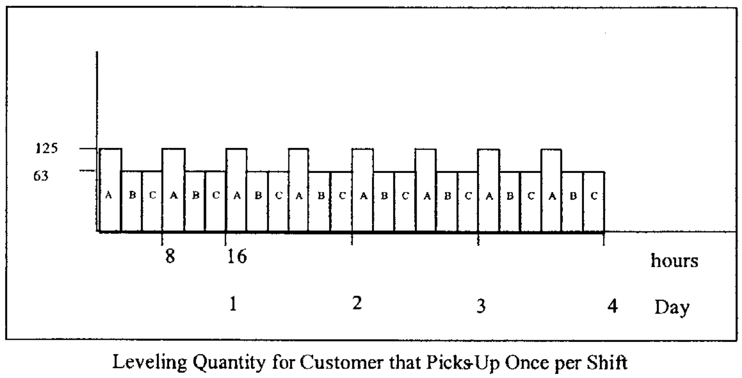


Figure 3-14 Production Leveling Example

3.4.1.2 Size SWIP Quantities / Determine number of inter-cell kanbans

RM, FG, and SWIP quantities are recommended by the system. The number of inter-process kanban cards and quantity of parts per kanban are also recommended by the system. As production variability and setup times are reduced, SWIP levels can also be reduced. The MP function uses the MIS as a decision support system to communicate the impact of demand volatility to the MC-MES. Run sizes are therefore not fixed and can be modified as necessary.

3.4.1.3 Determine Takt Time and Capacity Loadings of all production cells

Takt time is the fundamental idea around which the ideal Manufacturing Planning and Control System is built. The MIS represents a mathematical model of the production environment and can continuously calculate cell capacity loadings as new orders are entered into the system. Unlike an MRP system with requires an MRP-CRP run to determine capacity shortfalls, the MIS calculates capacity shortfalls at all times. Therefore, this corrects MRP's infinite capacity problem.

3.4.1.4 Provide what-if analysis and scenario planning for material, capacity, and sequencing

Simulation functionality enables intelligent decision making in response to production problems and material shortages. Area managers can utilize the MIS as a decision support system to determine the impact of machine breakages, worker shortages, and other production disturbances.

3.4.1.5 Serve as an Inter and Intra-Company Communications Medium

The MIS represents a central database which can drive supplier communication and forecasts as well as internal functionality enhancement. Basically, the MIS snaps into the ERP framework and enables data sharing across multiple company functions. Because all functions are automated, the long re-planning cycle associated with lean manufacturing as outlined in section 3.3.2.3.2 is reduced.

3.4.1.6 Minimize Reliance on WIP data

As depicted in figure 3-13, the ideal MPC is minimally dependent on production information and does not need production counts to re-plan the next schedule. By minimizing the reliance on production data, the system is much more robust and not susceptible to data integrity problems or information delays.

3.4.1.7 Serve as a Demand Management System

Central to the MPC is the concept of Demand Management. By keeping track of capacity loadings as orders flow in, the MP/MIS can intelligently quote due dates and lead times for any customer order. Build-ahead can be scheduled as needed. Therefore, the Demand Management System provides a process for matching customer demand with production supply. Additionally, the Demand Management System can provide a means of "pushing" some low volume orders through the system on a case-by-case basis.

3.4.2 Ideal Manufacturing Control and Execution System (MC-MES)

The MC-MES represents a shop floor where Kanban card loops control production planning and materials management. Professor J.T. Black outlines a theoretical model for the shop floor execution system in his book *The Design of the Factory with a Future*. In this MC-MES, management emphasis is placed on variability and waste reduction by reducing setup and process lead times. Through continuous improvement, shop floor managers proactively strive to understand and tune the production system instead of reacting to production problems and expediting late orders. Some of the characteristics of the MC function are listed below [Black, 1991]. Please note, this system is most beneficial in a repetitive manufacturing environment (automobile component assembly being an example) but tenants of the framework can be applied to other environments. Figure 3-15 depicts the shop floor arrangement of the "Factory with a Future."

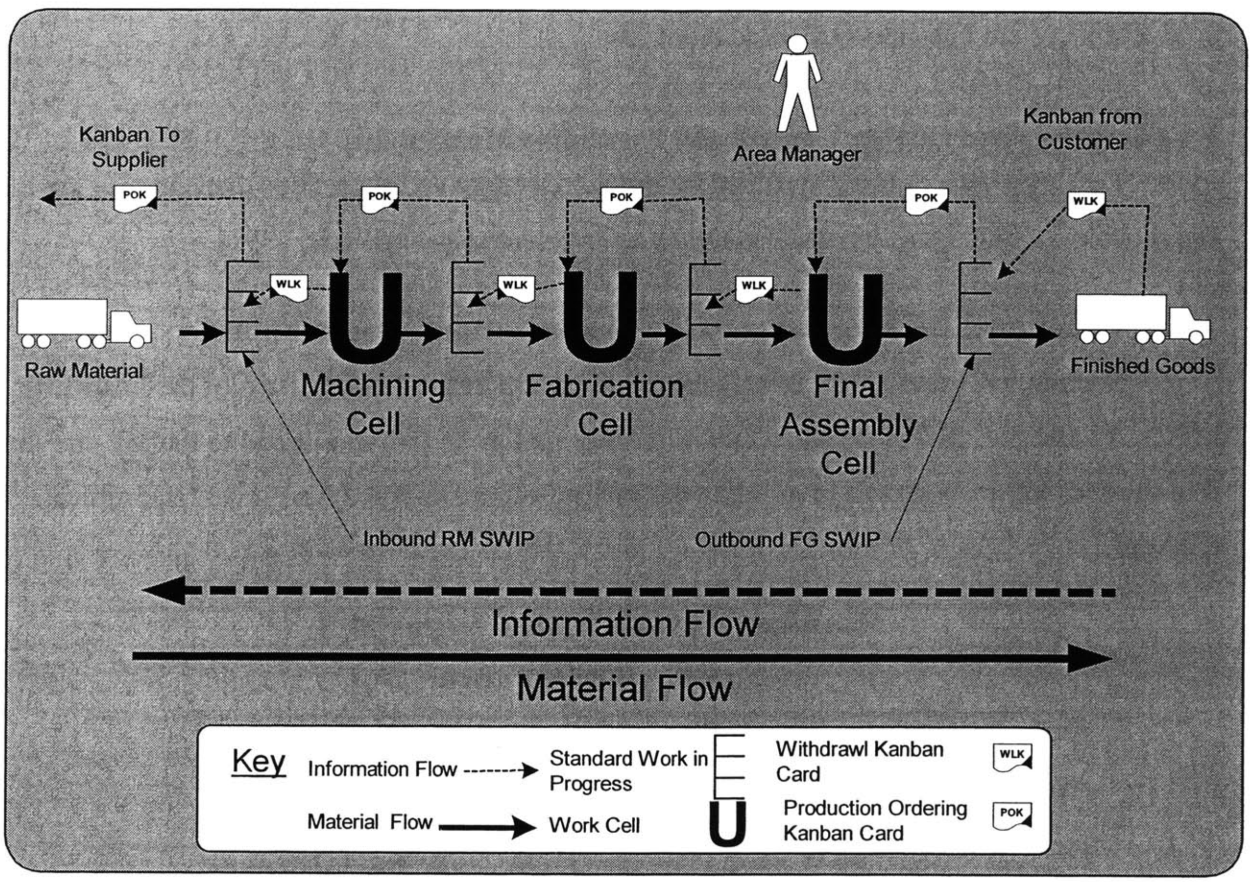


Figure 3-15 L-CMS Shop Floor Layout

3.4.2.1 Assemble to Order Final Assembly/ILVS

Final assembly is completed JIT as determined by actual customer order, ILVS as necessary.

3.4.2.2 Pull Processes

All material flows (including purchase parts from suppliers) occur via pull kanban loops. Low volume or special orders are handled by special kanbans on a case-by-case basis.

3.4.2.3 Lean, Linked-Cell Manufacturing System (L-CMS)

The shop floor is arranged as a L-CMS as depicted in [Black, 1991, 65]. Figure 3-15 depicts this shop floor layout.

3.4.2.4 Continuous Improvement

Shop floor management and operator enabled kaizen activities continuously redefine the production system in support of waste reduction.

3.4.2.5 Integrated Quality Control and Preventive Maintenance

In the "Factory with a Future," outlined by Black, operators and shop floor management are responsible for both quality control and preventive maintenance [Black, 1991].

3.4.3 Functional Requirements of the Manufacturing Information System (MIS)

Section 3.4.1 and 3.4.2 outlines the requirements of the 2 subsystems of the Lean-ERP MPC. As outlined above, the Manufacturing Information System in integral to the MP and links it to the MC-MES. With this in mind, the following summarizes the functional requirements of the MIS.

Manufacturing Information System (MIS) Functional Requirement
FR 1: Dynamically Smooth Demand and optimally sequence Final Assembly with a feasible schedule
FR 2: Size Standard Work in Progress (SWIP) Quantities / Determine number of inter-cell kanbans

FR 3: Determine Takt Time and Capacity Loadings of all production cells
FR 4: Provide what-if analysis and scenario planning for material, capacity, and sequencing
FR 5: Serve as an Inter and Intra-Company Communications Medium
FR 6: Serve as a Demand Management and Capacity Planning System
FR 7: Minimize Reliance on WIP Data
FR 8: Communicate Planning Requirements to MC for Decision Support

Table 3-1 Manufacturing Information System Functional Requirements

3.4.4 Chapter Summary

This chapter presented a theoretical framework for evaluating the Manufacturing Planning and Control (MPC) functions of different Manufacturing System Designs (MSD). In addition to the theoretical framework, background material on the evolution of both MSDs and the cultural impact of each was presented. The framework was developed in order to determine the functional requirements of the Manufacturing Information System (MIS) necessary to support an ideal hybrid MPC. Two different MSDs (MRP-Mass and Kanban-L-CMS) were then evaluated with the proposed framework and an ideal hybrid MPC system was outlined. The next chapter uses the MPC framework and the functional requirements of the ideal MIS developed in this chapter to further define the operations of the ideal MIS. This ideal MIS will then be used to evaluate two competing software designs.

4 Lean-ERP with Advanced Planning and Scheduling (APS)

Automotive manufacturing companies, like many modern industries, face numerous difficult decisions each year. Although not as glamorous as new product development or marketing and sales, strategic decisions regarding IT systems and Production System Design are key factors in determining a company's competitiveness.

As described in the previous chapters, MRP is a planning system that was designed to manage material in a functionally arranged job shop environment. Job shops are extremely difficult to schedule in that a part traversing a large factory can encounter billions of different flow-path combinations. A Lean, Linked Cell Manufacturing System (L-CMS) MSD removes a large portion of this complexity by integrating the MC and MES through JIT kanban control and single-piece flow cell design.

Similarly, in the supply chain, Toyota uses kanban card loops to order the "material release" of necessary components. Toyota holds very little component SWIP at assembly plants and thus, the kanban represents true customer demand. In the United States however, domestic OEMs (Visteon's Customers) do not issue supplier material releases by kanban but instead issue production forecasts via EDI. Automotive component suppliers initiate production as necessary based on the forecasts. Material shipments are then released to OEMs when the component supplier receives an EDI shipment signal [AIAG, 1998]. Since Domestic OEMs do not standardize the quantity of component inventory (as does Toyota with SWIP) or use a kanban signal to communicate true customer demand, domestic automotive component suppliers must rely on forecast accuracy and statistical models to identify the true customer demand rate. In comparison, In Line Vehicle Sequencing (ILVS) EDI signals represent the exact customer sequence and demand rate which produces a replenishment system with less safety stock held at either end. Thus, it is projected by the Automotive Industry Action Group (American OEM Forum) that domestic OEMs will increasingly require component items produced to customer order and delivered ILVS [AIAG, 1998].

As identified in chapter 2, OEMs are also attempting to reduce channel inventory by moving to a make to order model facilitated by the Internet. Automotive component suppliers therefore must prepare for increased ILVS requirements, decreased order to delivery lead times, decreased forecasting horizons, and increased mix and demand volatility. This chapter details how a new MPC design can be used to help meet some of the afore mentioned goals. Using the Manufacturing Information System (MIS) functional requirements developed in chapter 3, the following section outlines the "ideal" Lean-ERP MPC system design and then section 4.2 and 4.3 look at the operations of the two main MPC functions. Lastly, section 4.4 performs a qualitative comparison between two competing designs and the ideal Lean-ERP MPC system.

4.1 Lean-ERP MPC

4.1.1 System Design

As noted in the literature review in chapter 2, although there are volumes of books and articles regarding lean manufacturing, it is difficult to find many references to Manufacturing Information Systems (MIS) that support lean manufacturing. This section draws upon four main sources for the MIS design:

1) Yasuhiro Monden's *Toyota Production System* book which gives an excellent overview of Toyota's entire production system.
2) Wallace Hopp and Mark Spearman's *Factory Physics* book which outlines a pull production planning hierarchy.
3) Professor David Cochran's Production System Design axiomatic decomposition diagram.
4) Professor Jeff Liker's Automotive Manufacturing and Production article *Advanced Planning Systems as an Enabler of Lean Manufacturing.*

4.1.2 Lean-ERP MPC Architecture

4.1.2.1 Interaction of IT system and work environment

As noted in section 3.2, one advantage of the Toyota Production System (TPS) is that the Manufacturing System Design (MSD) enables a company culture which fosters continuous improvement. SWIP inventory buffers between work cells helps to facilitate much of the continuous improvement as does cellular shop floor layouts. By linking customers and suppliers with direct relationships, there are no information delays associated with decentralized planning and thus the manufacturing system produces to exact customer demand. Thus, when shop floor control is embedded in the MES, the entire MS can build to exact customer demand instead of forecasted demand. A schedule driven production system undermines this direct customer relationship in that the emphasis in this environment is placed on building to the schedule instead of building to the direct customer's need. A pull production system is therefore much more responsive to changes in customer demand, scheduling final assembly in a level, smoothed fashion.

As described in section 3.4 and figure 3-13, the ideal MPC system design consists of two components, the Planning System (MP-MIS) and the Control and Execution System (MC-MES). The "ideal" Lean-ERP MPC system design is further broken down into the following elements:

1) **MC-MES** consisting of 3 elements, A) Inbound Operations, B) Production Operations, and C) Outbound Operations.
2) **MP-MIS** consisting of 3 parts A) Database Transaction and Accounting System (DTAS) B) Memory Resident Scheduling System (MRSS), and C) Actual Performance Measurement System (APMS)

4.1.3 Lean-ERP MC-MES

The intent of this section is not to detail the design the MC-MES down to specific workflows, but rather to demonstrate the subsystem interaction with the MP-MIS. Therefore, only minimal details of the MC-MES are provided. Please note, as described in chapter 3, the ideal MC-MES described below represents the L-CMS shop floor arrangement described in [Black, 1991]. The main differences between the Lean-ERP MC-MES described below and the diagram shown in figure 3-15 is that the Lean-ERP design utilizes the MIS to prepare a final assembly schedule for the heijunka box and it uses EDI to communicate with customers and suppliers in the supply chain. Figure 4-1 shows the linkages in the overall supply chain. This figure helps to structure the decomposition of the MC-MEC into its three components: inbound receiving operations, production operations, and outbound shipping operations.

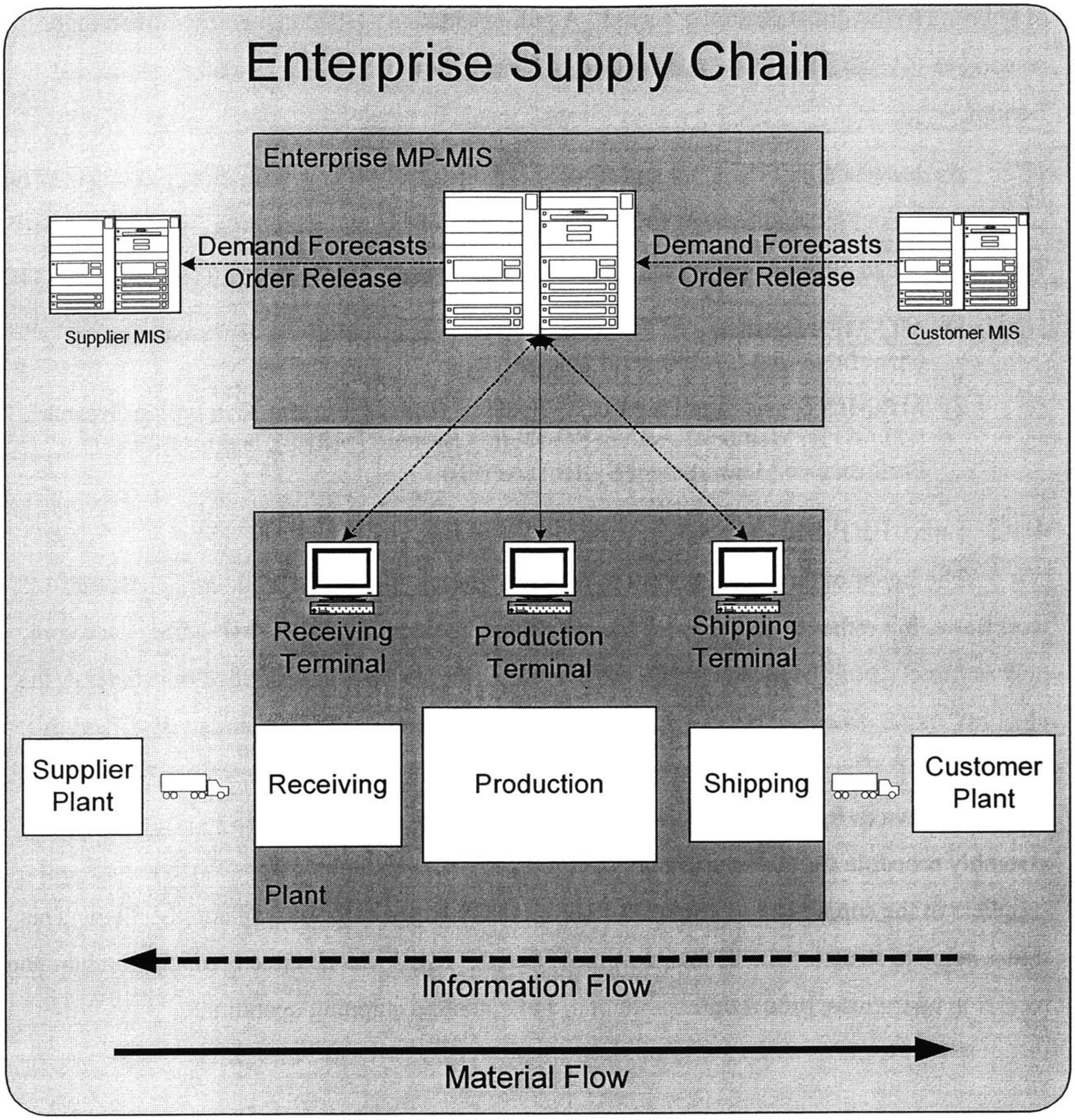


Figure 4-1 Enterprise Supply Chain

4.1.3.1 Inbound marketplace operations

Inbound Operations consists of receiving shipments from customers and preparing the material for the material handlers who replenish the line side stockage. All supplier replenishment shipments are ordered via an Electronic Kanban EDI signal based on actual consumption.

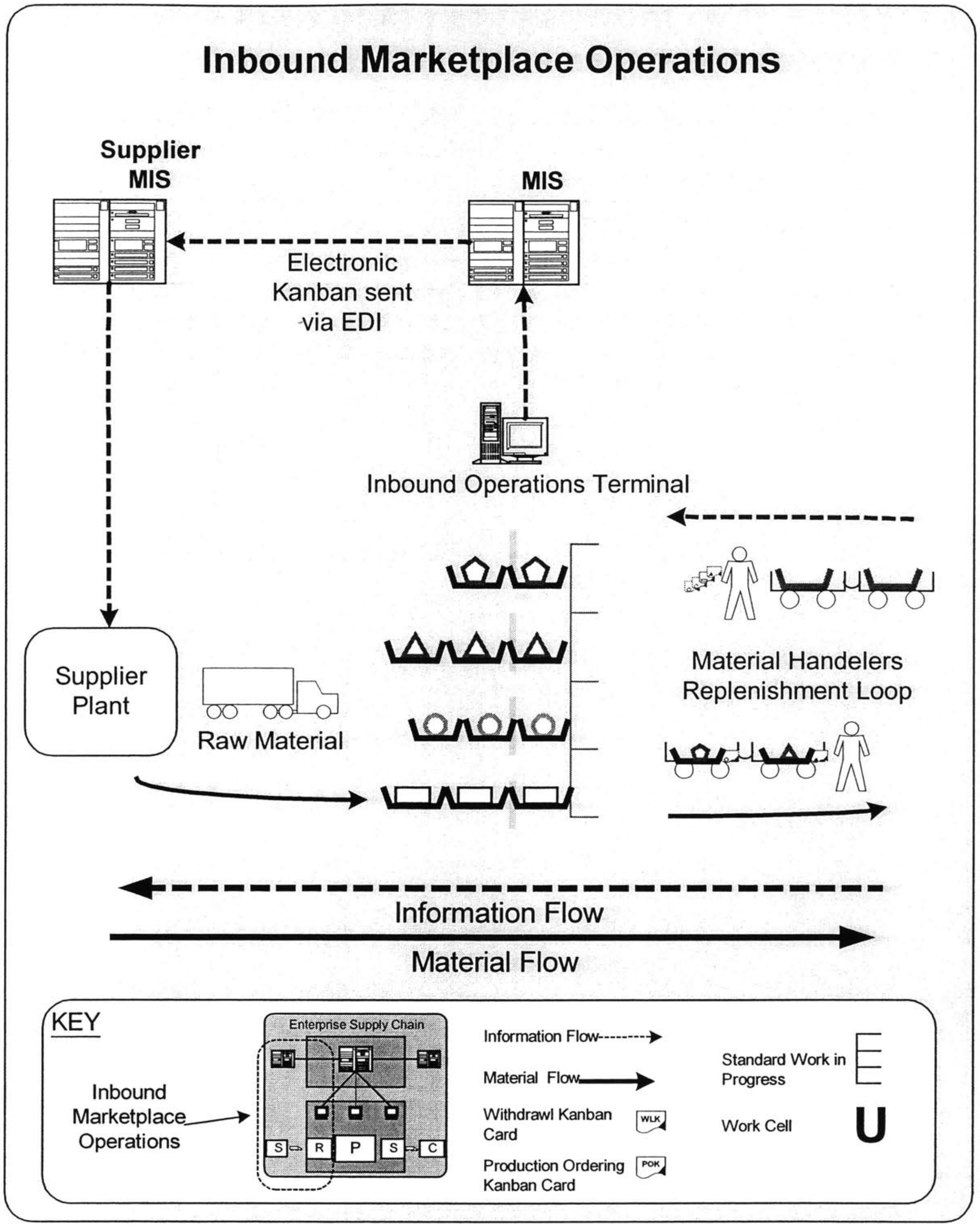


Figure 4-2 Inbound Marketplace Operations

4.1.3.2 Production Operations

Figure 4-3 shows a diagram of the production operation which consists of lean linked fabrication and assembly cells. All material flow for the MC-MSE occurs via sequential pull signals except for the final assembly cells which are scheduled via Heijunka box. The IT system interacts with production in two ways

1) Schedule the final operation via heijunka box. The IT system provides the loading schedule for the heijunka box. All other material flow throughout the plant is controlled by kanban loops.
2) Determines SQIP stocks and/or kanban quantities. The production supervisor uses the IT system to view the impact of demand volatility on his/her area by displaying a capacity loading projection. Using this data, the supervisor then enters the actual quantity of kanbans into the MIS system. Note: the MIS does not need to know the location of these kanbans at any given time, just the total quantity in circulation and the physical container size.

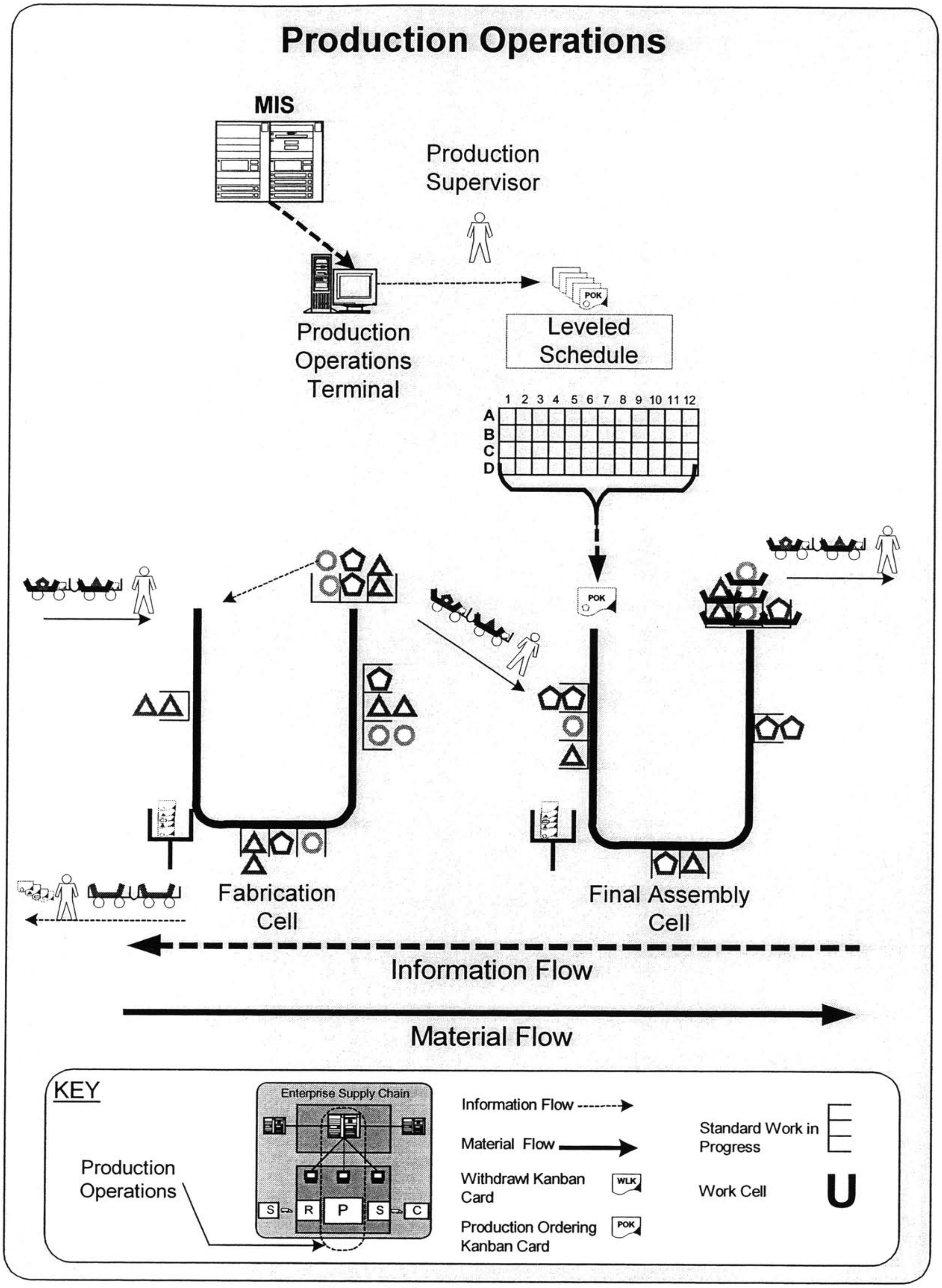


Figure 4-3 Production Operations

4.1.3.3 Outbound Marketplace Operations

Outbound operations consists of counting the finished goods into the outbound market place, applying barcodes to the shipping containers, and then packing orders as directed by the MIS system. As in the inbound marketplace, the IT system monitors the finished goods in the outbound marketplace. The MIS also provides all of the shipping documentation.

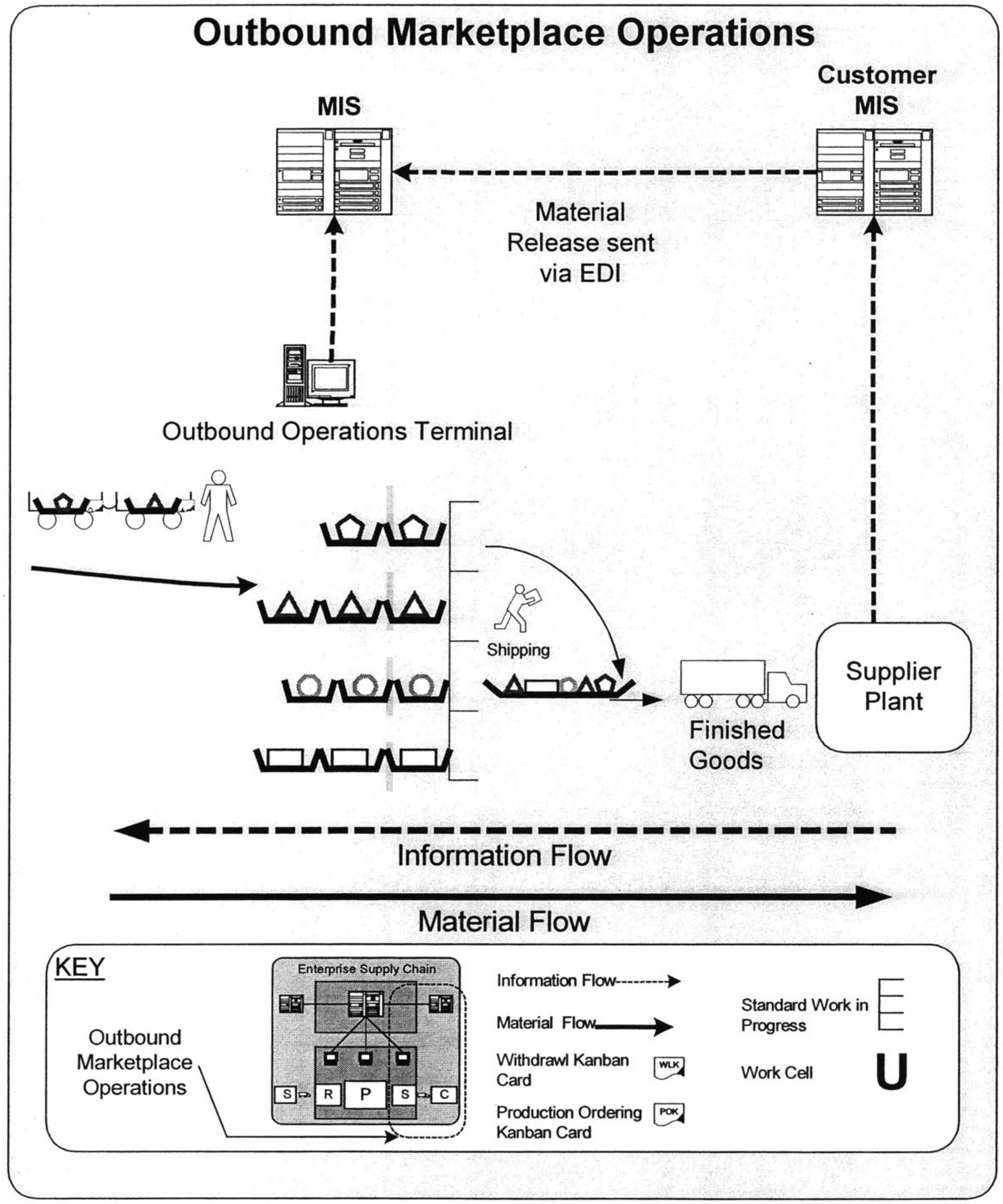


Figure 4-4 Outbound Marketplace Operations

4.1.4 Lean-ERP Manufacturing Planning-Manufacturing Information System (MP-MIS)

The MIS is a multi tiered architecture which consists of A) Database Transaction and Accounting System (DTAS), B) Memory Resident Scheduling System (MRSS), and C) Actual Performance Measurement System (APMS). The goal of the MP is to support the pull planning framework as described in Chapter 3, figure 3-11.

1) **DTAS** - Database Transaction and Accounting System: this software program is an ERP system without an MRPII planning engine
2) **MRSS** – Memory Resident Scheduling System: This is an APS software module that is used to perform Production Planning (PP) and Materials Management (MM). It is not dependent on WIP data to make its calculations and it is directly connected to the DTAS to receive continuous product and customer order data.

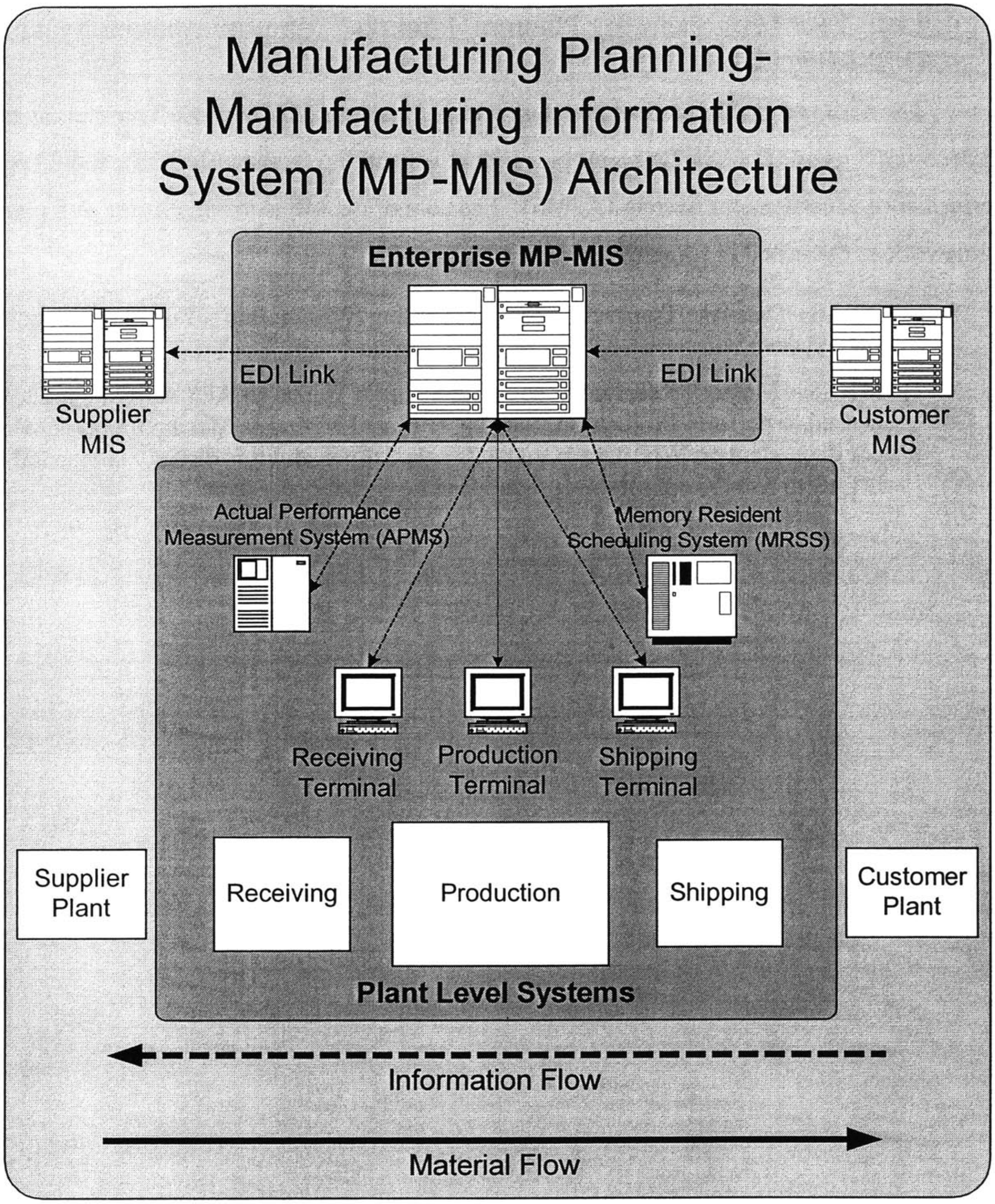


Figure 4-5 Lean-ERP IT Architecture

4.1.4.1 Database Transaction and Accounting System (DTAS)

The DTAS handles the day-to-day business transactions of the company. There is only one DTAS instance in the enterprise. The DTAS can be thought of as a traditional ERP in that all data is centralized to reduce data duplication errors. The main differentiation between the

DTAS and an ERP system is that this system does not utilize an MRPII engine to perform material and production calculations. This system contains all accounting, order status, finance, and product data for the entire company. All EDI transactions are controlled by the DTAS.

Inputs:

- Product Data: BOM Data, production part or purchase part, costs.
- Process Data: Routings for each part, locations, cell cycle times.
- Transportation Data: Outbound and inbound transportation requirements and schedules.
- FG and RM Inventory status- the DTAS receives input data from the inbound and outbound operations.

Outputs:

- Orders and due dates (after conferring with the MRSS on capacity and lead time projections).
- Any other accounting, financial, order, inventory, or production data as needed.
- EDI links to the supply chain and customer base.

4.1.4.2 Memory Resident Scheduling System (MRSS)

The Lean-ERP system controls production at the enterprise level by communicating with the MRSS at the plant level. Therefore, a single MRSS instance is needed for each individual plant. The DTAS communicates the demand orders and shipping schedules to the plant MRSS in real time. This real time link provides the functionality of an Available to Promise (ATP) server. The ATP server is necessary so that the DTAS can query new orders and forecasts against projected plant capacity as the orders and forecasts are received. The MRSS exclusively receives all data inputs from the DTAS so as to ensure centralized data integrity. The main function of the MRSS is to provide a smoothed, feasible production schedule based on the Takt time down to the plant floor via a Heijunka box.

Inputs:

1) Transactional Data from DTAS

- Orders and shipping schedules/due dates.
- Transportation arrangements and freight costs (frequency of shipments and legs, cost of premium freight, truck capacity, available modes of transportation).
- Finished Goods (FG) Inventory.

- Raw Material (RM) Inventory.
- Input from the Actual Production System (for statistical comparisons).

2) Product Data from DTAS

- Bill of Material (BOM) data.
- Product Routings and specific info for each product (specific setup times, cycle times, cooling times, etc).
- Supplier Lead times, shipping schedule, truck capacity, available transportation modes.

3) Factory Model from DTAS

- Number of kanbans between each work center for each flow path to estimate the lead times.
- Capacity estimate of each cell-the cycle time of the manufacturing cell scaled to an appropriate factor ($r_p = C^* r_b$). This concept was taken from [Hopp & Spearman, 1996, 386].

Outputs:

- Suggestion for the number of inter-cell kanbans (recommendation to production supervisors).
- Capacity utilization at the cell level for feedback to the area production managers.
- Single, leveled schedule to final assembly cell heijunka boxes.
- Minimum and Maximum levels for the inbound and outbound marketplaces.

4.1.5 Actual Performance Measurement System (APMS)

The APMS is used to identify areas of interest for Kaizen activities. This concept was taken from [Monden, 1998, 300].

Inputs:

- Order data and shipping schedule.
- Kanban recommendations.
- Actual production statistics.

Outputs:

- Identification of areas in need of continuous improvement.
- The information system estimates how long inventory is held in inbound marketplaces and suggests where kanbans can be removed and where safety stock can be eliminated.

- Calculates actual performance versus scheduled performance.

4.2 Lean-ERP Production Planning

4.2.1 Capacity planning

Capacity planning is completed by the MRSS system though an iterative process which maps the customer orders on to the capacity estimate of each work center. The MRSS is similar to a finite capacity scheduler (FCS) which tracks capacity utilization by resource in each area. The main difference is that a traditional FCS takes the Master Production Schedule after the MRP run has been completed and tries to fit the schedule into existing capacity. The MRSS in this configuration works in conjunction with the DTAS to quote capacity in real time as the orders come in from customers so that quoted lead times are achievable. This following algorithm can be used to determine the Takt time of shared upstream resources

MRSS Capacity Planning Algorithm

1) Using customer orders, cell cycle times and setup times, start at the final assembly point and determine the sequence of orders necessary to meet demand.
2) Using the time calculated above, use the BOM data and part routings to work backwards through the routing to determine each cell's utilization and Takt time.
3) Compare each cell's center's Takt time to its minimum cycle (r_p) time.
4) Identify any cell where the Takt time is below to the minimum cycle time and use a rules based algorithm to smooth and sequence final assembly order loading until the schedule is feasible. Determine the additional queuing time and changeover time associated with the most heavily utilized work center. Add the additional time onto each production sequence.
5) Iterate the above procedure until all work centers are loaded according to capacity estimates. If a feasible schedule cannot be completed, report the area with the capacity shortfall.
6) Report utilization estimations and suggest if kanbans should be added or removed from the system based on the Takt time changes.

Note: This algorithm is loosely based in part on Hopp and Spearman's MRP-C algorithm [Hopp & Spearman, 1996, 490]. If the product flow path does not have any shared resources, there is no need to run the algorithm.

4.2.2 Smart Sequencing and Demand Leveling via Heijunka

As described in the capacity planning algorithm above, an MRSS system can utilize a rules based sequencing of work at the bottleneck. In an ideally designed production system, the bottleneck would be the final assembly area and therefore the algorithm would converge on a solution very rapidly. As noted above, the heijunka box is the only point on the shop floor that is scheduled since this is the operation at which most products take on a unique identity and have the most configuration options. If automotive component suppliers increasingly produce integrated product architectures with multiple configurations, the final assembly scheduling system will become increasingly important.

The sequencing of the heijunka box has a tremendous impact on the rest of the production system. Monden notes that Toyota recently introduced advanced Artificial Intelligence to sequence painted car bodies onto the assembly line. Using an expert system, the company attempts to optimize the leveling pattern based on multiple production criteria [Monden, 1988, 272]. The MRSS described above would perform this exact same task at a Tier-1 supplier based on the order stream received from the OEMs. In addition to leveling, the MRSS system uses utilizing a smoothing algorithm which orders production in advance of demand spikes to prevent capacity shortfalls. Therefore, the MRSS creates a level, smoothed production sequence that meets all customer demands and provides minimal production spikes.

4.2.3 Simulation and What-if Analysis

A final Production Panning tool an MRSS system can provide is simulation. Since the MRSS system represents a mathematical model of the actual production floor, it is relatively easy to perform what-if analysis by modifying any of the system parameters. The memory resident system design provides very responsive computing performance so that many what-if scenarios can be evaluated quickly. Thus the MP-MIS also serves as a Decision Support System for Production Planning.

4.3 Lean-ERP Materials Management

4.3.1 Marketplace Sizing

4.3.1.1 Inbound Marketplace.

The MRSS also provides a Decision Support System for refining relationships with suppliers. The Automotive Industry Action Group (AIAG) provides guidelines for EDI processes between customers and suppliers [AIAG, 1998]. The guidelines dictate data standards in support of both "build to demand" forecast and "build to order" scheduling respectively. The EDI workflow outlined by the AIAG standards dictate how the EDI information should be transacted under both standards (pull and push). The flexibility of the MRSS enables it to be configured so as to use either of the EDI arrangements and still manage the inbound marketplace size. This is useful for manufacturers whose supply chain does not yet fully support lean processes or kanban flows.

The MRSS also calculates material forecasts for suppliers during the production smoothing iteration. Upon completion of the master schedule, the MRSS calculates the supplier forecasts to be communicated by the DTAS via EDI.

4.3.1.2 Outbound Marketplace.

The MRSS also provides a decision support tool for dealing with customers. Although automotive assembly lead times are decreasing, the assemblers must still provide a lock-in window for ILVS shipments. With a more direct sales channel, Automakers will be forced to reduce this window to a bare minimum. Although the lock-in window will shrink from today's levels, the assemblers will still have information about completed sales orders well in advance of the sequence lock-in. By tying supply chain information systems together, assemblers can refine forecasts with a continuous stream of sequencing information. The only way for component manufactures to respond to this continuous stream of information is with memory resident information systems that are not subject to batch processing delays.

4.3.2 Kanban Management

One of the most difficult challenges facing a manufacturer during a lean transition is determining the quantity and size of inter-process kanbans. One clever analogy used often in lean literature is that by reducing WIP, a manufacturing company is in effect "lowering the water in the stream so as to expose the rocks." The key is to avoid crashing headlong into the newly exposed rocks [Vollman, 1997, 95].

Kanban management is one of the key factors in determining a company's lean success. Monden outlines the details of kanban management very well in his book. One principle that separates a lean MPC system from a MRP MPC system is the decentralized nature of the materials management. The final authority to change the number of kanbans in the TPS resides with the area production supervisor [Monden, 1998]. Supervisors are the individuals who understand the production system capabilities the best and therefore they should control the amount of safety stock they own. The MP-MIS design detailed above does not deviate from this principle, but rather it provides a decision support tool for helping manage the kanbans and thus helps to negotiate the production system "rocks."

4.4 Qualitative comparison of MRPII and APS in support of Lean Manufacturing

4.4.1 Lean-ERP/APS as the MP-MIS

As described in Chapter 2, Advanced Planning and Scheduling (APS) software is a new concept in manufacturing software which takes advantage of recent advancements in computing power. Although APS systems represent a great advance in scheduling software, "traditional" APS systems violate the reliance on WIP data FR noted in table 3-2. "Traditional" means that APS systems utilize WIP data to produce MRP-like work orders for the shop floor. The MP-MIS system described in the next section does not utilize WIP data nor produce work orders.

4.4.1.1 APS as MRSS and ERP as the DTAS

Section 4-1 outlines the notion of a Memory Resident Scheduling System at the plant level for final assembly scheduling, production smoothing, and kanban decision support. The MRSS outlined above is based on the concept of APS. Therefore, APS can be configured to serve the functional requirements of a MRSS. Similarly, an ERP system backbone can provide the DTAS functionality.

4.4.2 Lean-ERP/MRPII as the MP-MIS

Current ERP systems utilize MRPII as the Production Planning and Materials Management engine. As outlined in Chapter 3, a "traditional" MRPII planning engine does not fulfill the FRs outlined in table 3-2. Thus, the following section will attempt to outline how MRPII could be used as the Lean-ERP MPC. Two articles by RAO to help define this framework [Rao, 1989] and [Rao & Scherga, 1988].

4.4.2.1 Schedule only at Final Assembly

The MPC will only schedule the final assembly sequence and not any other operation.

4.4.2.2 Phantom Bills of Material

Instead of detailed BOMs and production schedules, the planning engine will only communicate demand to suppliers via forecast (EDI 856).

4.4.2.3 Backflushing

Material will be recorded upon receipt from suppliers and will be deducted from inventory upon completion of the final assembly.

4.4.2.4 Forecasts sent to Suppliers with Fixed Lead Times

As noted above, the main purpose of the planning engine is to communicate forecasts to suppliers. The lead times associated with the forecasts will be fixed and thus are an approximation.

4.4.2.5 Material Ordered via Kanban Signals

Material ordering will occur in the same manner as depicted in the Lean-ERP description above.

4.4.3 Qualitative Comparison of APS and MRPII

This section builds upon the previous discussions in order to perform a qualitative comparison of IT system functionality in support of lean manufacturing. The functional requirements were taken from the ideal system discussion in Chapter 3. In order to be clear about what is being compared, please consider the following points:

1) Section 4.2 outlined an MP-MIS system architecture that supports a L-CMS MES using the terms DTAS and MRSS. In section 4.1.2, the terms DTAS and MRSS were developed to prevent confusion and prejudice associated with the terms ERP and APS. Please re-read section 4.1.2 if there is confusion regarding taxonomy.
2) The 2 software systems under consideration here are EITHER an ERP system with an MRPII scheduling engine OR an ERP system with an APS scheduling engine.
3) The Manufacturing Execution System (MES) is a Lean Linked Cell Manufacturing System (L-CMS). The goal of this thesis is to define a Manufacturing System Information System (MIS) that supports the planning functions for this MES design.
4) The following comparison is **NOT** MRP versus Lean/JIT, it is an ERP system which uses either a MRPII planning engine OR an APS planning engine in support of a L-CMS MES.

4.4.3.1 FR 1: Dynamically smooth demand and optimally level and sequence Final Assembly with a feasible schedule.

4.4.3.1.1 APS

This is possible with an APS engine. An APS engine uses the same type of Artificial Intelligence (Expert System) technology as described in the Toyota example of optimal assembly sequencing [Monden, 1989]. APS also operates in real time as a memory resident process. Because of this, the demand management (for demand smoothing) and optimal sequencing algorithms (for leveling) can run concurrently and thus the sequence can be updated as necessary when changes occur.

4.4.3.1.2 MRPII

This process is very difficult with MRPII. Manual workarounds or a Finite Capacity Scheduler (FCS) would be necessary after the MRP-CRP output as depicted in Figure 3-7. Since MRPII operates as a batch computing process and it lacks the level of fidelity needed to perform optimal scheduling, the system cannot perform the operation dynamically. See [Rao & Scheraga, 1988, 45].

4.4.3.2 FR 2: Size Standard Work In Progress (SWIP) Quantities / Determine number of inter-cell kanbans

4.4.3.2.1 APS

APS can perform this function by modeling the cell capacity loadings at all time. The APS system's mathematical modeling of the plant floor enables it to determine the impact of a final assembly schedule because the data model includes all of the component part routings. Using the demand forecast to predict the future plant loading, the MIS determines cell capacity loadings and the number of kanbans necessary to complete production with the predicted lead times based on the cell loading. Note: this function is most necessary for cells with multiple customers or multiple parts. If the cell only has one customer, then the calculation is not difficult and can be generated based solely on the end component demand rate.

4.4.3.2.2 MRPII

MRPII can set lot sizes and EOQ requirements, but these are fixed inputs into the MRP calculation and thus an additional processing algorithm would be necessary once the MRP-CRP output is generated.

4.4.3.3 FR 3: Determine Takt Time and Capacity Loadings of all production cells.

4.4.3.3.1 APS

This can be calculated with APS as the system tracks capacity loadings per each work cell.

4.4.3.3.2 MRPII

Very difficult with MRPII. Manual calculations would be necessary either before or after the Gross to Net BOM explosion.

4.4.3.4 FR 4: Provide what-if analysis and scenario planning for material, capacity, and sequencing

4.4.3.4.1 APS

Simulation is part of the APS design. Also, the APS system can provide recommendations to production problems, as the system represents a mathematical model of the shop floor.

4.4.3.4.2 MRPII

It is very difficult to perform decision support activities with the operational system. MRP was designed as a transaction system architecture and not as a Decision Support System.

4.4.3.5 FR 5: Serve as an Inter and Intra-Company Communications Medium

4.4.3.5.1 APS

APS is a decision support module which supports the ERP data transaction backbone. ERP is the centralized database which can handle all of the communications requirements. All functions can query the plant level APS systems as necessary. For example, a purchasing agent can query the projected material requirements of a certain supplier.

4.4.3.5.2 MRPII

Data management is integrated into the MRPII module and therefore MRPII can perform this function in conjunction with ERP.

4.4.3.6 FR 6: Serve as a Demand Management System

4.4.3.6.1 APS

Cell capacity is tracked in real time and thus the impact of orders can be shown in real time so lead times and due dates can be quoted when the order is taken.

4.4.3.6.2 MRPII

MRPII does include a Demand Management System, but the impact of the order cannot be calculated until after the next MRP-CRP run.

4.4.3.7 FR 7: Minimize Reliance on WIP Data

4.4.3.7.1 APS

As defined in section 4-1, APS can be configured so that it is not dependent on WIP data.

4.4.3.7.2 MRPII

MRPII can also be configured so that it requires no WIP data. However, this system configuration cannot track cell capacity loadings without WIP data.

4.4.3.8 FR 8: Communicate Planning Requirements to Manufacturing Control (MC)

4.4.3.8.1 APS

Final Assembly is scheduled via Heijunka box. Shop floor managers can query the system to determine individual cell capacity loadings.

4.4.3.8.2 MRPII

MRPII can provide a schedule for final assembly, but as described above, it cannot track cell capacity loadings without scheduling each operation.

4.4.4 Chapter Summary

This chapter details the functionality of the ideal Lean-ERP MPC system. The proposed system was designed to fulfill the functional requirements developed in chapter 3. The ideal MPC system was then compared to Visteon's two competing ERP configurations available: one which uses an APS planning engine and one which uses an MRPII planning engine. In short, the MRPII planning engine was not designed to support a Lean L-CMS Manufacturing Execution System (MES) and therefore it does so poorly. In comparison, APS was designed to be very flexible and perform planning for many different manufacturing environments. Therefore, as defined in 4.2, the APS planning engine adapts well to a Lean L-CMS MES.

5 Lean-ERP Simulation Model

This chapter describes the Discrete Event Simulation (DES) computer model developed to quantify the MRPII versus APS comparison. The model consisted of a Microsoft Excel Spreadsheet, Visual Basic for Applications (VBA) code modules, and a Simul8 DES model. This chapter first outlines the motivation for developing the model and then details the model functionality. The last section in the chapter outlines the simulation model results.

5.1 Simulation Motivation

5.1.1 Simulation Overview

The Visteon SAP project represents a capital investment of several hundred million dollars and several hundred man-years. Due to the volatile political nature surrounding the different factions of project Vista, the PMD team felt it necessary to quantify the system performance of the two competing ERP planning engines (MRPII and APS). Benton and Shin evaluated several different MRP-JIT analytical integration models and found that a hybrid system performs better than does either individual system [Benton & Shin, 1998, 432]. As none of the simulation literature quite represented the manufacturing environment or IT architecture the PMD team was considering, the author undertook the project of developing a quantitative analysis model.

The term "a picture is worth a thousand words" helps describes the need for a simulation model for evaluating the two competing MISs. A discrete events simulation model was chosen for two reasons: visualization and multiple-variable quantification.

- Visualization: The simulation model needed to be easy to understand and communicate, thus a graphical representation of the workflow was necessary.
- Quantification. A DES can simultaneously quantify the operational performance parameters of many different variables. Thus, a computer model is infinitely more flexible than a mathematical model.

Other types of quantitative analysis methods include 1) static statistical analysis, 2) mathematical modeling using Markov chains or 3) actual field studies using existing processes. Although the third choice may have proved ideal, very few L-CMS final assembly processes existed within Visteon at the time of the internship and those that did were not mature enough to perform experiments with. Thus, it was necessary to create a "virtual factory" to perform the MIS evaluation experiments. The PMD team therefore chose simulation as a means for testing the proposed IT functionality without spending large amounts of money and effort to pilot the proposed MIS systems in an actual plant.

5.1.2 Simulation Objectives and Scope

The objective of the simulation is to quantify the operational characteristics of a L-CMS Manufacturing Control and Execution System (MC-MES) with a Lean-ERP Manufacturing Planning and Information System (MP-MIS). The simulation models the Lean-ERP MPC using an Excel spreadsheet and VBA code modules. The Lean-ERP MP-MIS model will consist of two variants: one modeled as an APS planning engine and one modeled as a MRPII planning engine. A single L-CMS MES will be modeled using Discrete Events Simulation (DES). The following further defines the simulation scope.

- **Lean MSD Only:** This simulation will not compare the performance attributes of lean versus non-lean Manufacturing System designs. It will only compare the APS versus MRPII planning engines of the MP-MIS.
- **Area Level System Focus:** The simulation involves the production planning and materials management processes of the Manufacturing System at the Area Level. The MES model will simulate Cells as the lowest measure of capacity.
- **Generic Process:** The simulation is an amalgamation of the physical characteristics of several different Visteon manufacturing processes. The resultant process is generic with a stochastic cycle time.

5.1.3 Operational Variables to Model

5.1.3.1 Model Inputs

Model inputs consisted of customer demand inputs, physical operating parameters, and simulation duration.

5.1.3.1.1 Customer Demand Inputs

Demand inputs are a simulation of actual customer demand. These inputs consisted of Demand Volume, Demand Variability, and Forecast Accuracy. These parameters were changed for each run.

5.1.3.1.2 Physical Operating Parameters

Physical Operating Parameters refers to the machine reliability in the form of cell reliability and Mean Time to Repair (MTTR).

5.1.3.1.3 Simulation Duration

Simulation Duration controlled how many weeks the simulation was run for. The maximum number of weeks was set at 27 (1/2 of a year).

5.1.3.2 Model Outputs

The simulation was originally intended to convert all model outputs into the standard Ford Production System (FPS) measurables: First Time Through percentage, Dock to Dock time, Build to Schedule percentage, and Overall Equipment Efficiency. Upon further inspection and analysis of the formulas associated with the terms, it seemed unbeneficial to perform such calculations as the simulation could capture the ACTUAL performance parameters instead of the FPS approximations. The simulation therefore captures the following actual parameters

5.1.3.2.1 Inventory Quantity

This is the total Work in Process and Finished Goods Inventory (by part type) in the system.

5.1.3.2.2 Dock to Dock Time

DTD is the total time a part spends in the Manufacturing System.

5.1.3.2.3 Late Orders

This metric keeps track of the quantity of late orders. As a late order is a late order, the duration of "lateness" was not tracked.

5.1.4 Model Verification Process

"All models are wrong, but some are useful!" George E.P. Box

The intent of the simulation model was not to develop exact system parameters, but rather to gain insight on how a Manufacturing System should respond under each different MP-MIS configuration. With this in mind, the PMD team iteratively worked on the simulation model and developed the computer code to match the team's mental model of how the MIS would work. The simulation was developed over a period of about 10 weeks beginning in September 1999.

5.2 Lean-ERP Simulation Model Description

5.2.1 Simulation Modules and Information flow

The Lean-ERP computer simulation model is broken up into four modules. Figure 5-1 depicts the simulation information flow. Simulation users set simulation variables using the User Interface Module (UIM). The Demand Module (DM) takes this input to create a 27-week demand stream forecast for processing by the MIS module. The MIS module then takes the demand stream forecast and calculates system parameters based on the forecast and communicates the system parameters to the MC-MES module for execution. The MC-MES module then simulates shop floor execution for the allotted time period. Throughout the simulation, the Data Analysis Module (DAM) keeps track of the system variables. Upon completion of the simulation, the DAM then calculates the overall Manufacturing System performance.

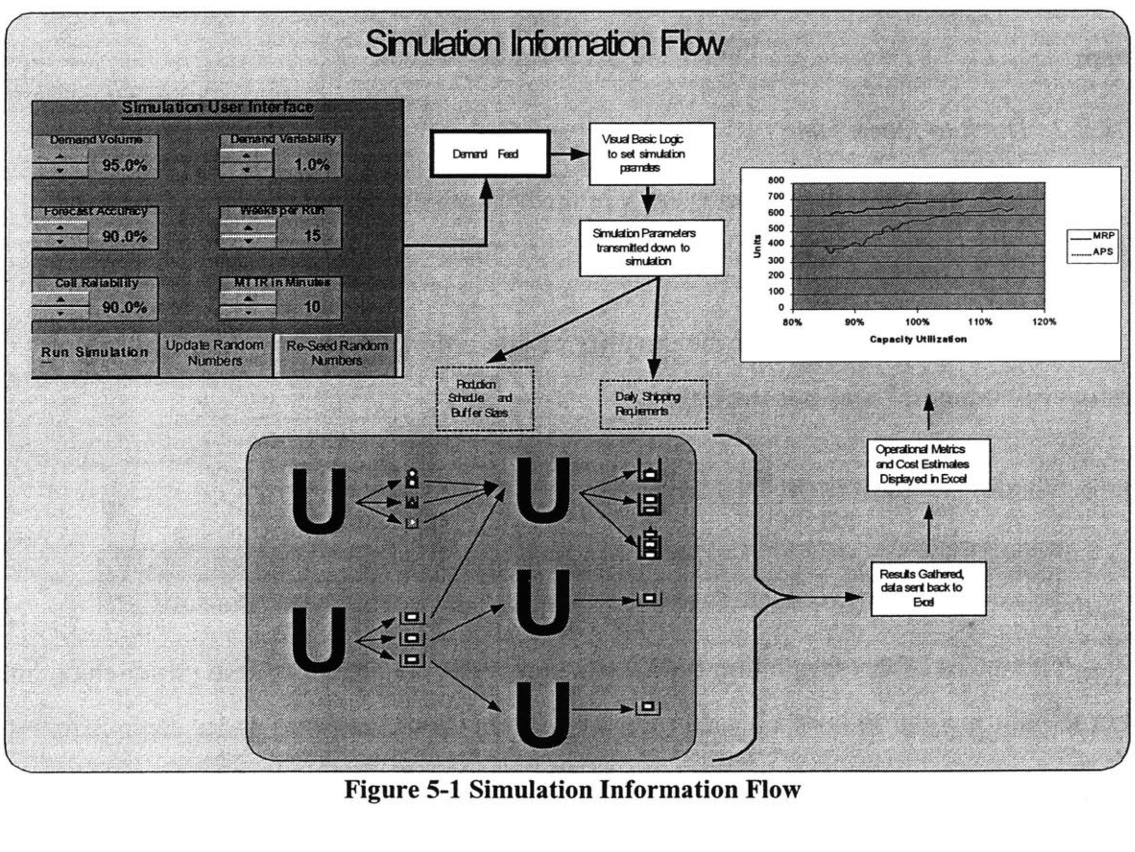


Figure 5-1 Simulation Information Flow

5.2.2 User Interface Module (UIM)

The UIM was the simplest of the five modules and consisted of a simple Microsoft Excel Spreadsheet with buttons for changing the data input. The figure 5-2 depicts the UI.

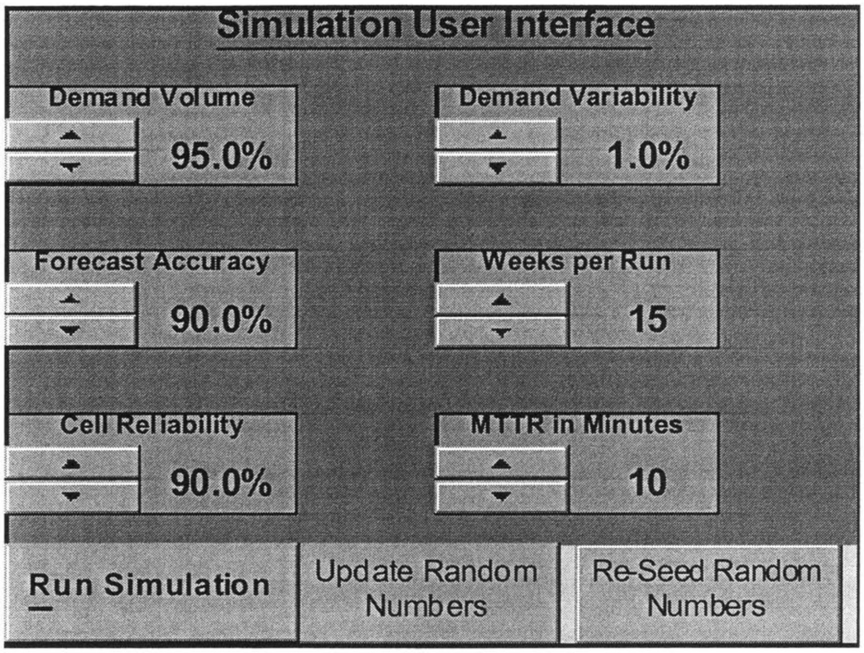


Figure 5-2 Simulation User Interface

5.2.3 Demand Module (DM)

The DM contains a detailed spreadsheet and Visual Basic code which uses a random number generator to convert the volume and variability input from the UIM into a stream of customer demand.

The final assembly volume and Takt Time is calculated via the following formulas.

$$AT = CR \cdot Seconds / Week - WorkDays / week \cdot \sum_i ST_i$$

$$TT_S = \frac{TT_{Min}}{DV}$$

$$MWD = \frac{TT_S}{AT}$$

Where

TT_s = Simulation Takt Time (Final Assembly) [seconds]
TT_{Min} = Minimum Theoritical Takt Time of Final Assembly Cell
DV = Demand Volume (Input from UIM)
MWD = Mean Weekly Demand [units/week]

AT = Available Time [seconds/week]
CR = Cell Reliability (Input from UIM)
ST_i = Setup Time (for each i products) [seconds]
i = Number of Products

A 27-week demand stream is then created using the following formulas:

$$SD = \sqrt{MWD^2 VI}$$

$$WD_j = NormInv(RN)MWD + SD$$

Where
SD = Standard Deviation
VI = Variability Input (Input from UIM)
WDj = Weekly Demand for Week j
NormsInv = Inverse Normal Function (Excel Spreadsheet Function)
RN = Computer Generated Random number between 0 and 1
j = Number of weeks in the simulation run (Input from UIM)

The Mean Weekly Demand (MWD) is then converted into a daily shipping schedule forecast for 3 Final Assemblies by multiplying the MWD by a shipping pattern and volume variable. The result of this calculation is a daily shipping pattern for 3 products for 27 weeks.

The daily shipping pattern is then manipulated further to create 27 weeks worth of 15 day demand blocks (5 day lock-in and 10 day forecast) by scaling each ship quantity each day by a random number from 1+/- the forecast accuracy percentage input.

The final output of the DM is a 27-week demand feed based on the Demand Volume, Demand Variability, and Forecast Accuracy. To help verify the DM, a demand forecast for a product manufactured by the Visteon Altec facility was used to establish a baseline variability setting. Both the Model Demand and the Altec demand equate to a Squared Coefficient of the Variance of 5%. Figure 5-3 is a graphical representation of the DM output and Figure 5-4 is a snapshot of the spreadsheet data feed. Note: the Altec data is disguised to protect proprietary volume figures.

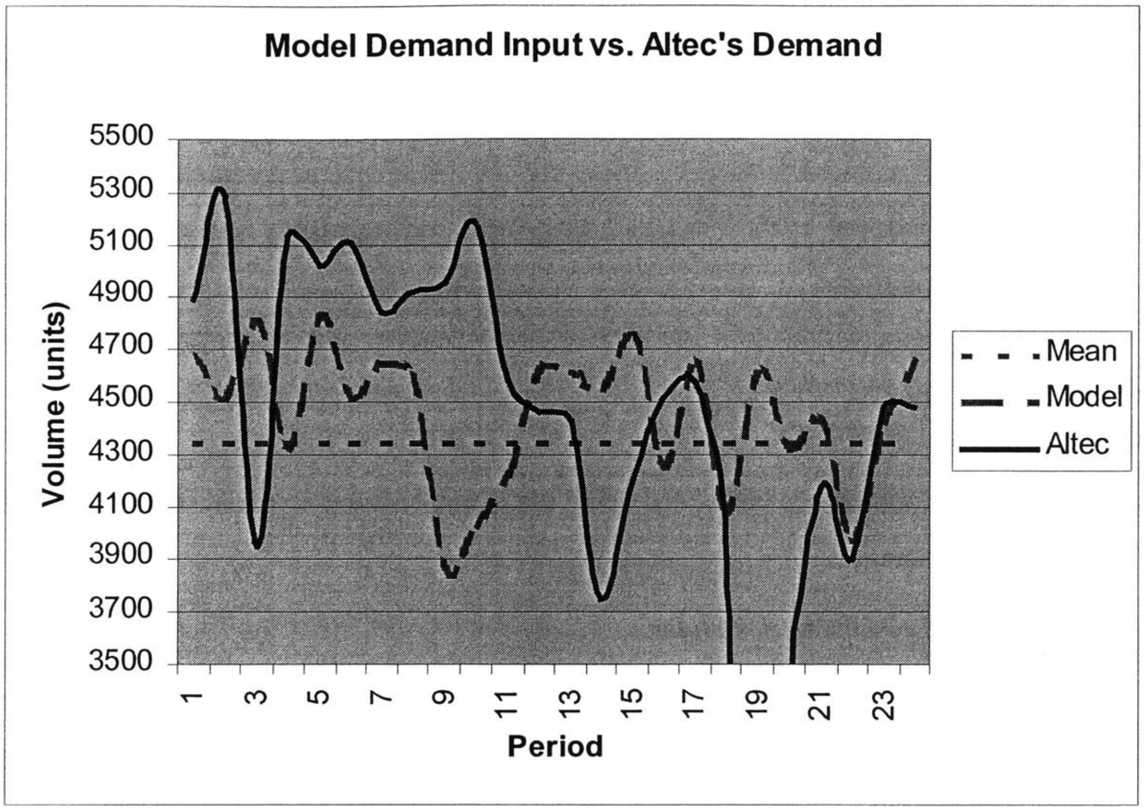


Figure 5-3 Simulation Demand Input

	Demand Feed 1					Demand Feed 2					Demand Feed 3				
Day	A_1	A_2	A_3	B_1	C_1	A_1	A_2	A_3	B_1	C_1	A_1	A_2	A_3	B_1	C_1
1	498	281	170	864	978										
2	230	130	78	399	451										
3	498	281	170	864	978										
4	575	325	196	997	1129										
5	498	281	170	864	978										
6	507	286	173	879	995	501	292	157	823	932					
7	234	132	80	406	459	219	125	75	379	480					
8	507	286	173	879	995	480	257	168	937	903					
9	585	172	200	1015	1148	607	187	182	1057	1198					
10	507	286	173	879	995	476	266	179	868	1004					
11	415	234	142	720	815	377	212	130	696	797	403	218	120	721	828
12	192	108	65	333	377	192	111	69	353	344	174	121	73	355	310
13	415	234	142	720	815	418	215	144	732	875	377	209	131	743	832
14	479	141	163	831	940	519	136	169	847	964	519	122	154	775	892
15	415	234	142	720	815	395	246	148	750	871	385	253	161	723	820
16						702	327	201	1085	1356	684	332	213	1036	1370
17						270	174	99	464	539	267	188	95	468	565
18						675	375	215	1019	1362	644	368	201	1087	1419
19						765	210	227	1175	1581	701	213	218	1145	1626
20						594	373	201	1001	1381	594	375	217	987	1245
21											716	352	237	1176	1308
22											298	186	102	567	615
23											645	411	243	1170	1400
24											778	248	251	1457	1433
25											646	372	245	1312	1310

Figure 5-4 Data Feed Snapshot

5.2.4 Manufacturing System Information System (MIS) Module

The third module simulates the function of the MIS that takes the demand feed from the DM and generates a final assembly production schedule and MC-MES system parameters. The simulation was programmed to vary the following MC-MES system parameters: intra-process buffer min/max levels, cell cycle times, cell setup times, cell reliability measures, and cycle time and reliability distributions.

5.2.4.1 Processing Sequence.

5.2.4.1.1 Startup Parameters

Startup Parameters are calculated using the entire 27 week forecast. All buffers are set to 1/2 mean daily production.

5.2.4.1.2 Weekly Production Schedules

Demand feeds are processed in 15-day chunks. The first 5 days are treated as customer orders while the last 10 days serve as a forecast. The processing sequence follows the following procedure.

1) Calculate Buffersizes
2) Determine Final Assembly Schedule
3) Transmit Schedule and Buffersizes to MC-MES Module
4) MC-MES Module executes production for 5 days
5) MIS Module captures MES operational performance measures and restarts process
6) Iterate sequence for the desired number of weeks
7) MIS captures final MES operational performance measures
8) DAM analyzes operational performance measures

5.2.4.2 Operation Modes

The module has two modes of operation: MRPII and APS mode. For each demand cycle, the simulation is run twice, once in MRPII mode and once in APS mode. The two modes calculate MC-MES system parameters differently and thus provide a means of comparison. The simulation uses the exact same DES "virtual" shop floor for both mode runs. The result of the following mode descriptions is that APS smoothes production and uses moving weighted averages for calculating buffer sizes, MRPII does not smooth production and uses global averages to set buffer sizes.

5.2.4.2.1 APS

Production Smoothing is performed by the APS system on a weekly basis. Each week the production schedule is smoothed by the following formula which uses the outbound inventory buffer to create a leveled weekly schedule for the final assembly operation [Cruickshanks, et al., 1984].

$$P_t = \max_{j=1,2\ldots n}\left[\frac{\sum_{k=0}^{j-1} D_{t+k} - I_{t-1}}{j}\right]$$

Where

P_t =	Production Schedule for period t
D_t =	Demand in Period T
I_t =	Ending Inventory Status in Period T
n=	Number of weeks over which to smooth production
j =	Iteration variable

Upon completion of the schedule, if there is any time remaining in the day, the outbound buffer is then topped off to the min-max levels that are recalculated weekly based on the 15-day demand snapshot.

Marketplace Calculations are performed on a weekly basis. The Takt time is calculated using the 5-day order status and 10-day forecast and then min-max levels are set using this Takt time. Run-lengths for each of the upstream cells are calculated using the Takt Time and Available Time. Buffer sizes are set by Min = 0.25MWD/Work Days/week, Max = 2MWD/Work Days/week.

5.2.4.2.2 MRPII

Production Smoothing is not a function of the MRP mode. The demand for the 5-day period is the exact demand transmitted to the MC-MES. As in APS mode, upon completion of the daily schedule the outbound buffer is topped off to the min-max level. The min-max level is calculated once at the beginning of the simulation and then never recalculated.

Marketplace Calculations occur at the beginning of the simulation using all 27 weeks of data and then are never changed throughout the weekly iterations.

5.2.5 Manufacturing System Control System-Manufacturing Execution System (MC-MES) Module

This module simulates the "virtual lean factory." The factory shop floor (MES) is simulated to represent a Kanban controlled materials handling and production control system (MC). The module consists of 5 production cells with 5 intra-process buffers. Figure 5-5 depicts the MC-MES module.

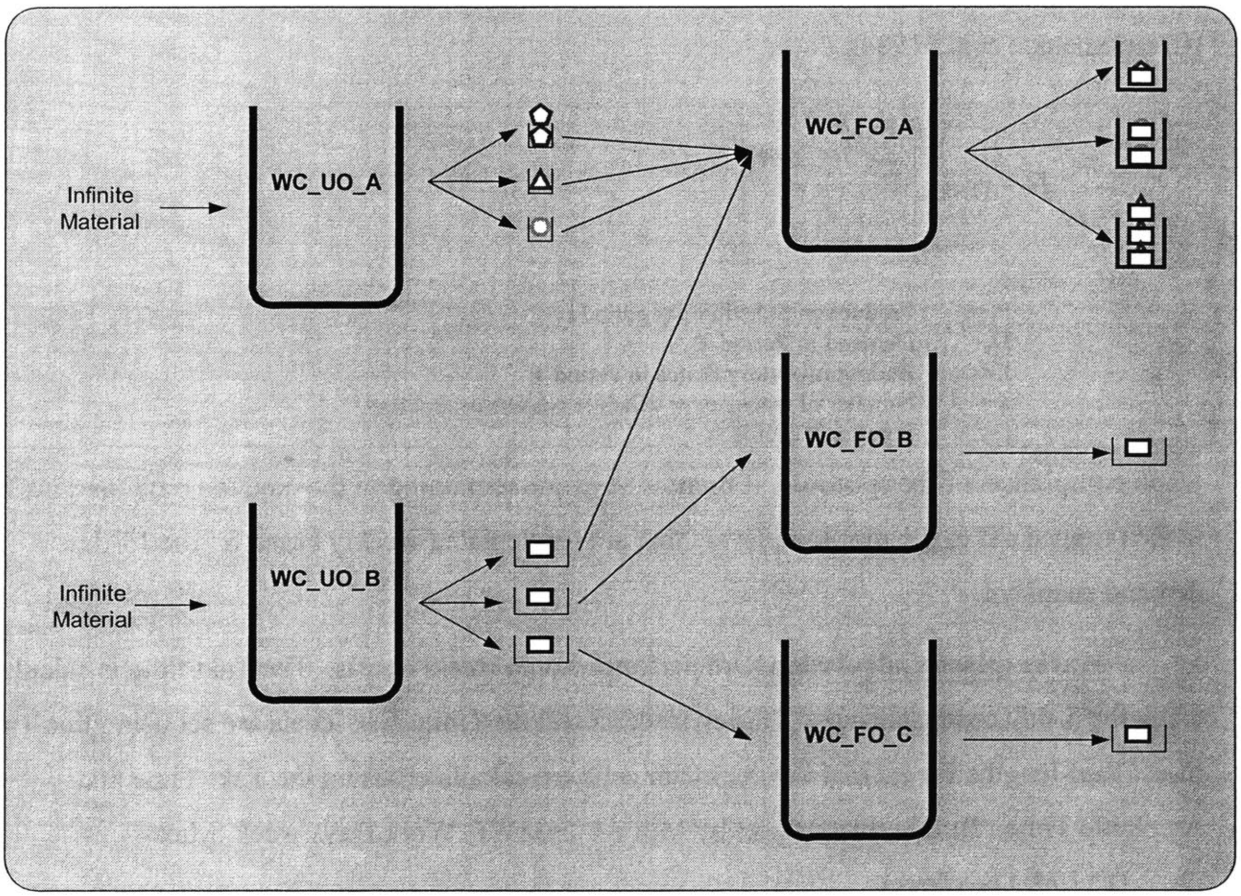


Figure 5-5 MC-MES Simulation Module

5.2.5.1 Upstream Operations

Upstream operations consist of 2 fabrication cells, each producing 3 different types of products for feeding the downstream processes. An infinite supply of materials feed each of the fabrication cells. Production is initiated at changeover by filling the downstream buffer with the lowest filled ratio (current/max). The MIS module calculates production run-lengths. Part time in system begins when the part is pulled from the infinite inbound buffer.

5.2.5.2 Intra-Cell Buffers

A bank of intra-cell buffers decouples the upstream and downstream operations. Each buffer contains only one part type. Buffer min-max levels are set by the MIS.

5.2.5.3 Downstream Operations

The final operation cells simulate final assembly. Final operation cells B and C act as a "load" on upstream operation B. Final operation A assembles three different end items by pulling a part from each of the upstream operations. Downstream operation run-length is controlled by the final assembly schedule of the MIS. Upon completion of the schedule, if there is any remaining time, outbound buffers are filled to max.

5.2.5.4 Outbound Buffers

Outbound buffers represent a finished goods marketplace. Outbound buffers facilitate "build ahead" so production spikes can be smoothed. Outbound buffer min-max levels are set by the MIS. Scheduled shipments occur at the end of the day by pulling the customer demand from the outbound buffer.

5.2.6 Data Analysis Module (DAM)

This module consists of a number of linked spreadsheets and Visual Basic macros that capture the output data from the MIS Module. The DAM then graphically manipulates the data for presentation. The next section contains examples of the DAM output.

5.3 Experimental Results

5.3.1 Model Experimentation Process

The intent of the simulation model was to quantify the performance of the MRPII versus APS modes of operation for the MIS. To systematically perform the comparison, four scenarios were developed and multiple runs were conducted for each scenario. After several trial and error runs, it became clear that the simulation was not sensitive to the number of weeks per run and cell reliability factors. The simulation was slightly sensitive to the forecast accuracy, but not nearly as sensitive as the demand volume and demand variability inputs. Table 5-1 lists the four scenarios.

Variability Setting		Demand Volume Setting
Zero:	0.0% SCV	85%-115%
Low:	2.5% SCV	85%-115%
Medium:	5.0% SCV	85%-115%
High:	10.0% SCV	85%-115%
Where SCV	= Demand Variability Setting from UIM = Squared Coefficient of the Variance	

Table 5-1 Simulation Scenarios

The scenario analysis attempts to find the capacity "breaking point" of each system. Graphically identifying the breaking point helps to determine if the APS system functionality is actually beneficial.

5.3.2 Model Results

The simulation was executed for 120 runs using the setting of Table 5-1. The scenario runs each took approximately 25 computer-hours while the data capture required about 1 workday per scenario. Comparing the four scenarios, the performance from scenario to scenario was not very significant. All four scenarios produced roughly the same graphic response for the three results categories. The difference between each run was a slight shifting of the curve up or down or left or right. Additionally, the randomness of the DES produced slightly different "bumps" in the curves that can be seen in the next sections. All of the next three graphs represent the "medium" variability scenario (the same as the Altec Data).

5.3.2.1 Inventory Quantity

Figure 5-6 represents the total system WIP and FG for both MIS. By using a moving weighted average to dynamically size the buffers, it can achieve better performance with less inventory.

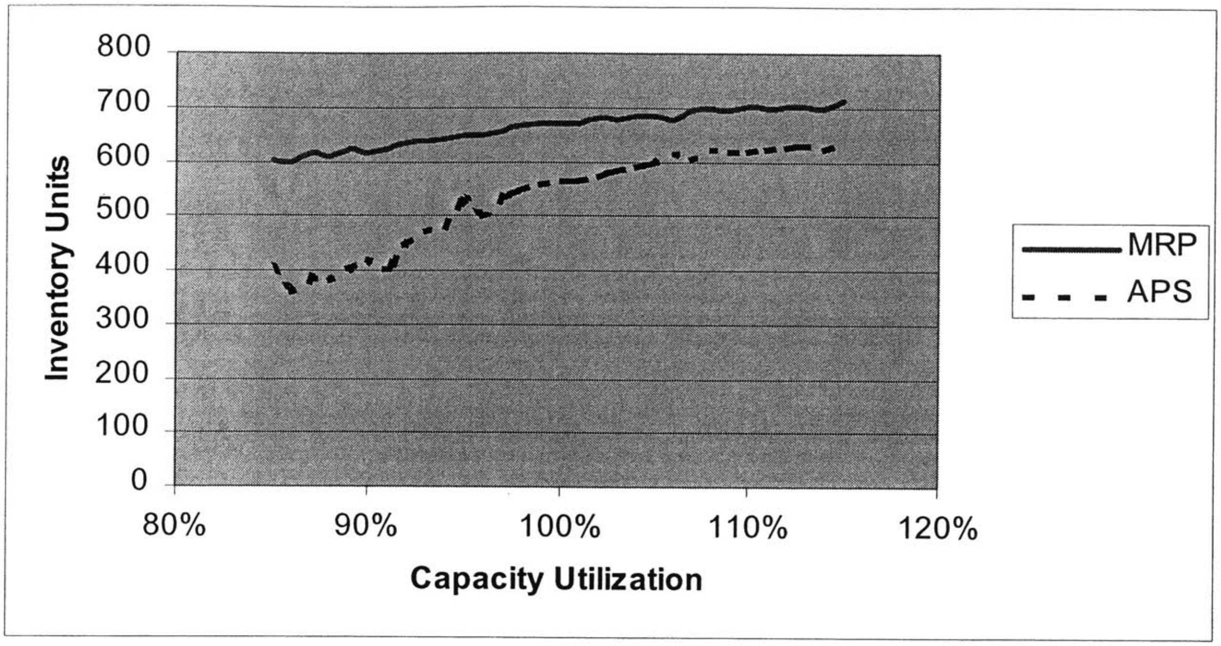


Figure 5-6 Inventory Quantities vs. Capacity Utilization

5.3.2.2 Late Orders

Late orders are a way to determine when the system "breaks" and no longer can achieve the required volumes. These curves roughly represent the exponential growth in waiting time in an M/M/1 queue when λ (mean arrival time) approaches and exceeds μ (mean processing time). The main takeaway from this graph is that the APS system's production smoothing and buffer management (through smaller WIP and FG inventories) provides for better on-time manufacturing system performance.

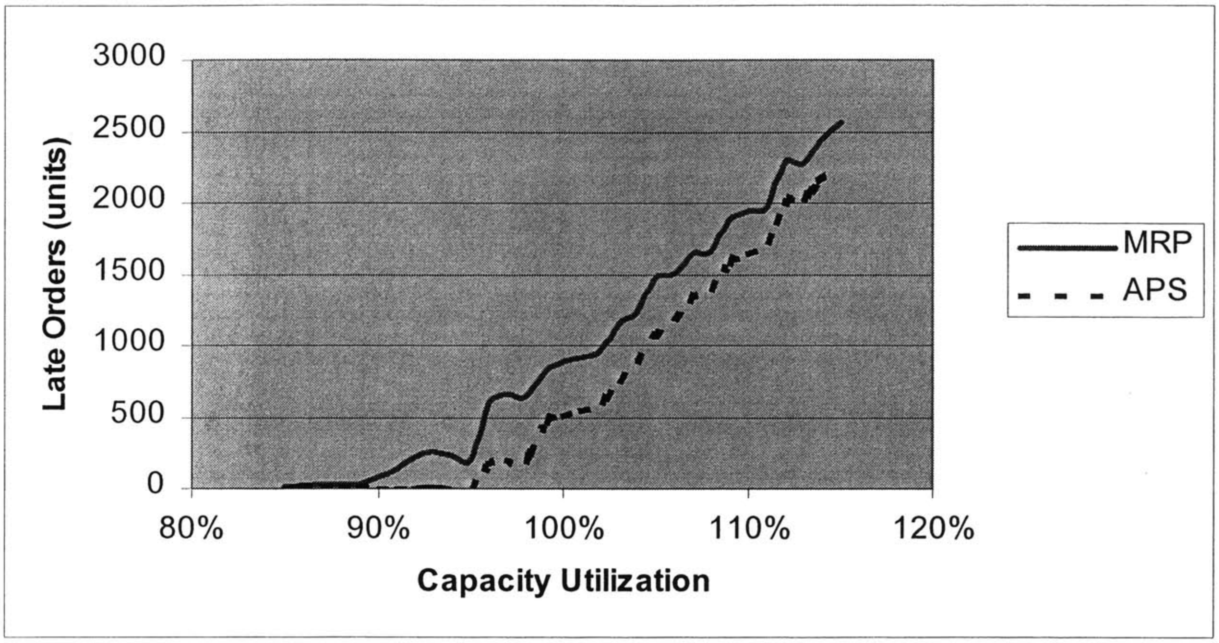


Figure 5-7 Late Orders vs. Capacity Utilization

5.3.2.3 Dock-to-Dock

Figure 5-8 shows that the stochastic nature of the simulation produces greater variability in the Dock-to-Dock time. All of the scenarios displayed the same amount of randomness moving from low capacity utilization to higher capacity utilization. Dock-To-Dock time is roughly the inverse of inventory so comparing figure 5-8 to 5-6 above, APS generally moves inventory through the system faster than the MRPII MIS.

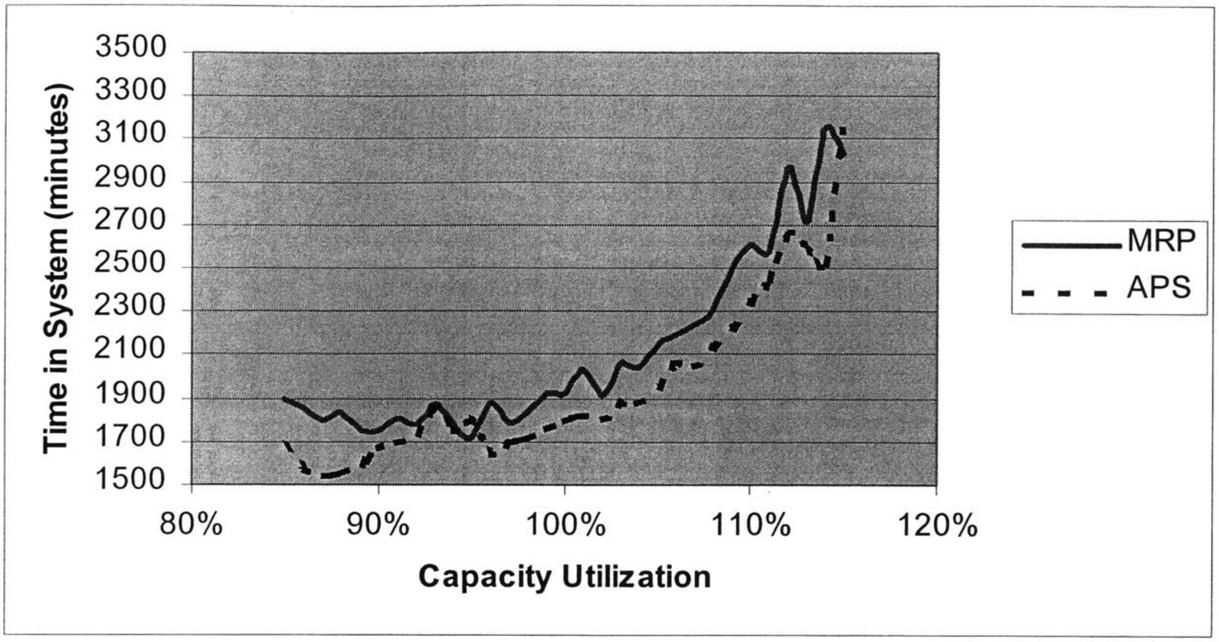


Figure 5-8 Time in System vs. Capacity Utilization

5.3.2.4 Final Results

Simulation development, verification, testing and analysis took approximately 10 weeks to perform. Although it would be difficult to extrapolate this small, very simplistic model to the many complex, dynamic manufacturing processes within Visteon, the results do seem to make intuitive sense. From the following tables, it seems clear that a Lean-ERP MP-MIS with APS's production smoothing and intelligent response to demand volatility characteristics represent potential performance gains and costs savings over an MISIS with MRPII.

Performance Parameters			Variability Setting: Zero	Low	Medium	High
	Inventory	MRPII	649	660	663	666
		APS	518	531	534	541
	Late Orders	MRPII	961	965	994	1004
		APS	693	694	736	721
	Time in System	MRPII	2058	2093	2118	2088
		APS	1867	1909	1958	1959

Table 5-2 Simulation Results

Performance Measure	APS versus MRPII
Dock to Dock	APS is 7.95% faster
Total Inventory	APS carries 19.5% less inventory
Late Orders	APS has 27.5% fewer late orders

Table 5-3 Simulation Final Results

5.3.3 Chapter Summary

This chapter presented a simulation model used to quantify the performance difference between the two competing MIS designs (Lean ERP with either an APS or MRPII planning engine). A simulation was used in order to capture multiple performance metrics and visually display the MP-MIS and MC-MES in action. The results of the simulation model predict that the APS planning engine would provide a significant performance advantage over an MRPII planning engine.

6 Recommendations and Conclusion

The final chapter summarizes the findings of the thesis and looks at three separate aspects of the internship. Recommendations are directed at the business and managerial aspects of the manufacturing software decision while conclusions summarize the key academic learnings from the discovery process. Finally, the last section looks at future areas for research, both from a business and academic standpoint.

6.1 Recommendations

This section addresses the managerial implications of the Lean-ERP Manufacturing Planning and Information System (MP-MIS) in the automotive components industry. To perform the analysis, the section will first review the key strategic issues of chapter 2 and then look at the managerial challenges and risks associated with the software.

6.1.1 Industry Drivers and Target Competencies

Chapter 2 attempts identify the industry drivers affecting the automotive component industry and define core competencies the supplier companies must develop in order to be successful. The drivers and target competencies can be grouped into two areas: velocity and transition.

6.1.1.1 Velocity and Time Compression

The increasing competitiveness of the global automotive industry has manifested itself in many ways. The "old world" economic drivers including overcapacity, economies of scale, new technology adoption, and workforce flexibility are being compound by the "new world" impacts of declining telecommunications and computing power costs. The result of all of these forces is a massive push to increase velocity and compress time. The following list identifies some of the issues affecting the velocity target competency of Automotive Component Suppliers.

- **Order to Deliver Time**. All car companies are in a race to copy the Dell build to order model. Automotive component suppliers who supply the build to order process will face much shorter order to delivery times.
- **Product Development Time**. Decreasing product lifecycles, fierce competition, and cheap computing and communications impact the Product Development cycle immensely. OEMs are pushing more and more of the design work out into the supply

base and component suppliers must develop procedures and information systems to meet these new customer requirements.

- **Manufacturing Process Development Time**. "Throw it over the wall" is no longer an acceptable means of manufacturing system engineering. Component suppliers who understand their costs and integrate product, process, and supply chain development will be dominate the industry. A robust three-dimensional concurrent engineering process radically reduces RFQ response time and provides a significant competitive advantage [Fine, 1999].
- **Supplier and Customer Communications Time**. The Internet enables cheap, seamless communications up and down the supply chain. All manufactures must develop information systems that can respond to this new wave of connectivity so that they can replace inventory with information. The build to order car configured in real time, quoted against available, unscheduled capacity is a great example of how the Internet can re-architect existing supply chain relationships.

6.1.1.2 Manage Transition to Future State

From the above discussion, it seems clear that companies who are unable to speed up their manufacturing and product development processes face extinction. However, the Internet enabled, fast-Clockspeed company is not achieved without significant sweat-equity. Existing strategies, employee compensation policies and literally tons of machinery have to be converted from their present state to the future vision of figure 3-15. Management of the transition from the current state to the future state is a major target competency. The following are key transition issues.

- **Lean Manufacturing**. As discussed in chapter 3, companies making the transition to a Lean PSD face significant inertia. This inertia is supported by existing policies and procedures embedded in the legacy IT systems. A new MP-MIS must help facilitate the transition instead of perpetuate it.
- **Assemble to Order (ATO).** Modularization, decreasing order to delivery times, and build to order cars require automotive component suppliers to assemble to individual OEM order. Increasing ILVS requirements absolutely demand it. The new MIS must speak ATO as its native language.
- **New Products and Customers**. Modularization and shrinking Product Lifecycles and Product Development times also require component suppliers to integrate new products and customers rapidly. Decreasing Product Development times also require the redesign of the make versus buy decision process. A MIS design that easily integrates new customers and new products empowers the sales force and management with tremendous flexibility.

6.1.2 Managerial Challenges

Given that velocity and transition management are two key competitive issues, how does this effect the decision of Visteon's IT department? To answer such, this section looks at the issues and system tradeoffs and then makes recommendations for Project Vista.

6.1.2.1 Issues

6.1.2.1.1 Alignment with Business Needs

This thesis presented a "business needs" IT Strategy. The discussion specifically avoided technology topics like database design or computer processing power analysis. Using this model, the Lean-ERP system configuration proposed in chapter 4 is "manufacturing based" and not "IT based." Large scale IT projects are notorious for having high failure rates. Knowing this, the IT support costs must be balanced with the manufacturing requirements to ensure a positive ROI of the software integration project. This balance must be driven from a solid business case that clearly delineates the system priorities. In addition to the business case, the design and implementation team should be balanced with both IT and manufacturing professionals. Lastly, the business case must map out a clear transition from the current state to the Lean-ERP future state. Continuous re-alignment of the business needs with the IT needs throughout the project makes for a computer system project with a high probability of success.

6.1.2.1.2 Implementation Velocity

A key variable for the project is its implementation velocity. IT project consultants are extremely expensive and thus the project "burn-rate" is very high. Implementing the project very quickly reduces costs but may also result in a sub-optimal or poorly thought out design. Implementing the project too slowly not only drives the cost up, but it also runs the risk that functionality or technology will be outdated before the system installation is completed. Balancing implementation velocity is very tricky and must be continuously re-evaluated.

6.1.2.1.3 Training and Communication

IT system transitions can be extremely painful as bugs are eliminated and users are trained on the new operations. Many companies implementing ERP system experience significant operational difficulties. As part of the transition roadmap, project leaders need to map out a common mental model to all constituencies to ensure that everyone involved understands the implications of the new Manufacturing Information System.

6.1.2.2 System Tradeoffs

6.1.2.2.1 Software Modularity and Integration

Chapter 4 depicted an IT architecture with a centralized database and decentralized Manufacturing Planning-Manufacturing Information System (MP-MIS) at the plant level. This modularity can decrease project deployment times by allowing parallel deployment. This flexibility does come at a cost however. A modular planning system must communicate with the central database and thus represents a significant computer interface. With multiple applications provided by multiple vendors, the interfaces must be continuously updated as unsynchronized software upgrades occur. Thus, modularity provides better flexibility, facilitates continuous improvement, and may decrease deployment times, but it also may simultaneously increase IT maintenance costs to support the interfaces.

6.1.2.2.2 Software Vendors

Choosing a "best of breed" strategy of using multiple software vendors reduces the reliance on one individual vendor, but it also increases the system complexity by requiring multiple interfaces. Best of breed does enable specialization in functional areas but at the cost of multiple software vendor relationships. Lastly, high switching costs dictate that project leaders need to ensure the financial longevity of their software vendors.

6.1.2.2.3 Software Functionality

Automotive IT departments replacing legacy systems must make difficult tradeoffs between system functionality and specialized code modules. Software vendors can change their existing source code to meet individual requirements but the resulting application may increase IT support costs in that the specialization must be re-coded for each version upgrade. Automotive Component Suppliers must therefore make the 80-20 tradeoff. The 80-20 tradeoff is a rule of thumb which states that the remaining 20% of specialized functionally will cost 5 times as much as the first 80%. One side benefit of industry consolidation is that the resultant companies provide a bigger target for software vendors. Thus, with lucrative contracts at stake, project leaders can leverage their scale in partnerships with software vendors so as to endure necessary functionality in future releases.

6.1.2.2.4 Project Costs

The discussion thus far has focused on the strategic issues of the ERP project. In the end, the project must balance strategic requirements with an ROI estimate or the IT investment risks economic failure. Measuring such aspects of the project such as flexibility and future functionality are very difficult. Despite the difficulty in quantifying the intangibles, a balanced scorecard approach should be used to make the tradeoffs poised above (strategic issues, system costs, manufacturing issues, customer requirements). Therefore, the resultant information system balances all project requirements so as to ensure a successful, affordable, on-time implementation.

6.1.2.3 Project Vista Recommendations

6.1.2.3.1 APS

The Lean-ERP MP-MIS application should use an APS planning engine to support the L-CMS shop floor. APS fills the Functional Requirements outlined in chapter 4 and is much more flexible than MRPII. The simulation results in chapter 5 predict that an APS driven Manufacturing Planning System produces significantly better operational performance with 20% less inventory.

6.1.2.3.2 Modularity

Project Vista should embrace a "best of breed" software solution which better enables continuous improvement of the manufacturing system. An entirely integrated solution provided by a single vendor locks the company into the release cycle of that software vendor. A modular infrastructure allows individual functions to upgrade as necessary. One difficulty with this recommendation that did not appear in this thesis is the technical feasibility of the computer architecture. Technical feasibility involves the scalability and performance tradeoffs of the software and hardware setup. Technical feasibility is compounded when multiple interfaces are used to transport data back and forth between systems. These interfaces often become the system bottlenecks and degrade application performance. Two developments mitigate this risk: 1) A new software field of "Enterprise Integration" is evolving to create data interface applications, and 2) software vendors are making significant technical progress towards solving many of the integration bottlenecks as integration with the web has become more important.

6.1.2.3.3 Project Implementation Velocity

The Best of Breed and APS recommendations are intended for the software architecture decisions. Velocity involves project management. Best of Breed and APS represent increased project risk and hence increased return. Project velocity involves the use of internal resources and IT consultants to complete the project business objectives. One method of project management is to outline functionality metrics and "gates" to manage the project velocity. Project management estimates of timelines and budgeting should be derived from the business metrics outlined in the project business plan. A balanced scorecard and business driven metrics provides a framework for making the system tradeoff decisions that arise in the middle of the project. A balanced scorecard weighs IT costs, software functionality requirements, business objectives, user preferences, and current manufacturing competencies. Given the balanced scorecard approach, it seems logical that Visteon should gather the best business and manufacturing talent in the company to drive the project as fast as they can afford in order to gain a competitive advantage during the current period of supply chain evolution and consolidation.

Many ERP projects rely heavily on IT and management consultants to help direct the implementation project. This is a very IT centric model and does not seem appropriate for the "manufacturing centric" software design as outlined in this thesis. Therefore, Visteon should use IT consultants for technical assistance only and rely primarily on internal resources to manage Project Vista. As identified in chapter 1, the resultant enterprise software system defines the company's competitiveness for the next several years.

6.2 Conclusions

This thesis developed a framework for integrating Enterprise Resource Planning and Lean Manufacturing. To perform such, the Production System Design was systematically decomposed to provide a framework for evaluating two proposed manufacturing software applications. The analysis began by looking at the industry business drivers and necessary future competencies. With an understanding of the business environment, the Manufacturing System model was broken down to segment Planning and Control (MPC) from Execution (MES). The MPC framework was then evaluated to determine the Functional Requirements of the Manufacturing Information System (MIS). A qualitatively and quantitatively evaluation of the two competing designs was then performed using the Ideal Lean-ERP model developed in chapter 3 and 4. From the analysis, the thesis concludes that it is possible to create a hybrid Manufacturing System Design, Lean-ERP which consists of an MP-MIS planning component and a L-CMS execution component. The following sections provide further conclusions in a top-down approach starting with the PSD.

6.2.1 Production System Design

MRPII was designed to support a Mass Production System Design and therefore is not appropriate for a Lean Production System Design.

From a PSD standpoint, the discussion from chapter 2 and 3 points out that MRPII was designed for a much different Production System, namely that of a job shop with low inventory turns. This is not to say that computer driven planning has no place in a modern production system, quite the contrary. A Lean Linked-Cell Manufacturing System requires smooth demand, tight links to suppliers, and reliable processes. An APS driven MP-MIS provides planning support for the Lean Manufacturing Production System Design and thus is quite complementary to the L-CMS Manufacturing Control-Manufacturing Execution System (MC-MES). A hybrid approach combines the planning and intra/inter-company communications strengths of ERP with the philosophy of waste elimination and continuous improvement associated with Lean Manufacturing. Lean-ERP thus simultaneously leverages the planning aspects of ERP with the dynamic production responsiveness of a L-CMS shop floor. The memory resident nature of an APS MIS provides much greater flexibility than does the less responsive MRPII planning algorithm.

6.2.2 Manufacturing System Design

The Manufacturing Planning-Manufacturing Information System (MP-MIS) needs to be functionally independent from the Manufacturing Control- Manufacturing Execution System (MC-MES).

It is very beneficial to uncouple the MP-MIS from the MC-MES for planning purposes. An uncoupled design facilitates continuous improvement and does not suffer from the information delays associated with a poorly designed feedback control system. Chapter 3 outlined the benefits and drawbacks of a JIT and MRP MPC system and then detailed the Functional Requirements of an ideal MPC system to support a L-CMS shop floor. Chapter 4 provided a qualitative assessment and chapter 5 developed a quantitative simulation model for comparing an APS MIS with one based on MRPII. Both chapters conclude that functional independence provides for a superior design.

6.2.3 Manufacturing System Information System (MIS) Design

The Manufacturing System Information System (MIS) requires both a Database Transaction and Accounting System (DTAS) and a Memory Resident Scheduling System (MRSS).

Chapter 4 presented a MIS design that consisted of a Database Transaction and Accounting System (DTAS) and a Memory Resident Scheduling System. A Lean PSD tightly embeds a very robust Manufacturing Control (MC) function in its Manufacturing Execution System (MES) via kanban loops. This design does not suffer from the information delays associated with MRPII. The transition to a Lean PSD is not easily achieved however as operators need training, processes need stabilization, and demand needs to be smooth. A MRSS provides a Decision Support System (DSS) to help facilitate the lean transition by smoothing demand and determining capacity requirements. With support of an APS planning engine, the resultant Lean-ERP MP-MIS provides much greater functionality than does a Lean-ERP MP-MIS with an MRPII planning engine.

6.3 Opportunities for Further Research

6.3.1 Implementation Roadmap

The author's assignment as a member of the PMD team was to develop the functional requirements of the Lean-ERP system and evaluate two competing applications. Throughout the research and development, the focus was to determine the feasibility of such a system, not to develop the implementation roadmap to get from the current state to the future state. As a large, global manufacturing company, Visteon consists of a very complicated combination of manufacturing processes, labor policies, and supply chain links. As noted in chapter 3, there is significant institutional inertia associated with a MRP/Mass Production System Design. ***A follow-on study that develops an implementation roadmap for charting how to navigate from the current state to the future state would be very valuable.***

6.3.2 ERP Accounting and Financial Integration

As this study was primarily focused on Production Planning and Materials Management, the accounting and financial integration aspects of the ERP system were not considered. Many ERP case studies note that the Information System itself provides little competitive advantage, but the information embedded in the software provides a wealth of data to assist in managerial decisions. As many managerial decisions revolve around financial implications, further study on the financial and accounting integration between ERP and the Manufacturing System could prove useful. Specifically, a study on integrating an alternative to direct labor based managerial accounting might prove particularly beneficial.

6.3.3 APS Configuration

Although chapter 4 outlined the use of an APS system as the MRSS in the Lean-ERP MP-MIS, it is uncertain that current APS software functionality could actually perform all of the tasks outlined in the chapter. The PMD team studied the software user manuals and white-paper literature of several APS vendors extensively and determined that many of the vendors could produce a system with relatively little modifications to the existing code base. Additionally, the author studied an existing APS implementation within Visteon and determined that with minor modifications, the existing system could function similar to the proposed MRSS design.

6.3.4 Factory Testing

As a last recommendation for further study, Visteon should test the proposed MP-MIS system design on a few product lines in an existing factory to determine if the software and Manufacturing Execution System design is valid. Used as a backbone for re-engineering existing processes, a successful test could gain significant momentum throughout the manufacturing organization.

Glossary

Advanced Planning and Scheduling (APS) – APS is a next generation of manufacturing scheduling software which uses mathematical algorithms to take advantage of the dramatic reduction in computing power and memory prices.

Assemble to Order (ATO) – To produce an assembled module or product to fill a unique customer order.

Balanced Production Flow–A balanced production system means that all components are designed to operate at the pace of customer demand, called the takt time.

Bill of Material (BOM) – A part listing of all components and sub assemblies for a final product.

Capacity Planning – Methodology for the strategic and tactical planning for production capacity.

Centralized Manufacturing Management System (CMMS) – Ford's legacy MRPII system.

Cycle Time (CT) – The time required to produce one product by a machine, station, and/or operator. The machine or station cycle time is not the takt time. Takt time reflects the customer's pace of demand.

Decision Support System (DSS) – A computer system used for planning and what-if analysis. A DSS typically consists of a mathematical model of the production environment.

Electronic Data Interchange (EDI) – A computer data exchange format used extensively in the automotive industry.

Enterprise Resource Planning (ERP) – The information system which handles all data transactions for a manufacturing company. Functions included are Finance, Accounting, Sales and Marketing, Purchasing, Product Development, and Manufacturing.

Finite Capacity Scheduling (FCS) – Computerized planning system that fits an MRP Generated Master Production Schedule into the existing shop floor capacity. The system generates very detailed plans for shop floor control.

FPS (Ford Production System) – Ford's implementation methodology for implementing the Toyota Production System.

Heijunka – "Load-Leveling" box used by Toyota to sequence production orders. Heijunka controls pace, run size, sequencing, and demand leveling.

In Line Vehicle Sequencing (ILVS) – Supplier shipping protocol for shipping individual modules in the same order the cars are produced on the assembly line.

Just in Time (JIT) – A production control component of the Toyota Production System that involves the synchronous flow of materials. Materials arrive at the right time, right mix, right quantity, with the right quality to the next operation.

Kanban – Kanban is a Japanese term meaning "card," that is, visible records. An inventory replenishment system associated with JIT, that was developed by Toyota. An order point scheduling approach which uses fixed lot sizes of materials in standard containers with the cards attached to each. Material reorder is triggered at the last minute, when the lot of material is moved to the point of use.

Lean Manufacturing (LM) – A very popular, generic term used to describe the Toyota Production System (TPS).

Level Production Flow – All operations make the quantity and mix of products demanded by the final customer within a given time interval. Level production smoothes the demand for parts through the manufacturing system and reduces the amount of inventory that must be maintained to meet customer demand.

Manufacturing Control (MC) – The manufacturing function responsible for production initiation (what, when, how many to build).

Manufacturing Execution System (MES) – Shop floor, performs fabrication and assembly operations.

Manufacturing Planning (MP) – Sub-function of the manufacturing system which involves capacity, material, workforce, and production system planning.

Manufacturing Planning and Control (MPC) – The information system for matching customer demand with manufactured products. An MPC concerns planning and controlling the manufacturing process –including material, machines, people, and supplies.

Manufacturing System (MS) – A manufacturing system is a complex arrangements of physical elements characterized by measurable parameters. Physical elements include machines and people. Inputs to a manufacturing system include materials, energy, and information and the outputs are products, services, and information.

Manufacturing System Design (MSD) – The process of determining and achieving the objectives and physical solutions to limit the interaction between elements within the manufacturing system, to most effectively achieve the measurable parameters. The elements of the manufacturing system are defined as: the machines, tools, material, people and information.
Manufacturing Throughput Time – Also known as "Lead Time." Elapsed time a part spends in a Manufacturing System – from raw material to finished component.

Material Requirements Planning (MRP) – The original computer based inventory management and production scheduling data processing system developed by Joseph Orlicky of IBM in the mid 1960s.

Material Requirements Planning II (MRPII) – An extension of the original MRP algorithm which "closed the loop." See description in Chapter 2.

Materials Management (MM) – The ordering, receiving, and accounting for all materials involved in the manufacturing process. Materials include all purchase parts, sub assemblies, and Work in Process (WIP) inventory.

Original Equipment Manufacturer (OEM) – Car companies/Automobile Assemblers – Ford, GM, DaimlerChrysler, etc.

Plan, Manufacture, Deliver (PMD) – The subteam of Visteon's ERP implementation project responsible for Planning and Forecasting Demand, Developing Manufacturing Processes, and Managing customer delivers and logistics. The author was assigned to this team during his 6-month internship.

Production Planning (PP) – The hierarchical process of matching a manufacturing company's production supply with customer demand. Production planning occurs on several levels. High-level production planning involves capital acquisition and capacity planning. Medium level production planning involves production line design and workforce sizing. Low-level production planning involves manufacturing sequencing and scheduling.

Production Smoothing – The process of fitting a demand stream into available capacity by building ahead or modifying the product due date. Production smoothing generally involves customer orders rather than forecasts.

Production System (PS) – The enterprise view of a manufacturing company. The production system consists of a manufacturing system and all of the supporting functions associated with such: engineering, marketing, accounting, sales, finance, and purchasing.

Production System Design (PSD) – Enterprise design of a manufacturing company's production system.

Project Vista – Visteon's ERP implementation project.

Run Size – The amout of product completed by a work center between successive setups.

SAP – This German software Company is the leading ERP vendor. This name is synonymous with their main ERP software product "SAP R/3."

Standard Work in Progress (SWIP) – The fixed amount of decoupling buffer stock of material held between two sequential processes in a L-CMS. The number of kanbans circulating between the two cells controls SWIP.

Takt Time – Takt is the German word for the baton used by an orchestra conductor to regulate or pace the tempo or playing speed of the orchestra, i.e., to synchronize the orchestra. The takt time represents the pace of demand from the customer.

Toyota Production System (TPS) – TPS is a customer centric Production System Design (PSD) which focuses on producing to customer demand and reducing waste. Waste reduction is accomplished through continuous improvement of lead-time, production variability, and excess inventory.

References

Automotive Industry Action Group, 1998. Supply Chain Recommended Business Practices for EDI Implementation. AIAG: Southfield, MI.

Bloomberg News, 2000. *GM, Ford sign alliances with AOL, Yahoo.* News.com [http://news.cnet.com/news/0-1007-200-1518870.html?tag=st.ne.1007.], 10 January.

Benton, W.C. & Shin, Hojung, 1998. *Manufacturing Planning and Control: The evolution of MRP and JIT Integration.* European Journal of Operations Research, 100, 411-440.

Bermudez, John, 1998. *Advanced Planning and Scheduling, Is It as Good as It Sounds*? The Report on Supply Chain Management, Advanced Manufacturing Research. March.

Bermudez, John, 1998. *Can I get APS from My ERP Provider?* The Report on Supply Chain Management, Advanced Manufacturing Research. December.

Black, J. T., 1991. The Design of the Factory with a Future. McGraw-Hill: New York.

Cauthen, Rich, 1999. *APS technology, Powering supply chain management.* Enterprise System Journal. September.

Cochran, David S., 1994. *The Design and Control of Manufacturing Systems.* Doctoral Dissertation, Auburn University.

Cochran, David S., Kim, Jongyoon, & Kim, Yong-Suk, 2000. *Alignment of Performance Measurement with the PSD.* Axiomatic Design Conference Seminar. MIT, Cambridge, Massachusetts.

Cruickshanks, Allan B., Drescher, Robert D., & Graves, Stephen C., 1984. *A Study of Production Smoothing in a Job Shop Environment.* Management Science, Vol 30, No. 3, March.

Dell, Michael S., 1999. Direct from Dell, Strategies that Revolutionized an Industry. Harper Collins: New York.

Grace, T., 1999. *ERP and Flow, the Status Quo meets its Replacement.* The Report on Supply Chain Management, Advanced Manufacturing Research. Boston.

Hamel, Gary & Prahalad, C. K., 1989. *Strategic Intent.* Harvard Business Review, May-June.

Harrell, C. & Tumay, K., 1995. Simulation Made Easy. Engineering and Management Press, Norcross, Georgia.

Hopp, Wallace J. & Spearman, Mark L., 1996. Factory Physics, Foundations of Manufacturing Management. Irwin/McGraw-Hill: Boston.

Huq, Ziaul & Huq, Faizul, 1984. *Embedding JIT in MRP: The case of job shops.* Journal of Manufacturing Systems 13 (3), 153-164.

Karmarkar, Uday, 1989. *Getting Control of Just-in-Time.* Harvard Business Review, September-October.

Kilpatrick, Jim, 1999. *Advanced Planning Systems Spark the Supply Chain.* APICS –The Performance Advantage, August.

Kippel, Brian, 1998. *A Design Methodology for Automotive Component Manufacturing Systems.* Leaders For Manufacturing Thesis, MIT.

Kirchmier, Bill, 1998. *Finite Capacity Scheduling Methods*. APICS, The Performance Advantage, Volume 8, August.

Latamore, G. Berton, 1999. *Master Planners Face Revolutionary Change*. APICS –The Performance Advantage, August.

Layden, John, 1999. *APS is here to Stay*. Manufacturing Systems, February.

Liker, Jeffrey K., 1999. *Advanced Planning Systems as an Enabler of Lean Manufacturing*. Automotive Manufacturing and Production. February.

Lu, David J., 1986. Kanban, Just in Time at Toyota. Productivity Press: Portland.

Magretta, Joan, 1998. *The Power of Virtual Integration, an interview with Dell Computer's Michael Dell*. Harvard Business Review. March-April.

McCullough, Stavie S., 1999. *Time to Replace your MRP?* The Forrester Report, February 19.

McQuivey, James L., Delhagen, Kate & Ardito, Carrie, 1999. *New Car Buying Races On-line*. The Forrester Report, January.

Miller, Randall, 2000. The Road Ahead for the U.S. Auto Industry. Washington, D.C.: Office of Automotive Affairs, U.S. Department of Commerce.

Monden, Yasuhiro, 1998. Toyota Production System, An Integrated Approach to Just-In-Time 3rd ed. Engineering and Management Press: Norcross, Georgia.

Mozeson, Mark H., 1991. *What Your MRPII Systems Cannot Do*. Industrial Engineering, December.

Myron, David L., 1996. *Paint Blocking in Fords In-Line Vehicle Sequencing Environment*. Leaders for Manufacturing Thesis, MIT.

Nahmias, S., 1997. Production and Operations Analysis, 3rd ed. Irwin: Chicago.

Orlicky, Joseph, 1974. Material Requirements Planning, the New Way of Life in Production and Inventory Management. McGraw-Hill: New York.

Ohno, Taiichi, 1988. Toyota Production System, Beyond Large-Scale Production. Productivity Press: Portland, Oregon.

Parker, Kevin, 1998. *What are solver technologies?* Manufacturing Systems, February.

PR Newswire, 1999. *Delphi Honored for Innovative Supply-Chain Management System*. NewsEdge Corporation, September 23 1999.

Proud, John F., 1999. Master Scheduling, 2nd ed. Wiley: New York

Rao, Ashok, 1989. *A Survey of MRP-II Software Suppliers' Trends in Support of Just In Time*. Production and Inventory Management Journal, Third Quarter.

Rao, Ashok & Scheraga, David, 1988. *Moving from Manufacturing Resource Planning to Just-in-Time Manufacturing*. Production and Inventory Management Journal, First Quarter.

Shingo, Shigeo, 1989. A Study of the Toyota Production System from an Industrial Engineering Viewpoint. Productivity Press: Portland, Oregon.

Sipper, D. and Bulfin, R.L., 1997. Production Planning, Control, and Integration. McGraw-Hill: New York.

Slywotzky, Adrian J., 2000. *The Age of the Choiceboard.* Harvard Business Review, January-February.
Spear, Steven & Bowen, H. Kent, 1999. *Decoding the DNA of the Toyota Production System.* Harvard Business Review, September.

Swanton, B., 1997. *Can Automotive Suppliers buy ERP off of the Lot?* The Report on Supply Chain Management, Advanced Manufacturing Research, Boston.

Swanton, B., 1999. *Automotive Plant Software Needs a Moving Target.* The Report on Supply Chain Management, Advanced Manufacturing Research, Boston.

Ulfelder, Steve, 2000. *Business QuickStudy: Cycle Time.* Computerworld [http://www.computerworld.com/home/print.nsf/all/000110DAB2], 10 January.

Vasilash, Gary S. 1998. *Surviving and Thriving as a Supplier.* Automotive Manufacturing and Production, www.automfg.com/articles/059805_p.cfm, May.

Vollmann, T.E., Berry, W.L., and Whybark, D.C., 1997. Manufacturing Planning and Control Systems, 4th ed. Irwin: Boston.

Womack, James P. & Jones, Daniel T., 1996. Lean Thinking. Simon & Schuster: New York.

Womack, James P., Jones, Daniel T., & Roos, Daniel, 1990. The Machine that Changed The World. Harper Perennial: New York.

Zipkin, Paul H., 1991. *Does Manufacturing Need a JIT Revolution?* Harvard Business Review, January-February.