A STRUCTURED APPROACH TO PRODUCTION CONTROL IN INTEGRATED MANUFACTURING SYSTEMS

by

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(ABSTRACT)

The planning and control of manufacturing systems is a complex activity involving a myriad of interrelated decisions and optimization algorithms. In a Computer Integrated Manufacturing System (CIMS) these decisions and algorithms span several functions, require information from several sources, and have consequences in several sectors of the manufacturing system. This dissertation is concerned with the development of a structured methodology for executing this activity. Therefore, the primary activities are first, to develop the framework for a Computer Integrated Production Planning and Control (CIPP&C) system, and second, to formulate and solve specific mathematical models which are nested in the developed framework. The framework functions as a "city plan" for the production control activity in a CIMS environment, while the mathematical methodologies are pieces of the decision architecture.

Achieving a CIMS implies achieving an integrated manufacturing system. Implying the production control system needs to be designed with specific consideration of the concepts, issues, and principles of integrated manufacturing. As such, these concepts, issues and principles are identified and developed in this research. A model of CIMS is developed and the role of CIPP&C is analyzed. A framework for integration in manufacturing is developed and used to guide the modeling efforts. The CIPP&C "city plan" is developed using an adaptation of the IDEF methodology.

The objective of the plan is to define the separate problems which are to be solved in production control, the interrelationships between these problems, and the synergy which causes them to behave as a single system.

This research specifically addresses the master aggregate scheduling (MA-Schedule) and the coordinating production scheduling (CP-Schedule) problems within the CIPP&C plan. The MA-Scheduling problem prescribes how much of a family is to be produced in a time period, and is formulated in detail as a non-linear 0-1 mixed integer program. The formulation aggregates capacity, time, and products; models routing and capacity flexibility; and considers the availability of material transporters. The solution procedure incorporates linearization methods, preprocessing algorithms, and large-scale MIP solvers. The CP-Schedule is formulated as two separate problems. The first disaggregates time and product and is to be solved as a MIP. The second problem determines the start time of each product batch at a cell. It is equivalent to the minimum makespan problem and solution approaches are discussed.

A network of programs was designed to execute the scheduling methodology. Experimental results with the methodology are reported. These results provide insights into system performance in various conditions. Specifically, the impact of flexibility, loading, transporter availability, and cost dimensions are analyzed.

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CHAPTER ONE

INTRODUCTION

1.1. INTRODUCTION

The science and process of manufacturing has been radically changing in the 80's, and will continue to do so in the 90's. This radical change is, and will be, driven first by an increased global competition in manufacturing, and second, the development and availability of advanced manufacturing technologies. The advancements in technology will provide the opportunity to develop ideal manufacturing systems in the future - systems which are highly automated, highly integrated, completely optimized, and strong competitive weapons. Such ideal and futuristic scenarios are described as Computer Integrated Manufacturing Systems (CIMS). A plethora of definitions for such systems are reported; most are inconsistent and often nebulous. But in this hazy vision, four major building blocks of CIMS are identifiable. These are: business management as related to manufacturing, Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), and Computer Integrated Production Planning and Control (CIPP&C). While the advancements in two of the components, CAD and CAM, have been considerable, the other two have not been investigated much from a CIMS perspective. The components of management and CIPP&C are critical both to achieving CIMS and its subsequent success. DeMeyer (1987), in a survey of integration issues in future manufacturing systems, found the issues relating to the planning and control function to be more oftenly cited than those relating to CAD and CAM. DeMeyer attributed this to the naturally integrative nature of CIPP&C, and predicted it will be the pivotal element in integrated manufacturing systems. Therefore, this dissertation is concerned with the development of a "city plan" for a generalized

CIPP&C system, and specific mathematical solution methodologies for decision support within the CIPP&C system.

Production control[1] has evolved rapidly ever since Henry Gantt observed that "it is not only how much you produce, but when and where you produce it," that are needed for effective control of a production facility. The literature is rich with papers describing sophisticated methodologies for solving production control problems ranging in size from the single machine to the multi-plant corporation. The early approaches were primarily graphical in nature, while later the emphasis was on the development of quantitative approaches using operations research methods. More recently, the emphasis has been on the systems approach incorporating the use of computer databases.

The pursuit of economies of scale, in addition to the incorporation of advanced technologies, has rendered manufacturing into a series of complex interrelated systems. These systems are often difficult to understand and even more difficult to control. Gone are the days when a single scheduler could adequately control production operations. Further, the application of individual methodologies for the solution of isolated problems is no longer an effective approach. Complex manufacturing systems require the application of an integrated system of production control methodologies. Designing such a system requires the incorporation of at least three basic methods: systems design, aggregation and disaggregation, and integration. Simon (1957) pointed out the need for decision makers to have frameworks with which they can simplify the problems of a complex system. Silver and Peterson (1985) observed that only a systems framework would enable decision makers to understand com-

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[1] The expression "production control" is used in this dissertation in its generic form to include all activities typically included in the production planning and control function. The major activities included in this function are listed on the next page, and are graphically defined in Figure 3.2.

plexity and thus overcome the bounded rationality of human beings. Nadler (1981) defined a system as a framework that "processes inputs into outputs to achieve or satisfy a purpose or purposes through the use of human, physical, and information resources in a sociological and physical environment." The function of production control is amenable to systems modeling, and the importance of this approach has long been recognized by researchers and designers in the discipline. Holstein (1968) presented one of the earliest frameworks for modelling the entire production control function as an interrelated system. Later portions of his framework would evolve into Materials Requirements Planning (MRP) and MRP-II to create a multi-million dollar software market. Holstein's framework consisted of eight subsystems which he defined as:

1. **Forecasting** - The activity of analyzing future market conditions and predicting product demand
2. **Long Term Capacity Planning** - The process of ensuring the organization can produce its forecasted demand and projected product line. It also involves the allocation of aggregate production to different sites
3. **Order Entry** - Every system must have an input, and order entry forms are the primary input for a production control system
4. **Master Scheduling** - The activity that determines the overall production plan for the next several months
5. **Inventory Planning and Control** - The mechanism for replenishing and ensuring the availability of materials required by the production process
6. **Short Term Scheduling** - The activity which develops the detailed plan to meet the delivery commitment represented by the master schedule
7. **Short Term Capacity Planning** - Determining whether the short term schedule is feasible and identifies the expected system bottlenecks

8. **Dispatching, Releasing, and Shop Floor Control** - This is the activity of executing all the schedules developed earlier. It involves controlling the level of in-process inventory, job sequencing, tracking down problems, and adjusting the schedule

The design and implementation of a system of production control, merging the above activities is essential to the successful control of a manufacturing system. Several approaches in this direction have been developed including: MRP, MRP-II, Optimized Production Technology (OPT), Just in Time (JIT), and Hierarchical Production Planning (HPP).

The second basic method involves the aggregation of decisions and parameters, and the subsequent development of aggregate solution methods. Aggregation allows the decision maker to compress problem size and thus facilitate higher level and longer term decision making. The first linear programming solution to the aggregate production control problem was proposed by Bowman (1956). Ever since, several approaches and variations of the problem have been reported. More recently, Hax and Meal (1975) extended the aggregate problem via a systems approach to develop a HPP system of control. Their system includes three levels of decreasing aggregation, and a disaggregation process for linking the levels. This approach has generated much interest in the discipline and several extensions and case studies are reported. One proposed effort is attempting to link HPP with MRP in an attempt to develop a more comprehensive control system (Meal, et al., 1987). The ability to efficiently solve mathematical programs is necessary for effective production control. Aggregation first provides a means for handling larger problems and secondly, for linking different decision levels. It is thus an applicable tool for CIPP&C design.

The third method or phenomenon has effected not only production control but the entire science of manufacturing. If the 70's were the decade of computerization, and the 80's the decade of automation, then surely the 90's will be the decade of integration. It is a word widely used in manufacturing but rarely understood. Mize (1987) attributes this misunderstanding to a confusion between the words "interfacing" and "integrating." He defines the two words to mean:

Interfacing - To interact and communicate with another system
Integration - The organization of various traits, relations, attitudes, behaviors, etc., into one harmonious personality

Mize argues the evolution of CIMS will first require the development of interfaced systems, followed by the development of integrated systems. However, he complains that most system designers stop at interfacing and believe they have achieved integration, leading to state of frustration. Mize's definition can be extended to define four types of systems:

1. Stand alone
2. Interfaced
3. Integrated
4. Universal

A stand alone system makes its own decisions and does not communicate with any other system. An interfaced system has one or two-way communication with other systems but makes decisions for its own benefit. An integrated system has two-way communication with other systems and decisions are made for the benefit of the group of systems. Thus, interfaced systems have a parasitic relationship, while integrated systems have a symbiotic relationship. A universal system is a group of subsystems which have no individual decision making capability and are managed by a central controller. While the appropriate type of system for a particular situation will vary, our emphasis here is on the development and design of integrated systems in a manufacturing environment.

There have been few efforts focussed primarily at the development and design of production control systems for a CIMS environment. The most well known effort is MRP-II (Wight, 1984) which is typically included as a part of a CIMS model. Most of the efforts are unstructured modifications of previous systems and it is doubtful whether they will meet the needs of CIMS. The Manufacturing Studies Board, on describing the technology of future manufacturing, observed:

> "The factory of the future will be managed and controlled through automated process planning, scheduling, modeling, and optimization systems. The successful implementation of large scale factory-level systems depends upon structured analysis and design systems that depend heavily on group technology. Only through such systems can a manager know the exact state of his factory, and only through such exact knowledge of the present can a manager intelligently implement systems of manufacturing for the future." - NRC Report (1986)

One significant study in this direction has been the Air Force's Integrated Computer Aided Manufacturing (ICAM) program. Using the structured analysis and modelling procedures pioneered by Ross (1977), the ICAM program has developed functional and information models of manufacturing which describe in detail the production activities in an organization (ICAM Report, 1981). Currently, the program is involved in the development of an architecture for an integrated manufacturing control system (ICAM Review, 1980). Several of the outputs from the ICAM program will be used in this dissertation.

Clearly, the subject of CIPP&C development will include several concepts and philosophies. A clear understanding of these is a prerequisite to building an effective CIPP&C. Thus, the essence of this dissertation will invoke primarily the concepts of integrated manufacturing, the systems approach to production control, and aggregate/disaggregate mathematical modeling and solution.

1.1.1. A Strategy for Research in Production Control

The research in this dissertation is divided into a macro section and a micro section. In the macro section the focus is on the general subject of production control and CIPP&C systems. The implications of production control to an integrated manufacturing environment are studied and a "city plan"[2] for CIPP&C system design is proposed (Figure 1.1). The "city plan" consists of a structured model which describes the interrelationships between components and the relevant decision making responsibilities. In contrast, the micro portion focuses on the development and solution of mathematical methodologies for some components within the CIPP&C plan. More specifically, it is proposed that a set of mathematical programs be formulated to solve the CIPP&C master aggregate schedule module and the coordinating schedule for production control. Solution methodologies for the individual schedules and their aggregation/disaggregation are to be developed. Thus, CIPP&C provides the fabric for linking the mathematical models, and the proposed schedules need to be formulated and solved such that they behave as a single system.

The rational of linking the macro and micro sections is based on the following three distinct stages in a model or system building effort:

1. Definitive Model - Defines the problem and its structure
2. Descriptive Model - Describes the behavior of the problem system
3. Prescriptive Model - Prescribes the optimal solution to the problem

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[2] A "city plan" is less detailed than a "system architecture." The "city plan" focuses more on the flow and interrelationships within a system while the "architecture" details the actual mechanisms for decision making and processing.

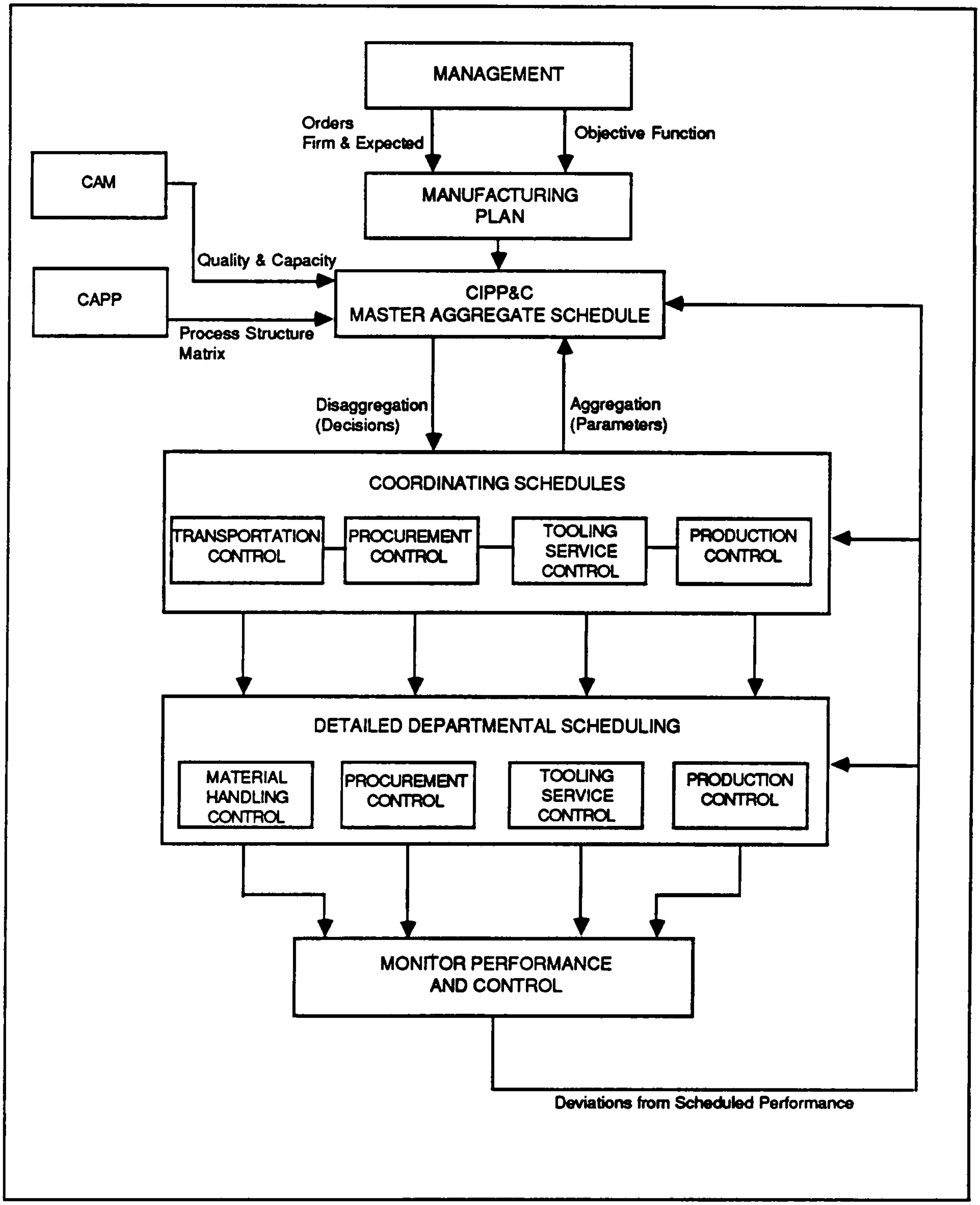

FIGURE 1.1. "City Plan" for a CIPP&C System

The three stages are equivalent to the three modeling representations as described by Geoffrion (1987): managerial communication, mathematical use, and computer solution. While all three stages are equally important to a modeling effort, traditional operations research modeling has focused more on the descriptive and prescriptive stages. Geoffrion (1987) lists poor managerial acceptance as one of the major problems facing OR modeling. Lack of a good definitive model decreases the effectiveness of the effort and its potential benefits to an user. The awareness of this problem has sparked an increased emphasis on the definitive stage. Likewise, the macro section of this dissertation is intended to define the "city plan" in which the later developed mathematical models are appropriately nested. One efficient method for developing definitive models is the structured analysis and modeling technique (Ross, 1977). This develops a series of hierarchical graphs that identify system activities and their interrelationships. The technique has long been successfully used in the development of software, and computer control systems. Variations of this technique are used in this research to develop the "city plan".

There is a specific objective which guides this research through the macro and micro portions. This objective can be considered as part of an overall research thrust towards the development of CIMS. From a production control perspective, the strategy behind this thrust is illustrated in Figure 1.2. Execution of this strategy required a clearer definition of the CIMS vision. More importantly, the meaning of integrated manufacturing needed to be researched and defined. In this dissertation the current literature in CIMS and Flexible Manufacturing Systems (FMS) is reviewed. Based on this review, a model for CIMS and its subsystems is proposed. The model identifies the role of CIPP&C in CIMS and its associated areas of integration. Further, a framework for defining integration in manufacturing is developed. The framework differentiates between the hardware and software elements of integration. The framework can be used as a design tool to ensure that a system achieves total integration. The different elements are also defined and discussed.

Designing production control systems for the future requires, first identifying the expected features of these systems. Twenty such features are identified and reviewed in this dissertation. Further, an analysis of the integrability of present day production control systems is reported. From this analysis four basic integration approaches are identified:

1. Integration via a single mathematical model
2. Integration via a decision framework
3. Integration via a network model
4. Integration via a structured model

The fourth approach was found to be the most promising for CIPP&C and it is the approach followed here. Integration via structured modeling involves a strong emphasis on the definitive stage of modeling. The structured approach is effective in capturing and understanding the inherent system interrelationships. Further, it helps decompose a larger problem into smaller pieces. Structured modeling has successfully been used in the design of computer systems, manufacturing systems, communication networks, and organizational restructuring (Ross, 1985). The USAF initiated a very large project to model the activity of Integrated Computer Aided Manufacturing (ICAM) using structured modeling techniques (ICAM Review, 1980). The ICAM program successfully created a functional architecture of aerospace manufacturing, and the outputs of the program now form the basis for the majority of CAD/CAM/CIM projects in the defense industry. Recently, Geoffrion (1987) introduced the subject in the operations research literature describing it as a means to "provide a formal

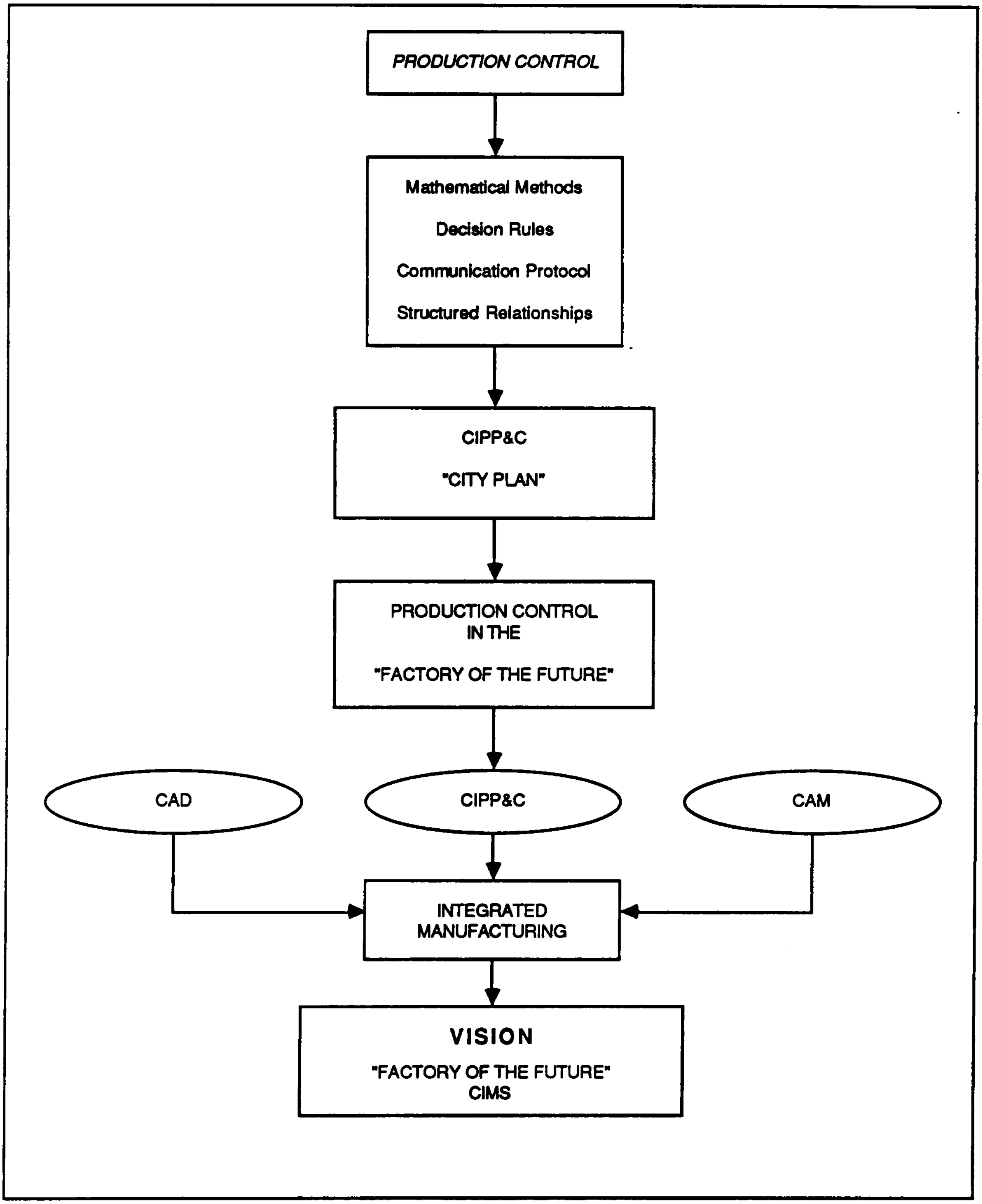

Figure 1.2. Strategy for Evolving from Production Control to CIMS

mathematical framework and computer based environment for conceiving, representing, and manipulating a wide variety of models." While Goeffrion's approach is aimed at all three stages, the structured approach of Ross is primarily aimed at the definitive stage. The approach of Ross is followed in this research. This implies the proposed CIPP&C system will be based on a structured model, but it will use mathematical models to describe behavior and to prescribe decisions. Thus, the system will have the advantages of all four approaches.

Existing production control approaches in each of the four integration approaches are reviewed and analyzed in Section 3.4. From the analysis, thirteen control issues to be considered in integrated manufacturing are identified. Each issue can be found in one or more existing approaches. The JIT approach was found to incorporate the largest number (8) of the issues. This research attempts to incorporate several of the issues in the CIPP&C system and mathematical formulations. Probably the most important element driving this research is the vision of the "factory of the future". In Figure 1.3, a control panel for the envisioned CIPP&C system is sketched. This research effort is concerned with building systems and models to generate and exploit the information on such panels.

1.2. PROBLEM DESCRIPTION

"Production control is a much needed means of obtaining better correlation between production and sales, to the end that a faster rate of turnover may come about." - Alfred Kaufmann (1930)

"Managers must look at decision making at all levels in seeking solutions to the problem. They must recognize that good short term performance results from an integrated and coherent set of decisions made over a long time span." - William Holstein (1968)

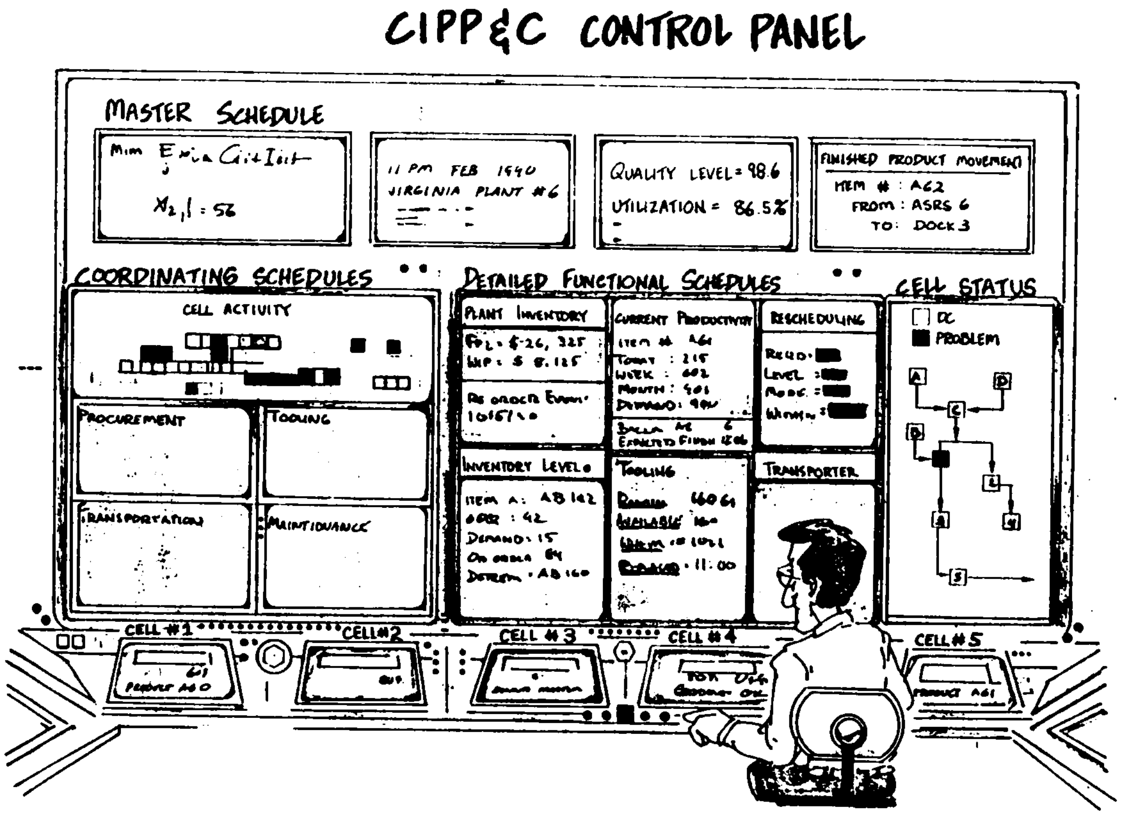

Figure 1.3. Envisioned Control Panel for the CIPP&C System

As Kaufmann observed, production control is the means for building a relationship between the activities of producing a product and its subsequent sale. Further, as Holstein observed, the efficiency of this relationship will depend on the scope and framework in which these decisions are made by the controller. In a production control system, there is a need to decide when to produce what and how much, where to produce it, when to procure what and how much, and how to utilize machines, transporters, tools, materials, and workers. Together, these decisions help minimize poor delivery performance, inventory costs, production costs, and wasted resources, and maximize product quality, resource utilization, and profits. In even a small facility, the multiplicity of these decisions can combinatorialy explode into a thousand interrelated decisions, making it difficult to coherently control the facility.

Researchers and practitioners have, over the years, successfully worked towards developing a variety of methodologies and frameworks to be used in solving the production control problem. But the transformation of traditional production into a complex CIMS scenario, coupled with the fierce competitiveness in the sales arena, is seriously effecting the efficiency of present day production control approaches. A wide spectrum of flexibilities, industrial automation, communication networks, real-time control, short product life, etc., are creating new decisions, new constraints, and new objectives. The situation is one in whereby what was optimal yesterday is sub-optimal today. The cause of this eroding efficiency does not necessarily originate from the individual methodologies themselves. Master scheduling, machine loading, job sequencing, lot sizing, etc., will always be major components of a production control system. Rather, a framework or "city plan" for more effectively integrating these methodologies, both functionally and mathematically, is needed. Subsequent to the availability of such a plan, the existing methodologies need to be enhanced or adapted to fit the plan. The plan and methodologies can then together make the production control function an integral part of a CIMS, and help ensure the realization of the vision of the "factory of the future."

Traditionally, the models of production control responsible for linking product demand and production have been aggregate planning and master scheduling. In a CIPP&C plan these models will be required to play an even more critical role. The two models are typically linked via a family/product aggregation/disaggregation process and have been solved using linear and goal programming methods. Objective functions have included setup costs, inventory costs, production costs, and opportunity costs. The constraints ensure that all the sales demand is produced and the scheduled production does not exceed capacity. Capacity is modeled as a single "lumped" resource in both aggregate planning and master scheduling. The decision variable in these models is:

$$X_{i,t} = \text{Number of product type 'i' produced in period 't'} \quad .$$

In a CIMS environment, $X_{i,t}$ would still be the decision variable, but the process of determining $X_{i,t}$ must consider:

1. The built-in flexibilities of the facility. Specifically, routing and capacity.
2. The disaggregation of time and capacity in addition to products.
3. The constraints imposed by other resources in addition to capacity. Specifically, material transportation.
4. The cellular manufacturing and group technology implications.
5. The integration implications on, and of, $X_{i,t}$

Routing flexibility is the ability to produce a product group by more than one process route, also called path or process flexibility, and capacity flexibility is the ability to start-up and shut-down processing units as needed, also called volume flexibility. The determination of $X_{i,t}$ in the absence of these, in a CIMS setup, will result in schedule inefficiency. Solution methodologies for this problem, either exactly or satisficingly, need to be developed. Mixed integer programming (MIP) methods, of the 0-1 type, are amenable to modeling of flexibilities. Several efficient methods and programs for the solution of MIPs are reported, and can be applied to the MA-Schedule problem. The modeling of flexibilities introduces non-linearities of the piecewise linear type, in both constraints and objective functions. These non-linearities are amenable to being transformed via standard linearization procedures. Further, the incorporation of preprocessing procedures will accelerate the solution of an enhanced master aggregate schedule (MA-Schedule).

In addition to a MA-Schedule, there are several other schedules in a production control system. Lack of coordination between the MA-Schedule and these other schedules is a common problem. For CIMS to be a reality, it is essential all activities be well coordinated. Thus, a set of coordinating schedules are needed to act as liaison between the MA-Schedule and operating schedules. The most important of these is the coordinating production schedule (CP-Schedule). The purpose of this schedule is to appropriately disaggregate the decisions of the MA-Schedule. Thus, the decisions to be made are:

$Y_{q,\tau,i,t,}$ = Number of product 'q' of type 'i' produced in bucket 'τ' of period 't'

$S^{k}_{q,\tau,i,t,}$ = Production start time of batch $Y_{q,\tau,i,t,}$

$F^{k}_{q,\tau,i,t,}$ = Production finish time of batch $Y_{q,\tau,i,t,}$

All three decisions are required before any further decisions can be made in the CIPP&C plan. The three decisions are not amenable to solution via a single model and must be solved in two models (CP1-Schedule and CP2-Schedule). The first decision can be made by a linear programming procedure. The other two decisions require determining the production sequence. A fundamental modeling assumption made by most present aggregate planning and master scheduling approaches (including MA-Schedule) is that all the resource required to manufacture a product is accessed in the same period. This assumption often leads to schedule infeasibility/interference due to two causes:

1. Precedence constraints will cause jobs to enter the previous period and attempt to access resources at the same time as jobs in that period.
2. With decreasing scheduling scope, the production lead time is going to be longer than the scope.

Since it is mathematically difficult to model this infeasibility in the MA-Schedule, the CP-Schedule must correct the schedule should there be an interference.

Determination of $S^k_{q,\tau,l,t}$ and $F^k_{q,\tau,l,t}$ is equivalent to the traditional flowshop problem of minimizing makespan. Attempts to solve this problem in conjunction with a master/aggregate schedule are not reported in the literature, however, there are several well known procedures for solving the individual flowshop problem. Of special interest in this research are the procedures that model a group technology setup, and these need to be incorporated in the CIPP&C plan as CP2-Schedule. Solution of this schedule will indicate any interferences. Thus, an iterative procedure needs to be developed to adjust the schedule and remove such interferences. The mathematical relationship between the MA-Schedule and CP-Schedules is shown in Figure 5.1. An integrated methodology for the solution of the MA-Schedule and CP-Schedule is thus needed, and developed in this research.

1.2.1. Problem Statement

There is a need for an integrated system of production control methodologies which will be applicable to CIMS and the "factory of the future." Such a system will optimize the overall manufacturing system and not just "islands" within it. The development of this system first requires a plan which describes the individual methodologies that constitute the system. Next in the development process are required individual methodologies which consider their interrelationships with the system and other methodologies in making decisions. Further, they must model the characteristics of CIM systems.

1.2.2. Significance and Contributions of this Research

Though several theoretical and commercial systems claim to be the production control module of CIMS, it is generally accepted that such a system is not as yet available. Such a system will consist of several methodologies. These will model the characteristics of a CIMS environment and meet its specifications. This research is a contribution in the evolution of such a system. The methodologies developed are the master aggregate schedule and the coordinating production schedule. These schedules model both capacity flexibility and routing flexibility, group technology and cellular manufacturing, and transportation and machine resources. Feasibility is ensured by constraining the solution space via several new constraints. The methodology is integrated in that objective functions and constraints are designed to consider interrelationships with other parts of the CIPP&C system. The MA-Schedule forms the basis for other methodologies to be developed in the future, and hence is an important development in production control techniques for CIMS.

Research on the development of systems of production control has produced techniques such as MRP, MRP-II, HPP, JIT, OPT, etc., in the past. Each of these is considerably different and is a potential candidate for CIPP&C. The methodology developed here is based on the basic concepts of HPP. Thus, this research contributes to the further extension of HPP to a CIPP&C system.

The development of the CIPP&C "city plan" is a contribution to the search for a more effective solution to the overall production control problem. The current emphasis in the discipline is on replacing the "physical buffers" of inventory, excess capacity, and waste with "bridges" of information. A CIMS demands that such "bridges" be built and they be "crossed". The disciplines of CAD and CAM have progressed considerably in the building of such bridges, and a weak and disintegrated production control system will only undermine their efforts to build a true CIMS.

Consequently, the development of a CIPP&C plan which defines the "bridges" to be built is a significant advance in production control theory. This new plan begins to model the structural relationships which link different decision modules, considers the control requirements of a CIMS, and describes how a series of sub-optimizations will lead to an optimal policy. The plan provides the guidelines for formulating individual solution methodologies which constitute the CIPP&C architecture. Further, the formulation and solution of MA and CP-Schedule methodologies for "crossing" the "bridges" is a significant development in production control theory. The methodologies are more intelligent than their traditional counterparts, and prescribe solutions which are realistically constrained and hence more feasible. They can be characterized by two distinct differences. First, they have more constraints to model the restrictions imposed by other upstream and downstream methodologies or systems. Second, they perceive as system variables many previously considered model parameters, since these parameters would in reality be determined by other interrelated methodologies. Analysis of the decision policies prescribed by the schedulers provides new insights to manufacturing performance. The impact of flexibilities, loading, routing, grouping, and other features on scheduling can be evaluated via the schedulers.

Implementation of the CIPP&C system offers significant benefits in terms of reduced inventory, better delivery performance, better quality, lesser capacity, and overall a stronger competitive advantage. In addition, there are significant secondary benefits in being able to exploit the productivity gains associated with CAD and CAM. The importance of these benefits is well recognized by practitioners and researchers in the field. The Office of Technology Assessment in predicting the key issues in CIM development identified the need for research in scheduling and logistics techniques for complicated factories (OTA Report, 1984). The OTA projects the first commercial applications of such techniques will occur in 1991-2000, and does not expect a widespread use of such technologies before the year 2001. Therefore, the development and testing of a CIPP&C system is an important step in the implementation of production control systems which are CIMS oriented and are integral parts of an highly automated and widely informed manufacturing system. In summary the significance and contributions of this research can be listed as:

1. Development of a plan, outlining the components and their relationships, for a CIPP&C system.
2. Identification and description of integration issues in production control.
3. Further extension of the HPP methodology.
4. Development and testing of a master aggregated scheduling model, and coordinating production scheduling model.
5. Investigative results on flexibility behavior in CIMS.

1.3. RESEARCH OBJECTIVES

The primary objective of this research was, first, to develop a plan for a Computer Integrated Production Planning and Control (CIPP&C) system for application in Computer Integrated Manufacturing (CIM) systems, and second, formulate and solve the master aggregate schedule (MA-Schedule) and coordinating production schedule (CP1-Schedule) problems within the developed plan. In achieving this primary objective, the intermediate objectives were:

1. Identify and define the characteristics of an integrated manufacturing system, with specific reference to the role of production control.
    - Construct an elementary model of CIM to show the place of CIPP&C
    - Define and describe what is meant by "integrated manufacturing"

2. Identify and define the integration issues to be considered in the design of production control systems
    - Review the current state-of-the-art in integrated production control
    - List the desirable features of production control in the "factory of the future"

3. Construct a generalized plan which defines the major decision modules that constitute a CIPP&C system, and defines their interrelationships
    - Analyze the structure of the production control function as defined by the "composite manufacturing function model" of the ICAM program (ICAM Report, 1983)
    - Apply structural analysis techniques to the decision modules to determine the decision and information requirements for integration, and the externally imposing constraints and objectives

4. Formulate and solve the MA-Schedule and CP1-Schedule problems as a series of linked mathematical programs.
    - Have an efficient computerized procedure for the sequential solution of the developed methodologies

5. Test and demonstrate the efficiency of the developed schedules.

6. Determine production control related guidelines for the design of CIM systems
    - Perform sensitivity analyses on certain key model parameters

In summary, the proposed CIPP&C plan and associated methodologies ensure that a manufacturing facility operates and behaves as an integrated system, and not as a set of stand alone or interfaced systems.

1.4. ORGANIZATION OF THE DISSERTATION

There are seven chapters, in addition to the introduction, in this research report. The chapters are organized to correlate, approximately, with the above listed research objectives. Chapter Two is concerned with objective one and describes the development of a CIMS model and an integration framework. The third chapter is concerned with objective two and reviews current approaches to production control. Based on the review, the key control issues in integrated manufacturing are identified. The fourth chapter is concerned with objective three and describes the development of the CIPP&C "city plan". Chapter Five is concerned with portions of objective four and describes in detail the formulation of the MA-Schedule and CP1-Schedule. Chapter Six describes the development of solution methodologies for both schedules. Descriptions of the systems of computer programs, and the MPS-III system are also included. Chapter Seven presents the results of experimentation with the schedulers. Analysis of these results, both in terms of scheduler efficiency and impact of decisions on CIMS, are reported. Thus, chapter Seven focuses on objectives six and seven. Chapter Eight summarizes and prescribes future research efforts. The appendices describe experiments conducted, and list system output.

CHAPTER TWO

INTEGRATED MANUFACTURING

2.1. INTRODUCTION

Of all the tools proposed for better manufacturing management, CIMS has received the most exposure and attention in recent times. CIMS involves the integration and coordination of design, manufacturing and management using computer-based communication network systems. In reality, it is not a specific tool but rather a concept, or approach, to organize and manage the process of producing goods. Achieving a CIMS implies achieving an integrated manufacturing system, but the question, what is an integrated manufacturing system? is not always easily answered.

No specific definition, either conceptual or operational, of an integrated manufacturing system is reported in the literature. Simplistic definitions which describe such a system as one linking all functional and management aspects of the manufacturing system, can not really be accepted as operational.The lack of a definition does not imply that such a system never existed. The first backyard engineering shops were integrated setups, the integrator being the owner who made all relevant decisions. But with time, as complexity increased, one dimension of integration increased while another decreased. Increased vertical integration resulted in increased control of upstream and downstream systems. Decreased horizontal integration resulted in islands of management and optimization. Integrated manufacturing requires a balance of both these dimensions. In the early industrial period there was such a balance. The 20's and 30's witnessed the creation of complex industrial systems, which were usually the brainchild of a single visionary. Many of these plants were designed to be, and truly were, highly integrated plants. It was in this period that Henry Ford built the River Rouge plant, the most awesomely integrated plant ever built (Halberstam, 1986). Barges would carry iron ore into the plant, and finished cars out of the plant. The production of a complete car, from raw material to finished product, took only four days. In 1982, when asked where they had learned the secret of Just-in-Time production, Eiji Toyoda, the Chairman of Toyota would reply "There is no secret to how we learned to do what we do, we learned at the Rouge" (Halberstam. 1986).

Integrated manufacturing is not an invention of the 70's or 80's, it has been a concept, consciously or subconsciously, practiced by many designers in the past. But after the 40's, there has been an increased imbalance in the integration equation. In the "big is better" drive, manufacturing became increasingly complex and disintegrated. The specific causes of this disintegration are not easily identifiable. Management style, performance evaluation systems, industrial cycles, societal trends, work ethics, lack of planning, technological trends, and financial pressures are just some of the possible causes of this trend in disintegration. It would be a trend which would go unnoticed till the early 70's.

With the 70's there was a growing realization that there was a problem with American manufacturing. Managers and researchers had become aware of the fact that manufacturing was costly, inflexible, of a low quality, and low technological content. It was during this time that a new technology, a new weapon, was created in the world of manufacturing. In 1974, Joseph Harrington would introduce the term and concept of CIM[1] in his book of the same name. In the next ten years it would become one of the hottest buzzwords in manufacturing. It would become the means for harnessing the new technologies, it would become the panacea for all problems, it would

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[1] The acronym CIM is used in this report only when referring to the concept/philosophy of computer integrated manufacturing. The acronym CIMS is used when referring to a physical entity incorporating the CIM concept.

become the tool for becoming competitive, and unfortunately, it would become a dream many a manager would chase in futility. CIM would be a technology in whose search we would build islands of design, manufacturing, production planning and control, material management and information systems, but not achieve true integration. Ironically, ten years later in 1984, Joseph Harrington would publish his last book, *Understanding The Manufacturing Process*, a guide to designing CIMS.

The concept of CIM, and those who have implemented sub-systems of it, have taken a beating in the literature. In spite of these criticisms, CIMS remains the only means we have for achieving the "factory of the future." Many of the failures and struggles with CIM have been due to a lack of understanding of what integrated manufacturing really means in operational terms. Thus, the focus of this chapter is on developing the issues and characteristics which define an integrated manufacturing system and the relationships between CIMS, computers, and integration. It is not the intent of this dissertation to find a solution to the problems of CIMS, or to develop the complete framework of an integrated manufacturing system, for such an intent would be beyond the scope of this project. The focus is on the area of Computer Integrated Production Planning and Control (CIPP&C), which is one element of CIMS. The intent in discussing integrated manufacturing is to avoid the trap of developing a CIPP&C which is another "island of automation or optimization."

2.1.1. CIM, Computers and Integration

The CIM concept is a fusion of two elements: computers and integration (if viewed as separate subjects they would be termed Computer-Aided-Manufacturing/Design and Integrated Manufacturing). The two elements are significantly different in that computers is a technological element while integration is a managerial element. There is a tendency in the literature to assume the presence of one implies the other, but the two elements are mutually exclusive and may exist in the absence of the other. The concept of CAM/CAD is well defined in the literature and has been much researched. In contrast, the concept of integrated manufacturing is not well defined. There are several reasons for this lack of reported literature on integrated manufacturing. Consider the evolution of CIM as recounted by one expert (OTA Report, 1984), who describes the reasons for the development of the CIM concept as:

1. Realization that automation for discrete activities in manufacturing often decreased the effectiveness of the entire operation.
2. Development of computers and Data Base Management Systems (DBMS) allowing information sharing between functional areas.
3. The arrival of micro-computers which began to allow machines to be remotely programmed, and talk to each other.

Translating the above reasons to events, the evolution of CIMS can be described by Figure 2.1. CIMS appears to have evolved from CAD/CAM, as a medium for permeating the CAD/CAM concept throughout the factory. It would seem logical to assume CIMS evolved from the application of computers to integrated manufacturing concepts, but in reality the present focus on integrated manufacturing is due to the increasing popularity of CIMS. An effective and workable CIMS strategy is possible only if the concepts of integrated manufacturing are clearly defined and understood. In the absence of such concepts, CIMS is going to be a partial solution.

The difference between computerizing a technology and integrating a technology is not clearly defined either in the literature or in practice. It is commonly assumed the use of computers in a particular area integrates that area with itself and other interacting areas. For example, MRP is defined as a computer integrated pro-

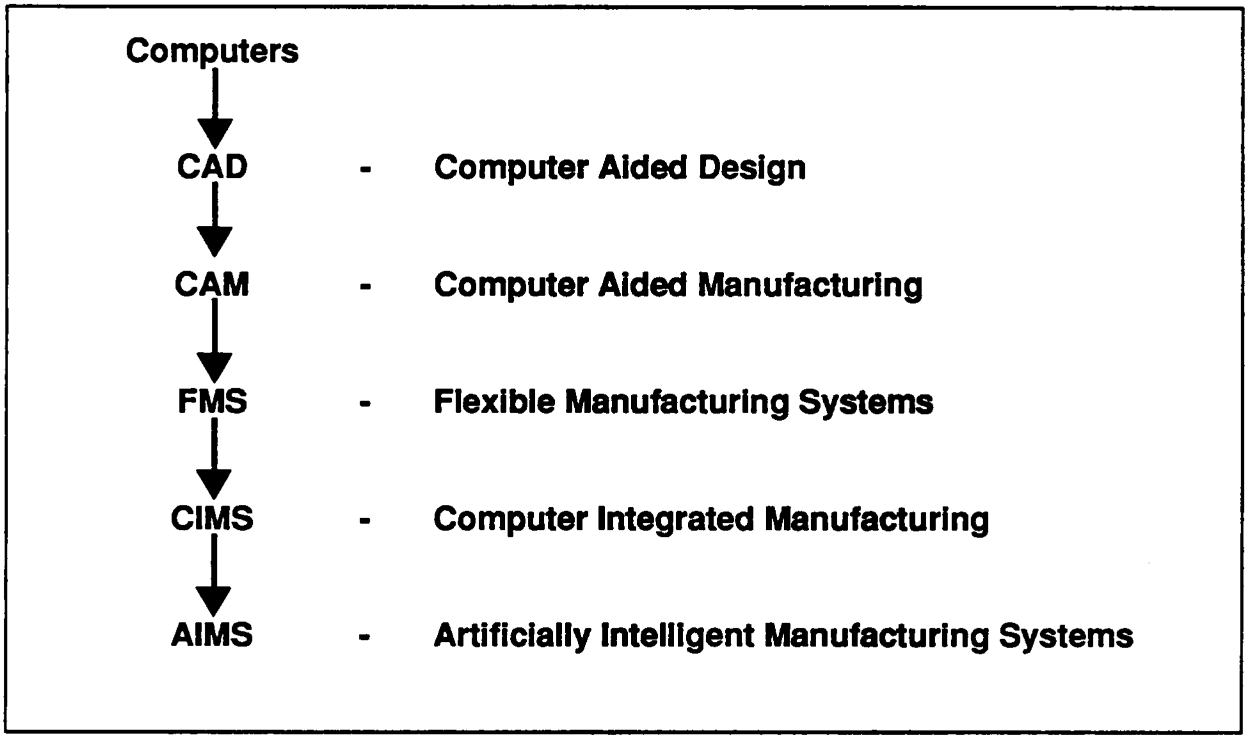


Figure 2.1. Evolution of Manufacturing Technologies

duction management system (Groover, 1980). MRP was developed by Orlicky (1975) using the concept of dependent demand. The subsequent computerization of the MRP procedure earned it the computer integrated label. But, in reality, the integrability of MRP will depend on whether the dependent demand concept, on which MRP is based, integrates the system or not. There is a clear distinction between the prefixes computer-aided and computer-integrated, and the presence of one does not imply the presence of the other. The appropriate prefix should be determined by how the computer is used in a particular situation. In any manufacturing system, computers may be involved in four types of activities:

1. Control of physical automation
2. Information storage and retrieval
3. Information transfer
4. Decision support

A technology may use computers in one or more of the above modes simultaneously. But only one of the above four modes is a must for an integrated system, that is, the activity of information transfer. Even the presence of this does not necessarily imply integration. It is how the transferred information is used is that determines integration.

In this chapter, the characteristics of an integrated manufacturing system will be defined and described. First, the CIM concept is closely tied to integrated manufacturing and a review of CIMS is done. Next the technology of Flexible Manufacturing System (FMS) is reviewed. FMSs are being described as the first truly integrated manufacturing systems, and they are forming the foundations of many CIMS. Finally, the concepts of integration are discussed and the framework of an integrated manufacturing system defined and described.

2.2. COMPUTER INTEGRATED MANUFACTURING SYSTEMS (CIMS)

Current industrial practices and research thrusts indicate that CIMS will be the dominant feature of the "factory of the future." CIMS is not a specific technology but rather an approach to factory organization and management. A variety of definitions have been proposed for CIM:

"A series of interrelated activities and operations involving the design, materials selection, planning, production, quality assurance, management, and marketing of discrete consumer and durable goods ...... CIM is the deliberate integration of automated systems into the process of producing a product ...... CIM can be considered as the logical organization of individual engineering, production and marketing/support functions into a computer connected system." - CAM-I definition (Bance, 1985)

"CIM involves the integration and coordination of design, manufacturing, and management using computer based systems." OTA Report (1984)

"CIM is the application of computer technology to the tools of production in an interconnected hierarchy." - CIM Handbook (Teicholz and Orr, 1987)

"CIM occurs when all the processing functions and related managerial functions are expressed in the form of data. These data are in a form that may be generated, transformed, used, moved, and stored by computer technology,and these data move freely between functions in the system throughout the life of the product." - NRC Report (1984)

"CIM integrates the factors of production to organize every event that occurs in a manufacturing business from receipt of a customer's order to delivery of the product. The ultimate goal is to integrate the production process, the material, sales, marketing, purchasing, administration and engineering information flows into a single, closed-loop, controlled system." - Production Engineer (1986)

> "The use of computer and information/communication technologies to effectively integrate all of the engineering/design functions, manufacturing planning functions, equipment/process technologies, manufacturing control processes and management functions necessary to convert raw materials, labor, energy and information into a high quality, profitable product within a reasonable amount of time." - Garrett Turbine Engine Co. (Mize, et al., 1985)

Almost all the definitions are very macro and really just define a concept. It would be almost impossible to use these definitions to label an actual facility as being a CIMS or not. Some experts (IIE Roundtable, 1985) believe CIM is more a philosophy of operation than a function itself. Clearly, the CIM concept is not rigorously defined and has many interpretations. Groover and Zimmers (1984) describe CIMS as incorporating many of the individual CAD/CAM technologies, and there is a growing perspective that CIMS is the umbrella encompassing all the computer aided technologies. The ESPRIT project (Kochan & Cowan, 1986, Maconaill, 1985) on design rules for CIMS defines the computer aided technologies as "islands of automation" and CIMS as the medium for interconnecting these "islands". The concept of computer aided and automated processes has proliferated into all functions of the manufacturing system. The process of defining, designing, building and controlling a modern manufacturing system is becoming increasingly complex and confusing. Several projects are focussing on simplifying this process by the integration of computers. These projects are investigating the cause-effect relationships and cost/benefit ratios of the various technologies to develop a structured and patterned approach. The National Bureau of Standards Automated Manufacturing Research Facility (NBS-AMRF) has been conducting research in this area (Magraby, 1986).

The perspective that the CIMS approach is directly related to the use of computer assisted technologies is shared by several researchers (Groover and Zimmers 1984, MaConaill, 1985, Bullinger et al, 1986). The primary reason for this perspective is that the "factory of the future" is visualized as being an highly automated unmanned facility. Further, it is widely believed the factory of the future would result from the installation of such technologies as numerical control (NC) machines, flexible manufacturing systems (FMS), and other computer assisted technologies. Appleton (1985) argues this assumption is incorrect and quotes Toffler (1985) in support - "The advance of technology does not necessarily bring progress and, in fact, it may, unless carefully controlled, destroy progress already achieved." There is a growing school of thought which echoes the sentiment of Appleton. Their (Skinner, 1980, 1985; Sadowski, 1986) opinion is that CIMS and the factory of the future will always be in the future, unless we increase our focus on management and control issues. We need to determine and investigate the decision making process which guides the operation and control of a CIMS facility. We need to realize that we must first achieve an integrated manufacturing system, before we can attain computer integrated manufacturing, because the simplest of all CIMS definitions is - the use of computers for information transfer and decision support in an integrated manufacturing system.

The CIM concept and it's associated technologies are only briefly reviewed here from an integration perspective. More elaborate descriptions of CIM are reported by Kochan (1986), Barash (1980), Ranky (1987), and Groover and Zimmers (1984).

2.2.1. CIM History and Evolution

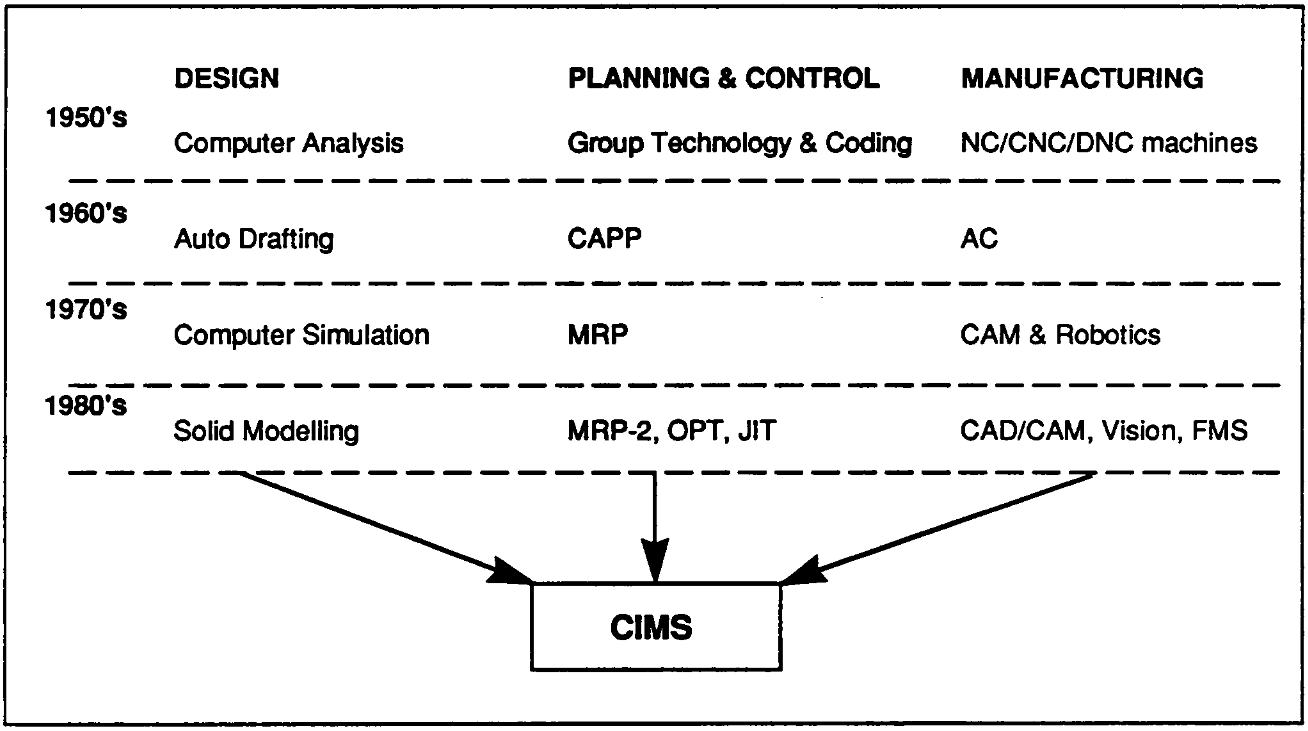
The term Computer Integrated Manufacturing was first introduced by Dr. Joseph Harrington in his book in 1974. The term evolved from the perceived need for a concept/technology that would integrate the major functions of manufacturing: product design, production technology, and production/process planning and control. the use of computers in these three functional areas began much earlier in the 1950's.

Figure 2.2 traces the historical development of the separate technologies in the evolution of CIMS. Full CIMS has not been realized, as yet, anywhere in the world, though many systems have many major elements in operation (NRC Report, 1984). It is expected that total CIMS will be achieved by the mid 1990's.

2.2.2. Components and Structure

Clearly CIMS is a complex network of subsystems, the subsystems in turn being comprised of sub-subsystems. The interrelationships between these subsystems, and sub-sub systems defines the structure of a CIMS. CIMS is generally described by the entire process of manufacturing, and all elements and functions which are part of this process will be parts of CIMS. Manufacturing is defined by Harrington (1984) as "the conversion of naturally occurring raw materials into desired end products." The functions which define this conversion process may be grouped in several ways, a commonly accepted grouping being: engineering design, product manufacturing, manufacturing control, and manufacturing management. these four groups form the major components of a CIMS, or any manufacturing system. A fifth component is the medium which is responsible for data conveyance between the four components. Gunn (1985) argues that this fifth component, apart from automation, is the primary differentiating element between CIMS and traditional manufacturing. Figure 2.3 redefines these components from traditional manufacturing to CIMS. The main theme illustrated in Figure 2.3 is the evolution from manual to computer-aided to computer integrated.

Figure 2.3C provides only a general structure of CIMS. Several detailed structures of CIMS have been presented in the literature. The scope of these structures vary from just considering the manufacturing process to the entire organizational system. Four such structural models of CIMS are discussed here (Figures 2.4a and 2.4b).



	DESIGN	PLANNING & CONTROL	MANUFACTURING
1950's	Computer Analysis	Group Technology & Coding	NC/CNC/DNC machines
1960's	Auto Drafting	CAPP	AC
1970's	Computer Simulation	MRP	CAM & Robotics
1980's	Solid Modelling	MRP-2, OPT, JIT	CAD/CAM, Vision, FMS

Figure 2.2. Evolution of CIM sub-systems

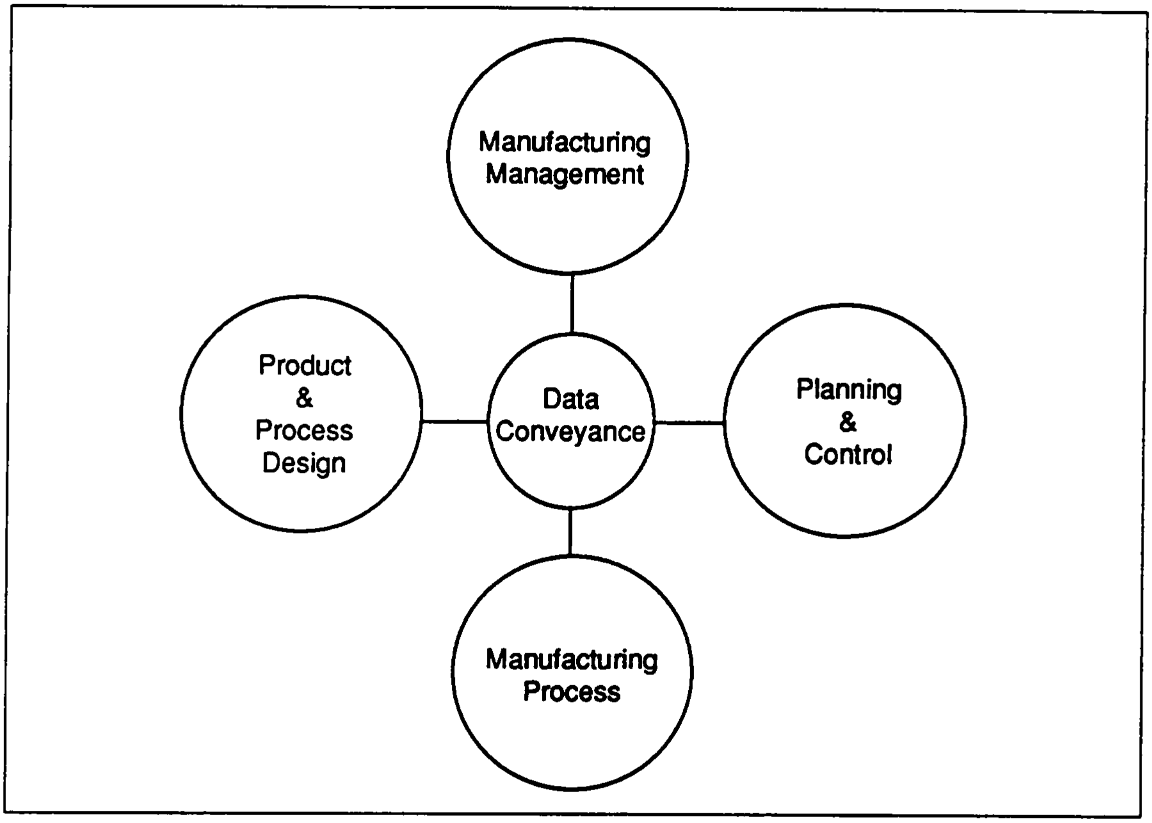


Figure 2.3A. Traditional Manufacturing Systems

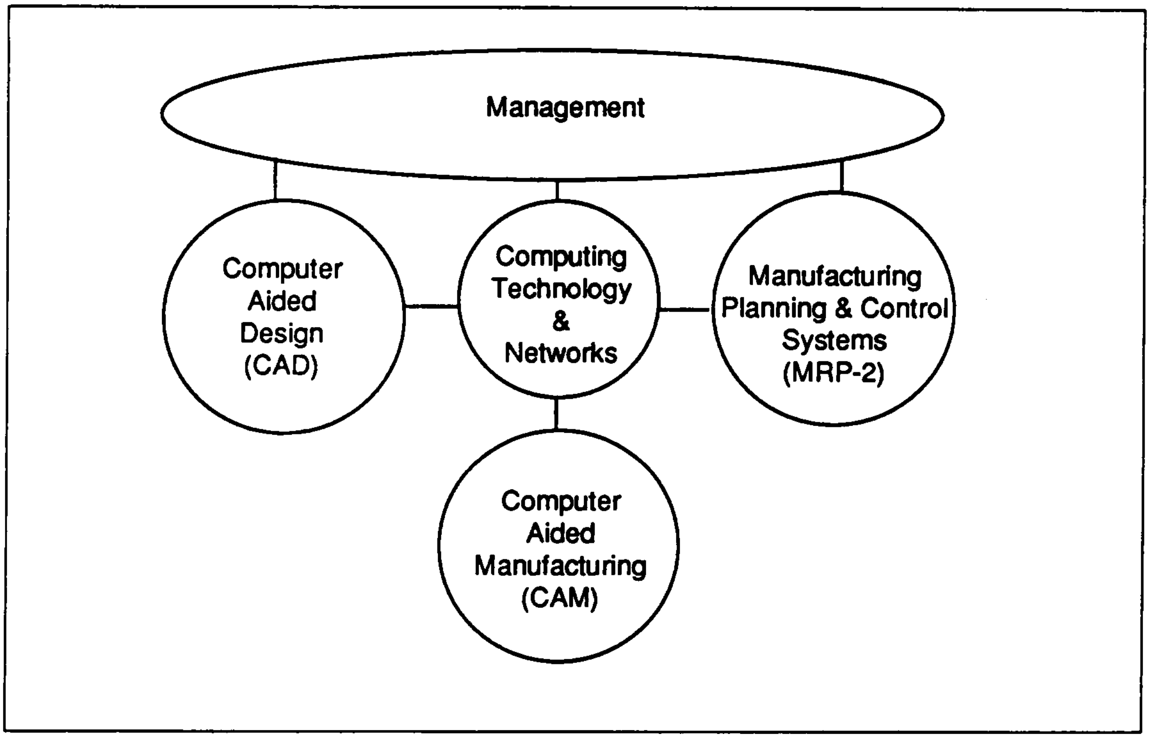


Figure 2.3B. Computer Interfaced Manufacturing

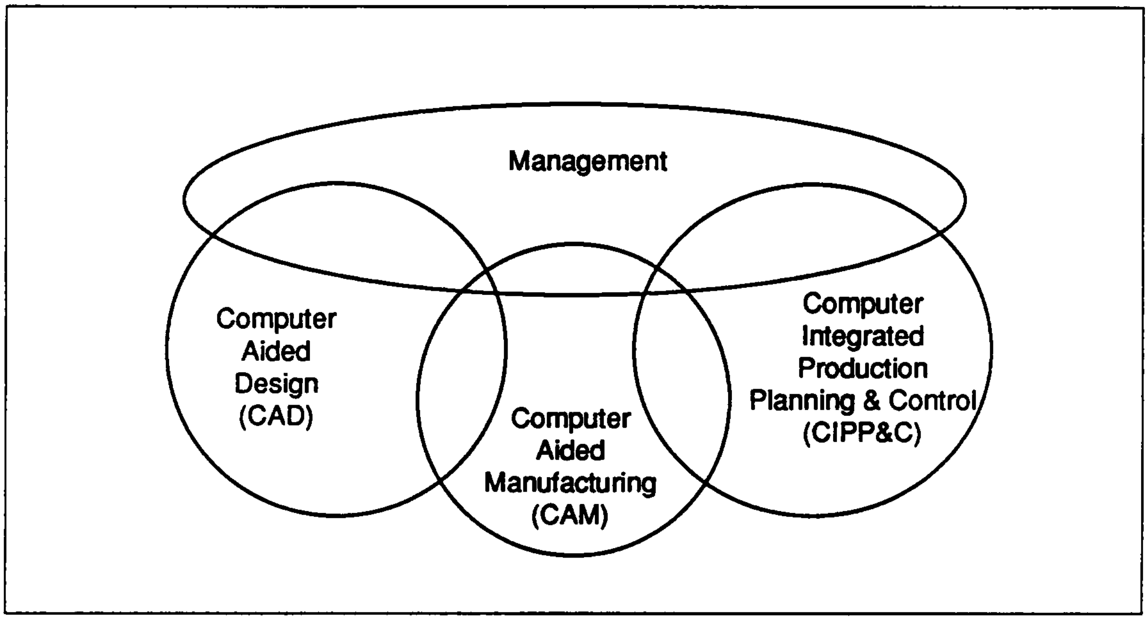
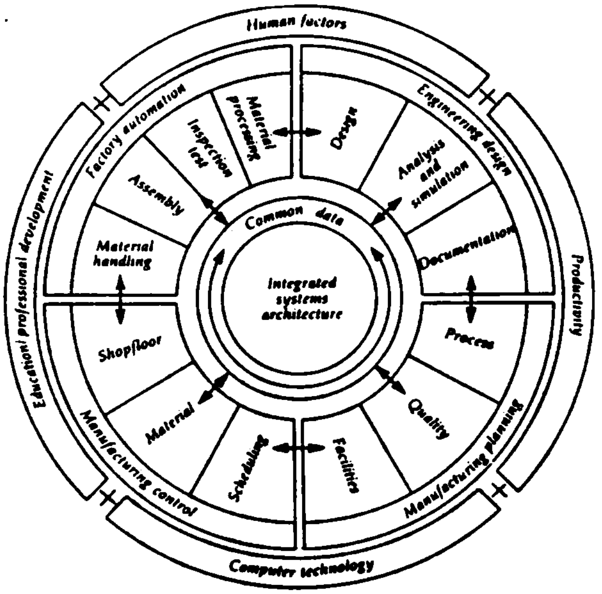


Figure 2.3C. Computer Integrated Manufacturing

CASA/SME (Lardner, 1986)



Merchant (1980, 1986)

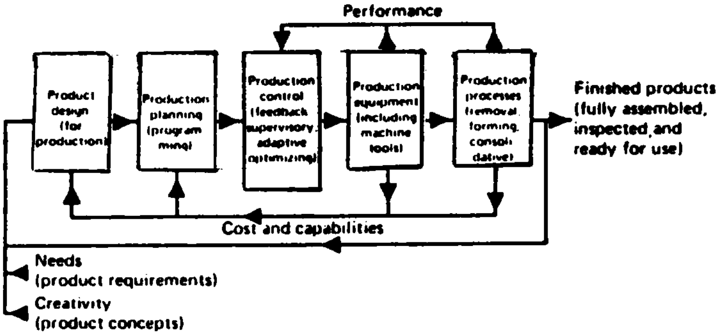
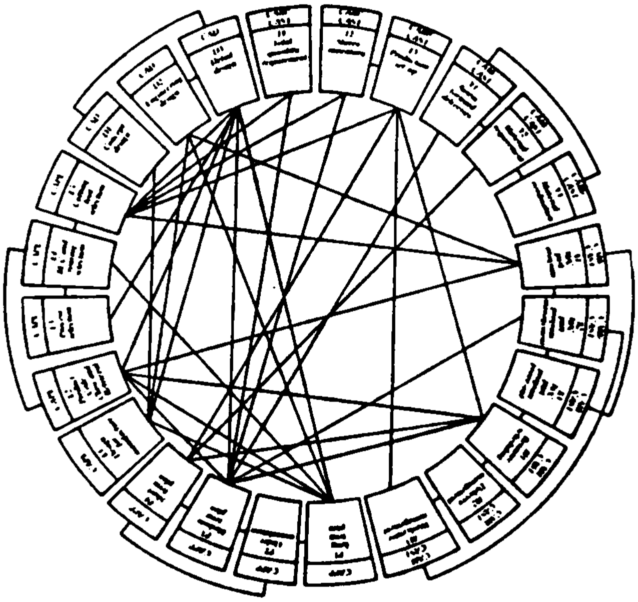


Figure 2.4A Structural Models of CIMS

ESPRIT (Kochan & Cowan, 1986)



Fujistu's Model (Lipchin, 1987)

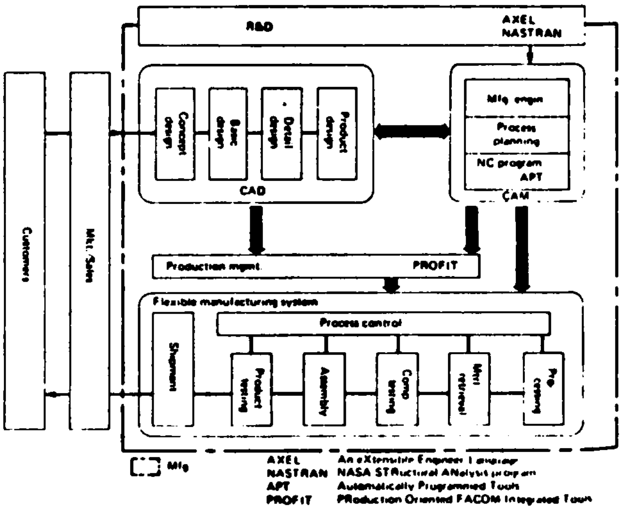


Figure 2.4B Structural Models of CIMS

The models by CASA/SME and ESPRIT are similar in that both are of the "wheel and spoke" type and are basically attempts at defining an integrated computer systems architecture. There are two major differences between the two models. First, the CASA/SME model prescribes a common data base, while the ESPRIT model prescribes a distributed data base with a network providing the necessary linkages. Secondly, the CASA/SME model is functionally defined, while the ESPRIT model is technologically defined. Both models are conceptually the same. The ESPRIT model is more rigorously defined and is an attempt to create a marketable (off the shelf) CIMS. The drawback of the ESPRIT model is that it defines a network architecture for CIMS, but does not define the decision framework for achieving a CIMS.

Both the Merchant and Fujitsu models structure CIMS as a closed loop feedback system in which the prime inputs are product requirements and technological forecasts, and the prime outputs are finished products. Merchant's model is one of the earliest models, and presents the generic structure of a CIMS. The important concept illustrated in this structure is that all functions of the manufacturing system must be automated, optimized and integrated by applying the computer. The various functions must be interrelated by suitable feedforward and feedback loops. Merchant (1987) discusses the interrelationships between the five elements, and sets the basis for defining an integrated decision process.

The Fujitsu model is an actual practical application of CIM, and is primarily a more detailed and operational version of Merchant's model. Fujitsu's objective in developing this model was to shorten the entire product development and manufacturing cycle. Their approach is based on a careful investigation of inefficiencies in synergy between the engineering and production departments involved.

The variety of CIM structural models can be classified as ranging from the conceptual to the operational (technology specified) type. Of the four models reviewed here, the CASA/SME model and Harrington models are primarily conceptual in nature, while the ESPRIT and Fujitsu models are primarily operational. Other CIM structural models are described in the literature by Biles and Zohdi (1984), Bullinger, et al. (1986), Ranky (1987), Gunn (1985), Kochan (1986), and Sarlin (1985).

A predominant feature of CIMS is the required communication interfaces between the various functional elements of manufacturing. Thus, a major research focus in CIMS technology has been these interfaces. A simple CIMS model is used here to review the interfacing technologies. The model is of the Venn diagram type (Figure 2.5) and borrows from the approaches of ESPRIT (Kochan & Cowan, 1987) and Gunn (1985). The model has three technological elements, CAD, CAM and CIPP&C. A fourth element is management. These four elements form the building blocks of a CIMS. The model can be enriched by superimposing a flow diagram, similar to the Fujitsu model, over the Venn diagrams. The areas of integration focus are identified in the model. There are three such areas:

Integration 1: Management ---> CAD, CAM, and CIPP&C
Integration 2: CAD ---> CAM
Integration 3: CAM ---> CIPP&C

Most of the current research in manufacturing systems integration can be classified in one of these classes. The specific technologies identified in integration-1 are: Manufacturing Automation Protocol (MAP), Technical and Office Planning (TOP) standards, and Open Systems Interconnection (OSI). MAP, TOP and OSI are primarily focussed on systems architecture and organization. Both MAP and TOP are expected to ultimately result in a system of standards for the entire CIMS. Current status of MAP, TOP and OSI is documented by Beale (1986). ICAM (1000)[2] focuses on the ar-

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[2] Integrated Computer Aided Manufacturing (ICAM) is a research program of the U.S. Airforce. Started

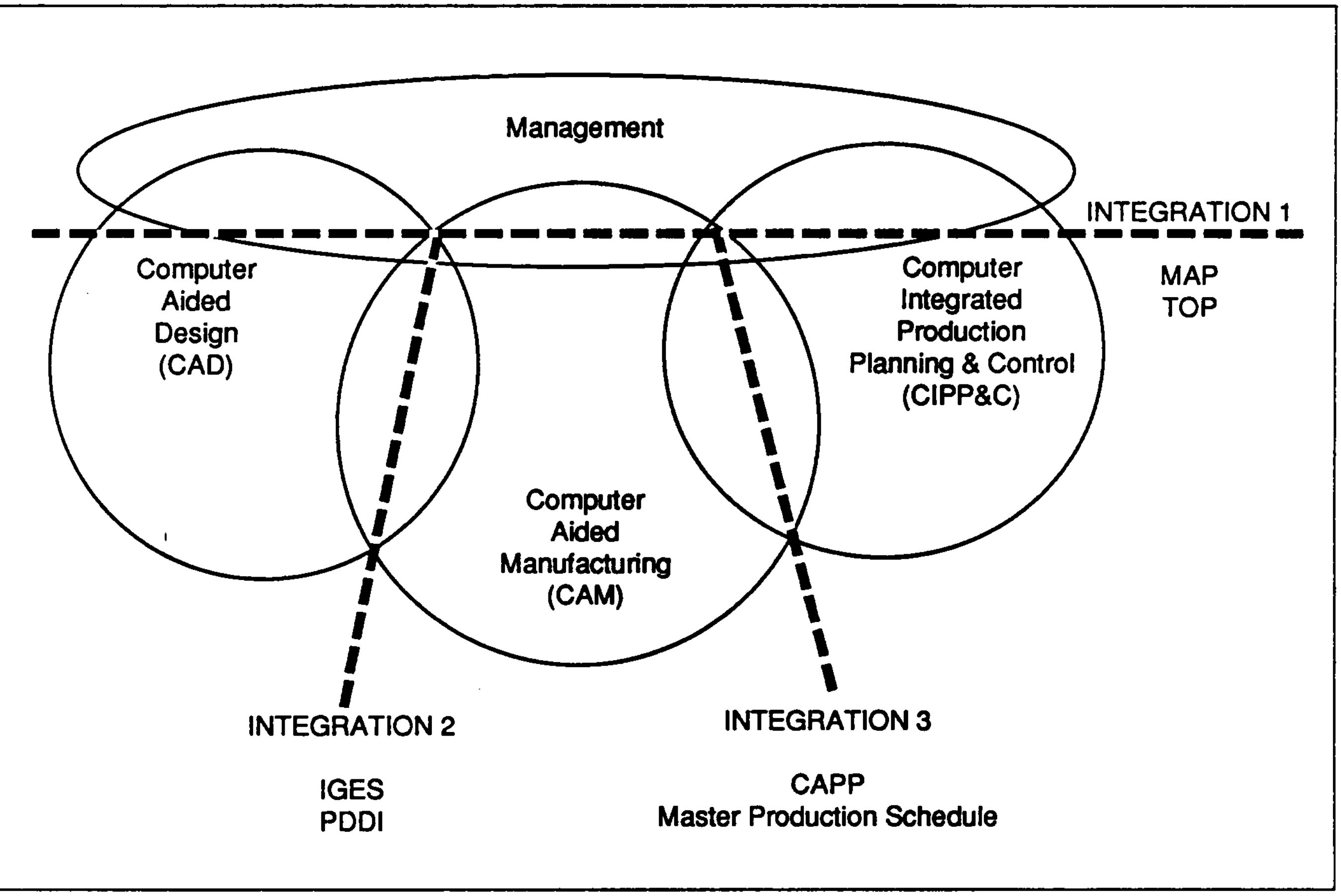

FIGURE 2.5. Computer Integrated Manufacturing and Associated Technologies

chitecture of the factory of the future. It presents a framework for organizing all the functions, information types, and interactions typical of a manufacturing system. The technology is reviewed in ICAM Review (1980).

The technology of CIMS will be a major area for research activities during the next decade. The concept has been well defined and several microcosms of CIMS have already been implemented. But the focus has been more on computerization and automation than on integration. CIMS provide the technological requirements for achieving an integrated manufacturing system, and it is imperative the issues of integration be researched more for total CIMS to become a reality.

Many researchers describe a FMS as CIMS implemented at the shop floor level (Saul, 1985). The research activity in the area of FMS technology has grown considerably in the last few years. The nature of FMS research has been quite dissimilar to that in CIMS. While CIMS research focussed on computer networks and architecture, FMS research has focussed on operations planning and control and system optimization. In the next section a review of FMS technology is presented.

2.3. FLEXIBLE MANUFACTURING SYSTEM (FMS)

During the last few years. many manufacturers have struggled with the design and implementation of various forms of automated manufacturing. Resounding successes have been achieved by several of them. One of the areas in which consider-

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in 1978 and located at the Wright Patterson AFB, the ICAM program is the largest single program in the DoD's Manufacturing Technology (ManTech) program. The annual budget for ICAM being in excess of $20 million. The objective of ICAM is to advance the state of the art of CAM in the aerospace industry. There are several research thrusts in the program, the numerical code after ICAM indicates a particular research thrust. Further information on ICAM can be obtained from ICAM Review (1980).

able success has been reported is Flexible Manufacturing System (FMS). Research in almost every area of FMS has been extremely active. The literature abounds with FMS case studies from all parts of the world, and at least one company, LTV - Vought Aero Products, boasts of a showcase for the factory of the future (Knill, 1985). A FMS is a CIMS in microcosm and is designed as set of mini-factories. In the study of integrated manufacturing it is important we understand the principles and rules on which these systems operate.

The original concept of FMS is attributed to D.T.N. Williamson (Jablonwski, 1985). Williamson developed a working system in the early 60's for Molins Ltd. (London). In 1983, Molins was granted the U.S. patent for the concept. Within the patent a FMS is defined as an "installation comprising a plurality of complementary NC machine tools along a predetermined path, work piece storage, work piece transport means, and central programmed control of both individual machine tools and the transport system". Given the structure of present day FMS technology, a more appropriate definition is that due to Stecke (1983), namely, "FMS is an integrated, computer controlled complex of automated material handling devices and machine tools that simultaneously process medium-sized volumes of a wide variety of part types". Figure 2.6 depicts the processing of jobs in a FMS and Figure 2.7 shows the detailed layout of an FMS. Physically, the FMS consists of M machines arranged in Q cells with a fixed number of transport vehicles which have a fixed path.

The early developments in FMS technology (primarily in the U.S., Japan, and Germany) were fueled by the specific demand by companies to fill a gap in their manufacturing strategy. The gap developed as the need arose for producing medium-sized volumes of a large number of part varieties within short lead times. Table 2.1 shows the classification of FMS in relation to job shops and mass production lines. A FMS attempts to achieve both the high flexibility of a job shop and the

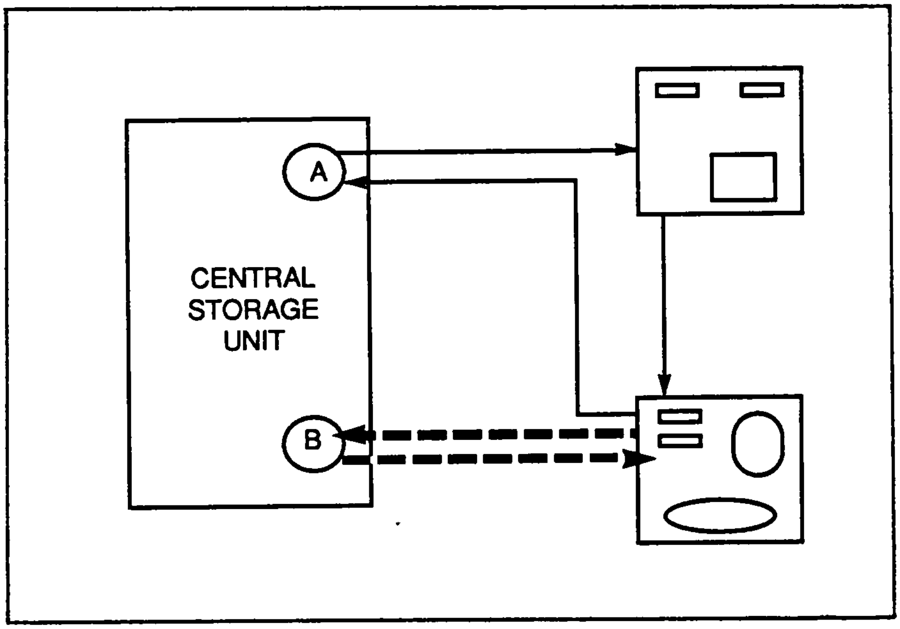

Figure 2.6. Processing of Two Jobs in a Two Cell FMS

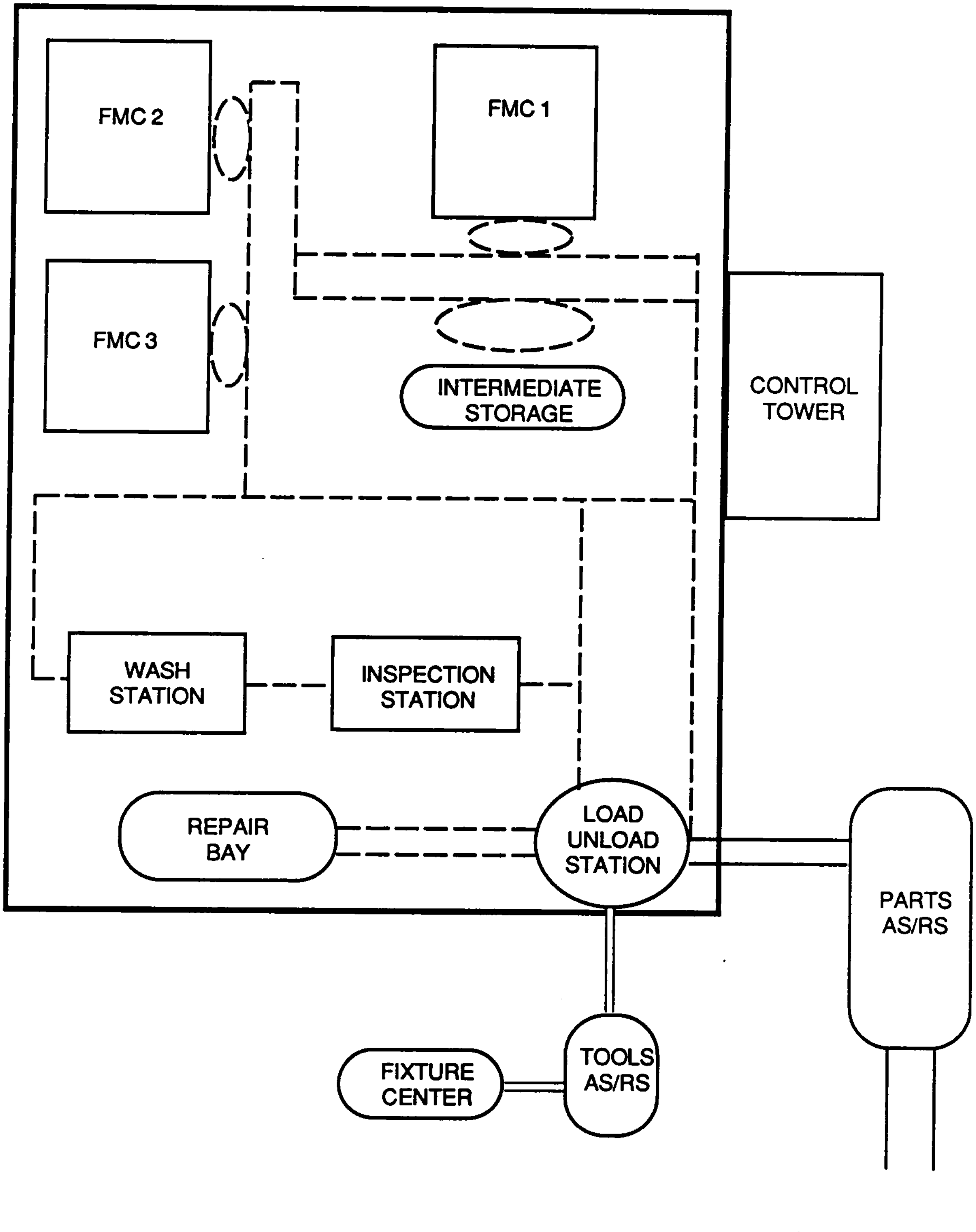

Figure 2.7. Detailed Layout of a FMS (Adapted from Knill, 1986)

VOLUME PRODUCT TYPE	LOW	MEDIUM	HIGH
CERTAIN	Job shop or flow shop production to order	FMS	Hybrid shop with stock and assemby to order
UNCERTAIN	Batch or intermittent production to stock	FMS	Repetitive or mass production to stock

Table 2.1. Manufacturing Systems Classification

high volume and lesser unit cost of a production line. There are four features which distinguish a FMS from other production approaches. These are:

1. Computer linked systems
2. Common automated material handling system
3. Cellular/Group technology approach to manufacturing
4. Projected real time system control

These four features are the primary reason for the recent emphasis of research on FMS in the production research literature. These features enable the FMS to meet production targets for a variety of part types in the presence of a dynamically changing environment and/or production system.

2.4. INTEGRATED MANUFACTURING

Prefixing the word "manufacturing" with the word "integrated" is now a common trend in the literature. In contrast, the definition and meaning of the expression "integrated manufacturing" is not commonly known and is not explicitly reported. In most uses of the term, the implied meaning is a system in which all the functional and management aspects of the manufacturing system are linked (Martino, 1972). Our intent in this section is to better understand what these linkages are, and how they effect the working of the individual functional components.

Why is integrated manufacturing so important? Manufacturing may be viewed as a series of systems and sub-systems which are inextricably related. It is usually assumed that these subsystems are inherently compatible and complementary. Lardner (1986) contends this is is a wrong assumption, and that in fact these subsystems are frequently in conflict, and optimization of each of these sub-systems results in sub-sub-optimization of their objectives. This can only be avoided if an integrated approach is adopted.

Only by managing the operational components as an integrated system can manufacturers exploit the full potential for delivering added value to customers through lower prices, greater service responsiveness, or higher quality (Haas, 1987). Most efforts to develop CIMS actually develop computer-linked systems instead. The resulting systems are usually highly computerized and are able to provide data access to all elements of the production system. Managers in such systems are not able to effectively utilize the data available to them and consequently have what is termed a DRIP (data rich information poor) problem. Decisions made in the presence of a CIM system and in its absence tend to be only marginally different. In most cases the hardware emphasis during design is so strong that the management support tools element is underdeveloped. Lack of appropriate management support tools implies a lack of systems integration and subsequent failure since the system is unable to meet expectations. In designing any type of integrated manufacturing system the concept of integration needs to be emphasized as much as the hardware content.

In interpreting the term Computer Integrated Manufacturing, we find there are two possible meanings:

1. Integrating the use of computers in a manufacturing system
2. The use of computers in an integrated manufacturing system

Many managers assume the first interpretation to be correct, and/or are unable to differentiate the difference between the two. The author's belief is that the second interpretation is correct and essential to achieving the "factory of the future" or any kind of competitive system. The potential benefits, or improvements in performance, associated with CIMS and its two meanings can be described by an S-curve[3] (Figure 2.8). Journals and magazines are filled with reports by managers who have achieved the first meaning and are either happy with the incremental improvement or disillusioned with the lack of expected performance. Thus, it is evident, achieving systems integration is critical to achieving orders of magnitude in improvements and the promised benefits of CIMS.

Systems integration is defined by Shunk and Filley (1986) as "the optimization, over time, of all components comprising an organizational system that generates a measurable output. These components include all the organization's fixed, potential, tangible and intangible assets, including people, money, information, capital investments, energy and technology." From this definition it is apparent a completely integrated system would be extremely difficult to achieve. In reality, designers must strive to achieve the maximum feasible level of integration given a particular scenario. Notice that the above definition does not refer to computers. A widely held misconception is that an integrated system must be computerized. The Japanese Just-in-Time/Kanban system is a highly integrated system ~~but~~ that had only minimal computer support initially.

2.4.1. Definition of Integrated Manufacturing

Webster's dictionary defines the verb "integrate" as: "to form or blend into a whole, to unite with something else, to incorporate into a larger unit." Based on this definition, several researchers have attempted to define integrated manufacturing. The majority of these definitions describe what integration does and not what integration is. Further, many definitions confuse computer integration with integration,

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[3] The concept of an S-curve was introduced by Foster (1987) as the relationship between the effort put into improving a process and the results one gets back for those efforts.

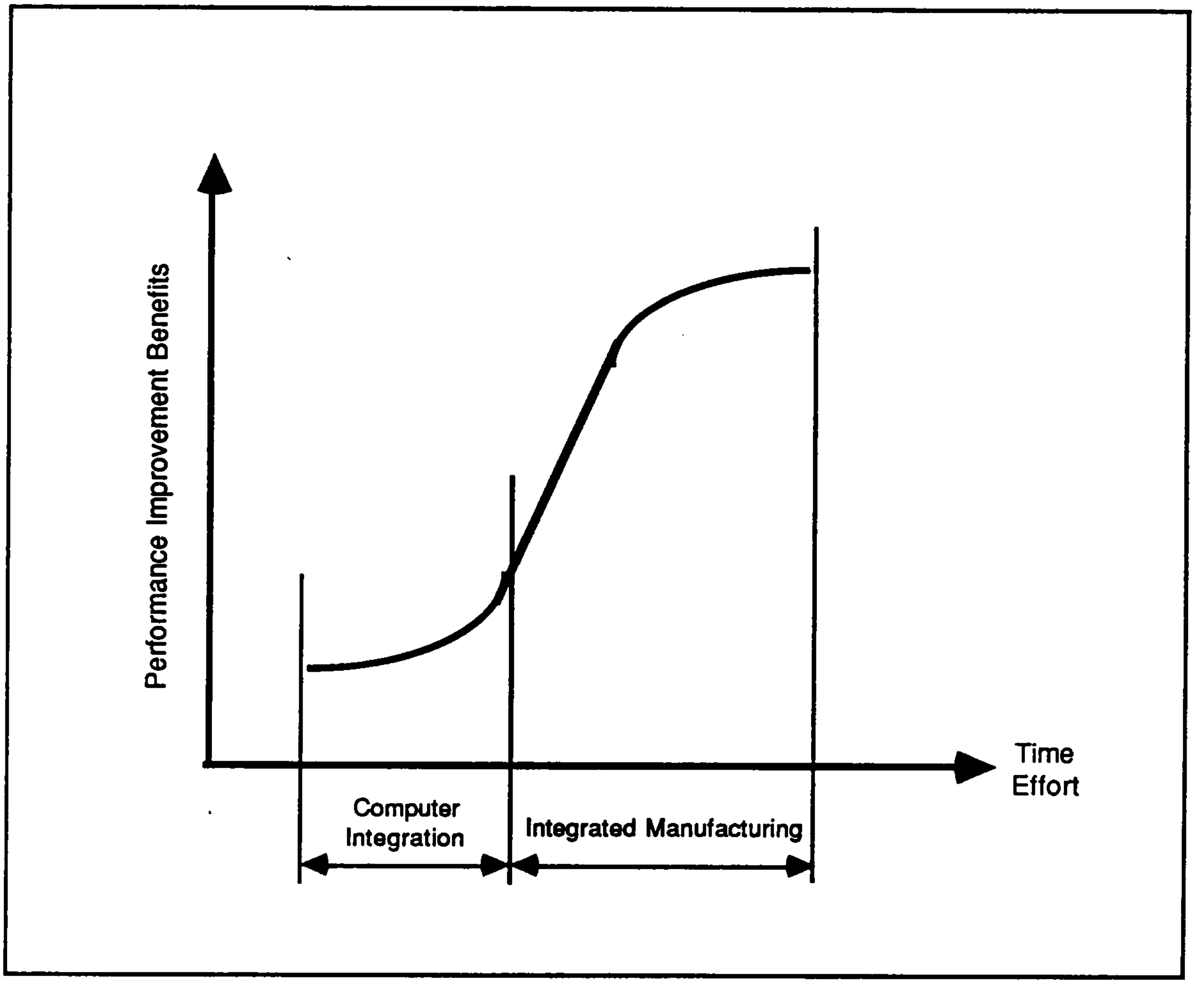

Figure 2.8. Performance Improvement Potentials in a CIMS Environment

and/or assume a common database implies integration. Deming (1986) describes an operational definition as one that people can derive communicable meaning from and do business with. None of the existing definitions of integrated manufacturing are of the operational type.

One definition of integrated manufacturing (NRC Report, 1984) describes it as a system in which,

- all the processing functions and related managerial functions are expressed in the form of data,
- these data are in a form that may be generated, transformed, used, moved, and stored by computer technology,
- these data move freely between the functions in the system throughout the life of the product.

This implies that all manufacturing processes can be described in the form of data. This data will define the processes, where? how? and when? they will be performed, and what the constraints are. Further, this data should be freely and easily available to anyone in the system. Zgorzelski (1986) argues that this only defines one type of integration - data integration. Zgorzelski uses a Management Information System (MIS) terminology to describe three types of integration: data, transactional, and operational. Data integration implies a common definition for all system information; transactional integration implies a single system input for every event; and operational integration implies a common format for all data entered into the information system. All three types have a common element: that of data/information and this can be called information integration.

Just as there is information integration, there are several other types of integration in a manufacturing system. Devaney (1984) describes integration to be a

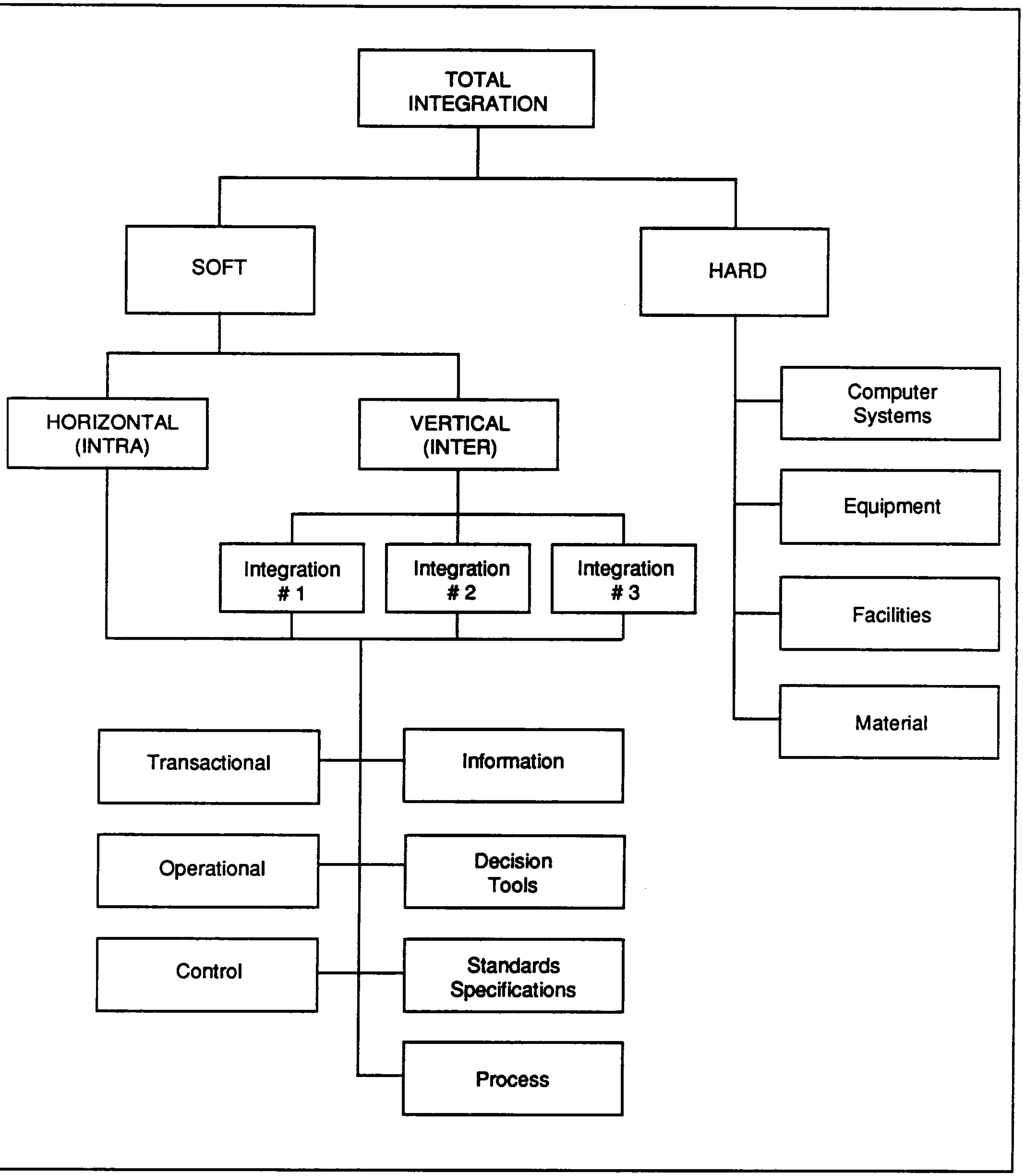

Figure 2.9. Integration Framework for a Manufacturing System

multi-dimensional process depending on what are the components or decisions being integrated: management functions, processes, equipment, facilities, standards and specifications, decision tools, or information. In Figure 2.9 a framework for defining the dimensions of integration in a manufacturing system is introduced. The framework is an attempt to operationalize what is meant by "total integration" in a manufacturing system.

2.4.2. Hard Integration

The first classification in the integration framework is hard and soft integration. Hard integration concerns the physical elements in the system, while soft integration concerns the non-physical elements. The two elements are analogous to the user and technology views proposed by Appleton (1984), since most of the physical elements are technology based while the non-physical elements are user based. Hard integration has received relatively more attention than soft integration, and significant progress has been achieved in this area. The elements of hard integration are typically supplied by vendors, and the research motivation is primarily due to the high marketability of the resulting products.

Hard integration can further be subdivided into four elements: computer systems, equipment, facilities, and materials. Computer systems are the medium for achieving integration in the modern factory, and it has been an area of extensive research activity. Database management systems (DBMS), distributed databases (DDB), local area networks (LANS), and data exchange systems are just some of the example products in this area. Current research projects in the area include, ICAM-1000 & 3000, IEEE Project 802, MAP/TOP, IGES, PDES, and NBS-AMRF[4]. Computer systems

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[4] MAP/TOP - Manufacturing Automation Protocol/Technical Office Protocol
IGES - Initial Graphic Exchange System

integration is discussed in detail by Beale (1986). Though there has been a lot of development in this area, there has been a tendency to neglect soft integration questions in the developments. The ICAM Review (1980) criticized the developments as being overly driven by computer science considerations rather than the needs of manufacturing and design.

In any manufacturing there are a variety of different equipments. These equipments include production machines, data processors, material handling equipment, storage and retrieval devices, and support equipment. Integration of this equipment is the second element of hard integration. With the increasing use of automated and semi-automated equipment, this dimension of integration is becoming increasingly critical. Equipment integration ensures that information, material, and control procedures are efficiently transferred from machine to machine. Magrab (1986) discusses equipment integration in a robotic work cell, and pinpoints the control equipment as key to achieving integration.

Facilities planning is a traditional subject of industrial engineering, and most facilities planning techniques are based on an integrated approach. The popular techniques described by Muther (1961) and Tomkins and White (1984) have focused on material flow integration. But, the design of facilities considering information flow, inventory reductions, group technology requirements, and cellular and automated manufacturing is needed for achieving facilities integration.

Material integration is the fourth element of hard integration. Material integration ensures that the various materials used are compatible with one another and the machines on which they are used. Factories have traditionally been modeled based

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PDES - Product Data Exchange System

NBS/AMRF - National Bureau of Standards/Automated Manufacturing Research Facility on the flow of materials through them. As a result, material integration, of all elements of hard integration, is probably most commonly achieved in existing systems.

2.4.3. Soft Integration

As already noted, research and development in the area of hard integration, particularly computer systems, has been extensive. The area of soft integration, in contrast, has been neglected and is only now being researched. The attitude has been that once hard integration is achieved, the presently available tools and management systems can be used to fully exploit the new technology. Designers and developers have a tendency to become fascinated by the new hardware capabilities. The issues of soft integration are especially important in the design and execution of operational activities. Achieving soft integration is considerably more difficult, since it usually is more complex and dependent on the commitment of the people in the system.

The first classification in soft integration is horizontal and vertical integration[5]. Vertical integration coordinates activities and information flow across the basic components of a manufacturing system. Horizontal integration coordinates activities within the components (OTA Report, 1984). Vertical integration occurs across the three integration zones identified earlier in the CIM model (Figure 2.5). Horizontal integration occurs between individual modules of the four components.

All soft integration issues can be divided into seven major sub-elements: information, standards, decision tools, processes, transactions, operations, and control. The study of these issues is a necessary prerequisite for designing decision support

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[5] The terms horizontal and vertical integration of manufacturing systems are defined by the Office of Technology Assessment (OTA Report, 1984) and should not be confused with horizontal and vertical integration of marketing.

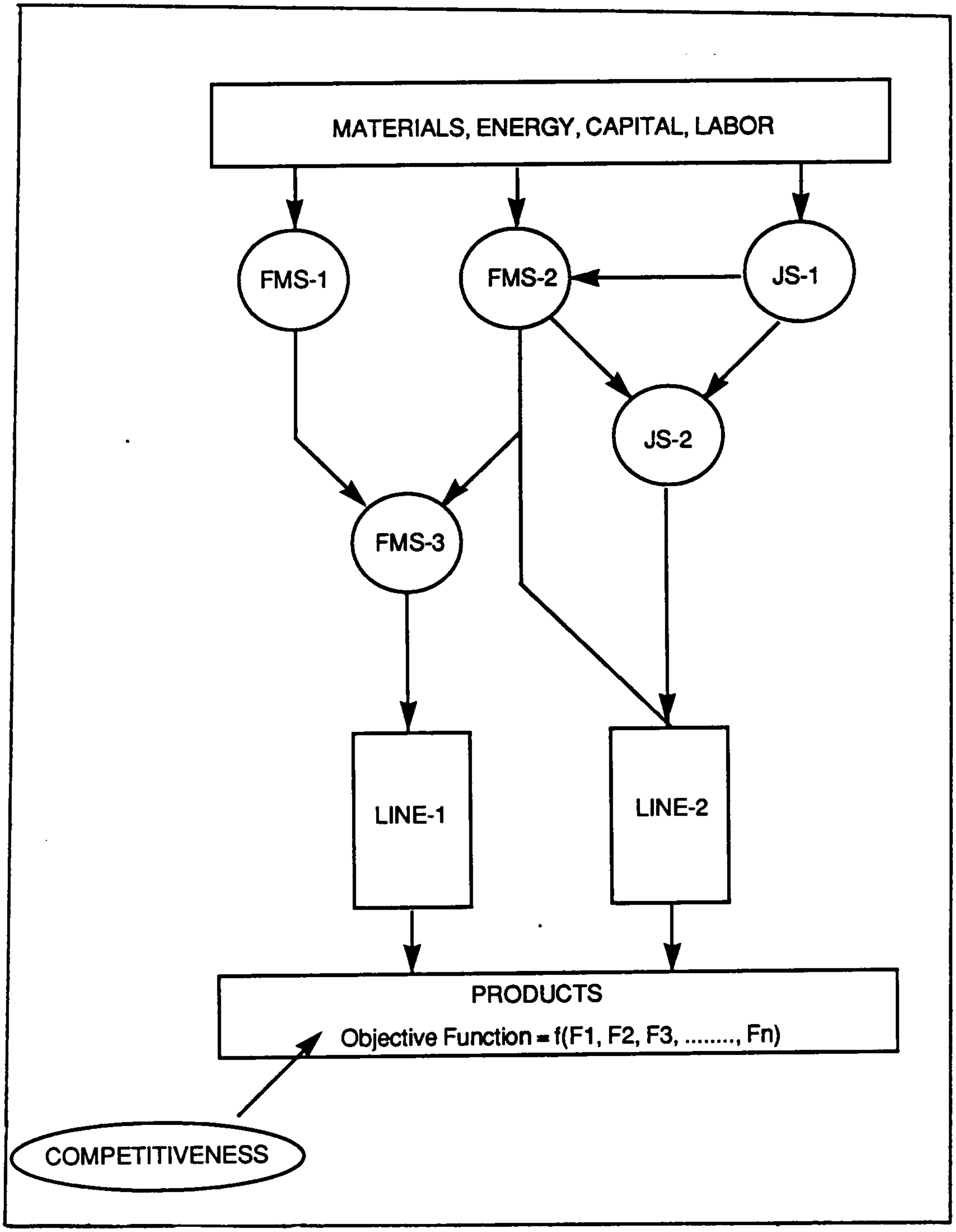

Figure 2.10. Flowchart of a Production System

tools or operation control tools. The issues are primarily of two types, those concerning the design of the tools and those concerning the operation of the tools. Consider Figure 2.10 as an example production process. In this process there are three types of manufacturing: FMS's, job shops, and assembly lines. Assuming appropriate levels of hard integration are present, then some of the soft integration issues are:

1. What should be the control hierarchy of the plant? That is, should FMS-3 receive instructions from Line-1, FMS-1&2, or some other node.
2. Which flow routing should be used for processing a part? A product can be manufactured by one or more different routings through the system. At a given instance, which routing should be used? Further, part routing may be changed at any stage of the production process. Each part routing has different characteristics in terms of quality, cost, timeliness, etc.; these have to be analyzed for routing selection.
3. What should be the production rate of each node? Ideally, in a completely integrated system each node should be operating at approximately the same level (there may be some technological constraints to this). That is, there are no islands of optimization and few bottlenecks. There is a tendency to assume that in a optimized system each component is optimized. In reality, system optimality is bound by the optimal level of one or more of the components, and all components should operate at this level. For instance, we may optimize the operations of FMS-2 and JS-2 independently. If FMS-2 produces 100 parts/hour and JS-2 is able to utilize only 70 parts/hour, we would literally have designed a bottleneck.
4. When and how should the movement of material handling vehicles be scheduled? The material handling system should not only maximize material flow, but also support the operational rates of the manufacturing elements and minimize work-in-process inventory. For instance, if a transport vehicle is scheduled to depart

from FMS-1 in 10 minutes, and processing of a certain part at FMS-1 will finish in 12 minutes, should the vehicle wait for the part or depart as scheduled? Traditionally, material handling systems tend to be scheduled independent of production. This is acceptable in an integrated system.

5. How should the system react to machine breakdowns and other disruptions? In the event that production is disrupted at one stage, part loading has to be reassigned, and other stages adapt accordingly. Other nodes may have to increase production load while others may have to slow down. Depending upon schedule flexibilities, jobs can be prioritized.
6. What are the cause-effect relationships between nodes? For instance, if a quality problem occurs in FMS-1, what are the implications to Line-2? The systems need to become proactive as opposed to reactive.

Each of these six issues can be classified as integration #1, #2, or #3. Further, they may concern one or more of the seven sub-elements comprising soft integration.

2.4.3.1. Integration #1, #2, and #3

Study of integrations #1, #2 and #3 needs to be a major research thrust towards achieving CIMS. The need for this integration has been recognized by builders and users of CIMS. DeMeyer (1987) conducted an empirical study to determine what would be the structure of future integrated manufacturing systems. He asked respondents which, of twelve subsystems, would be integrated in the future. The results of his study are summarized in Table 2.2A. The twelve subsystems can be grouped into the four basic components of CIMS. Doing this, DeMeyer's data was used to create Table 2.2B. This table shows the relative importance assigned by the respondents to the three integrations. The table indicates that the most important areas of integration are:

COMPUTERIZED SUBSYSTEMS	Inventory Status	MPS/MRP	Shop Floor Control	Design Eng.	Manufacturing Eng	Process Controls	Quality Reporting	Accounting	Order Entry	Purchasing	Distribution
Sales Planning	43	68	11	10	11	4	7	22	34	26	28
Inventory Status		48	21	3	5	4	9	29	18	40	15
MPS/MRP			43	8	17	17	12	19	38	36	20
Shop Floor Control				5	23	27	33	19	7	10	6
Design Eng.					44	10	14	3	4	4	5
Manufacturing Eng.						40	23	7	3	5	4
Process Controls							56	10	6	9	4
Quality Reporting								14	8	19	4
Accounting									30	30	16
Order Entry										26	29
Purchasing											12

Number of repondents = 150

Table 2.2A. Frequency of Indicated Integration in the Future (DeMeyer, 1987)

	B	C	D
A	5.2	7.67	25.27
B	▨	22.66	5.33
C	▨	▨	16.35

Integration #1 = AB + AC + AD

Integration #2 = BC

Integration #3 = CD

(Scores = Sum of votes divided by combinations)

A = Sales Planning
Accounting
Order Entry
Purchasing
Distribution

B = Design Eng.

C = Manufacturing Eng.
Process Control
Quality Reporting

D = Inventory Status
MPS/MRP
Shop Floor Control

Table 2.2B. Perceived Relative Importance of Integration #1, #2, & #3

a) Management and CIPP&C

b) CAM and CAD

c) CAM and CIPP&C

When viewed from the perspective of integrations #1, #2, and #3, there is an almost equal weighting, though integration #1 is observed as most important. The weightings are based on a maximum score of 150, implying the scores are generally low. The low scores indicate two points: first, total integration is not desirable, only those subsystems which are relevant to each other need be connected; second, the potential and reality of integrated decision making is not realized by all managers.

DeMeyer's study investigated desired integration, but did not specify what that integration would be. Though the specific integration issues will depend on the particular scenario, there are some generic issues across the integration boundaries. Many of these issues are currently being studied by a variety of research programs. The results of these programs will take us closer to achieving CIMS

Integrations #1, #2, and #3 should be considered by all managers of production systems, since they are not only relevant to CIMS but to the achievement of any type of integrated manufacturing. Designing a system with these three integrations in mind requires extensive analysis and hardwork. Traditionally, design within the four basic components has been done independently. Such an approach is inappropriate for the design of CIMS. What is required are multi-disciplinary planning teams. Burbidge (1987) proposes a structured approach for the design of integrated manufacturing systems. He proposes the following approach:

1. Start with clearly defined objectives.
2. Base planning on the general division of management into functions.
3. Determine the data output required from each function and the input required to generate the output.

4. Plan the hierarchy of functions and sub-functions.
5. Plan the methods to be used by each function and sub-function.
6. Analyze the way data flows between functions.
7. Design the data storage, processing and communication system.
8. Plan the organization of the work.

Burbidge's method is still very macro and has to be experimented with and developed in more detail. Several companies are implementing such approaches. Mize, et al. (1985) describe the efforts at one company. They observe that achieving integration will require fundamental changes in philosophy, management practices, and organizational structure. Such changes require top management commitment and leadership. Companies need to give the same importance to soft integration as they have given to hard integration. Only then can success be achieved.

2.5. SUMMARY

The basic concepts and structure of CIMS and FMS have been reviewed. A Venn diagram model for CIMS was developed and the primary areas of integration focus were identified. Based on the review of CIMS, FMS, and integrated manufacturing, an operational framework for integration in manufacturing systems was developed. The framework differentiates between hard and soft integration, vertical and horizontal integration, and integrations #1, #2, and #3.

The review indicates that the bulk of the past and current research has focussed on the issues of hard integration. The developments in this area have been considerable and several major projects continue to make advances in the areas of hard integration. The review of FMS indicates that several of the issues of hard integration have been implemented successfully. Further, FMS technology is achieving several of the desired characteristics of CIMS.

Only limited research activity on the basic concepts of integrated manufacturing were identified. The review indicates that several researchers are aware of the need for better understanding of soft integration issues prior to the development of decision and operation tools. The framework developed here is an initial approach in this direction.

The review and models developed in this chapter provide a sound base for the focus of this dissertation. The design and development of a CIPP&C involves consideration of parts of integration #1, integration #3, and horizontal integration within the production control module. Based on the findings in this chapter, it was possible to develop the relevant integration issues for a production control system and the basic framework for the CIPP&C system.

CHAPTER THREE

REVIEW AND ANALYSIS OF INTEGRATION IN PRODUCTION CONTROL

3.1. INTRODUCTION

The planning and control of manufacturing systems involves organizing and managing the process of converting raw materials into a pre-designed finished product. In the last chapter we identified the four basic elements of CIMS. The planning and control function was one of these elements and was labelled Computer Integrated Production Planning and Control (CIPP&C). The subject and concept of CIPP&C is relatively less developed than the more prominent elements of CAD and CAM. In reality, CIPP&C is an outgrowth of CIMS rather than the converse. But in the achievement of CIMS, the component of CIPP&C is expected to be most critical. DeMeyer (1987) in a survey of integration issues in future manufacturing systems found the issues relating to the planning and control function to be more frequently cited than those relating to CAD and CAM. DeMeyer attributed this to the naturally integrative nature of CIPP&C and predicted it will be the pivotal element in integrated manufacturing systems.

Bedworth and Bailey (1987) observe that, as the degree of automation increases, the production control function becomes the key to the success of the manufacturing facility. Further, with a concurrent increase in automation and computerization there is an increase in the domain of the production control function. Thus, the development of sophisticated and well designed CIPP&C systems must parallel the developments in CAD and CAM. In recent times this parallel development has not occurred. Skinner (1985) argues that the present relative weakness of technologies and concepts in the production management area is primarily due to the nature of the people who manage this function. Top management has generally given a low priority to production management and, as a result, production managers have been cautious and reactive in nature. Skinner contends that unless the control function is given more visibility the developments will continue to be limited in the future.

Present attempts at designing CIMS typically substitute for the CIPP&C element by using an existing computerized production control system such as MRP-II. While some researchers claim these systems provide a natural hub for CIMS (Fox,1984), others argue they won't schedule the "factory of the future" (Mather, 1986). The fact is that there has been a limited effort at developing a CIPP&C system with a CIMS focus. The intent of this dissertation is to provide the framework for an operating CIPP&C system, and this chapter is a review of the relevant elements which constitute such a system.

The review may be classified into three categories. First, we will briefly review some of the general literature in the production control area. Second, we examine and project what production control systems will look like in the "factory of the future." Third, we will review integrating approaches and tools in the production control area. Primarily tools such as MRP, MRP-II, JIT, OPT, HPP, FMS Scheduling, and Synchronized Manufacturing will be reviewed. Their applicability and integrability with CIMS will be evaluated. The intent of the review will not be to downgrade these techniques or to compare them with each other. Rather, the aim of the review is to identify their strengths, which may be incorporated in the proposed framework. Based on this review, the relevant issues/characteristics of an integrated production control system will be identified. The review is by no means exhaustive of all methods. Capacity requirements planning, due date setting, and other modules of production control are not reviewed here.

3.2. REVIEW OF PRODUCTION PLANNING AND CONTROL

The literature on production control is diverse and extensive. The subject not only concerns the problems of scheduling and materials management, but also overlaps into the sciences of inventory control, operations management, material handling, maintenance management, and information management. Tools and techniques vary from single machine sequencing algorithms to large scale MRP systems. A comprehensive treatment of the subject is provided by Holt, et al (1960), Burbidge (1979), Buffa and Miller (1979), and Vollmann, et al. (1984). Collections of significant papers edited by Hax (1978), Lawerence and Zanakis (1984), and Jacobs and Mabert (1986) are also available. Several texts in the operations research area, including those by Ravindran, et al (1987) and Hillier and Lieberman (1980) discuss typical problems in the production control area. The subject of machine scheduling is a subset of production control. A comprehensive treatment of scheduling is provided by Conway, et al (1967), Baker (1974), French (1982), and Bellman and Esogbue (1984).

The trend in current- day production control is to build large scale computer based systems. These systems are typically based on well known approaches such as COPICS, MRP, JIT, and OPT. Several commercial packages such as SCHEDULEX, MCS-3, Cullinet, AMAPS, PMS, Factorial, and MAC-PAC[1] are currently available. Koelsch (1988) provides an exhaustive list of commercially available packages. These packages are usually designed for very specific types of manufacturing environments

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[1] The referenced packages are products of the following companies

COPICS - IBM Corporation, Armonk, NY
SCHEDULEX - Numetrix Limited, Toronto, Canada
MCS-3 - Micro Manufacturing Systems, Columbus, OH
Cullinet - Cullinet Software Inc., Westwood, MA
AMAPS - Comserv Corporation, Minneapolis, MN
PMS - Boeing Computer Services, Seattle, WA
Factorial - Factorial Systems Inc., Austin, TX
MAC-PAC - Arthur Anderson, Washington, DC

and are not based on a generic framework. To the author's knowledge, no survey of the logic on which these packages are based has been published. Similarly, no comprehensive survey of production control techniques at the macro level was found in the literature. However, several comparative studies of specific techniques have been reported. Ritzmann, et al (1984) and Krajweski, et al (1987) present a comparison of MRP, Kanban, and ROP based on simulation results of a manufacturing system. Gelders and Van Wassenhove (1985) present a critique of MRP, JIT, and OPT in capacity constrained situations. Seward, et al (1985) compare MRP and HPP. Most of these studies conclude that there is no global best technique, and success will depend on selecting the right technique. Shivnan, et al (1987) trace the evolution of production control approaches from EOQ to MRP to JIT and OPT. They show that this evolution describes a transitional trend from strictly limited scope quantitative models to a systems perspective.

The bulk of the comparative studies focus on the performance of these systems in a simulated environment. Few studies truly analyze the basic difference in control logic, strategic issues, decision framework, integrability and competitiveness of these approaches. One excellent review of recent control trends in manufacturing systems is provided by Gershwin, et al (1984). They list the central issues in future systems to be complexity, hierarchy, discipline, capacity, uncertainty, and feedback. An evaluation of recent work in the area of production control is made along these issues in their paper. An exhaustive literature review of production control as applicable to the shop floor is provided by Melynk, et al (1985). They conclude the nature of shop floor control has changed greatly in the last 40 years. During the 50's and 60's, most of the focus was on scheduling and dispatching algorithms. During the 70's, perspectives began to broaden and the interdependence of activities within and outside the shop floor was recognized. During the 80's, these interdependences are being integrated into single large-scale computerized systems.

There have been at least two very extensive surveys on the subject of machine scheduling. Panwalker and Iskander (1977) surveyed existing algorithms and methodologies for machine scheduling problems. Graves (1981) briefly reviewed production scheduling theory and categorized existing research activities in relation to theory. Graves also compared scheduling theory and practice, and concluded there is anything but a one-to-one correspondence between the two. Graves recommends that future research be directed towards reducing this gap, and particularly emphasizes integrated scheduling approaches and a focus on computerized manufacturing systems. Emmons (1987) lists the assumptions, objectives, and optimal policies for several job shop scheduling algorithms. Such a listing can be used by a practitioner to integrate an existing algorithm into a macro control system. Eilon (1978) attempts a classification for the numerous solution approaches to the production scheduling problem. He identifies the following four dimensions in his classification scheme:

1. The type of production and the environment in which it is carried out.
2. The objective or objectives to be attained.
3. The constraints on the systems and on the scheduler.
4. The control or decision variables to be determined.

These dimensions are also applicable to the production control problem. Eilon further elaborates on each dimension. The dimensions provide the framework for creating a library of scheduling techniques.

The subject of inventory control is closely related to production control and ideally should be an integral part of a CIPP&C. Maintaining inventory is a non-value adding process and it's reduction is one of the primary objectives of production control. There is a common misconception that certain approaches to production control, such as JIT, will result in zero inventories (Hall, 1983). The reality is that zero inventories are not possible, and it is only an expression referring to a situation of very low inventories. A common analogy used by the Japanese to describe inventories and production problems is to liken the inventory to water in a river and production problems to rocks in the river (Monden, 1983). When the water (inventory) is high the rocks (problems) are covered and the waterway is clear. Reducing inventory exposes the problems and forces their detection and removal. What is often not realized is that draining the water (zero inventories) will result in no flow (production). Clearly, there will always be inventory and the study of inventory models will continue to be an important subject.

A general treatment of inventory models is presented by Naddor (1966) and Silver and Peterson (1985). While Naddor provides a classical treatment of the various inventory models, Silver and Peterson approach inventory management as a part of the production planning and control problem. The subject of inventory modelling is one of the most developed applications of operations research. But, just as in the case of production scheduling, there is a considerable gap between theory and practice. Barancsi, et al (1983) identify five causes for this gap, namely:

1. The organizational structure of companies do not allow for the creation of comprehensive models.
2. Decision makers are skeptical of theoretical models and averse to their application.
3. System designers are not aware of available models and when and how they are applicable.
4. Current computer support is oriented towards database activities and not decision making.
5. A great proportion of models were created because of the mathematical aspect of the problem without considerinq the possibility of application.

Barancsi, et al (1983) have developed a detailed classification system of existing inventory models as a guide to their implementation by managers. Their classification scheme is based on ten codes which represent the operating characteristics of the models. They have currently incorporated 336 models in their system and plan to expand it to over 1000 models. Their system is computer based, and is a pragmatic approach to closing the gap between theory and practice. A similar classification system is needed for machine scheduling algorithms.

The determination of lot sizes is a classical problem in both shop floor control and inventory control. Extension of the simple EOQ model, to the myriad of situations which characterize manufacturing, gives rise to some formidable problems. Though the current focus is on minimizing setup times, lot sizing remains an important area of production control. Bahl, et al (1987) provide a comprehensive survey of lotsizing approaches. They identify four types of production control scenarios:

1. Single level unlimited resources
2. Single level constrained resources
3. Multiple level unlimited resources
4. Multiple level constrained resources

In these scenarios, single level denotes independent demand and multiple level denotes dependent demand. Their review is categorized on the basis of these four scenarios.

The subject of production control is quite broad, and considerable research in this area has been done. Although many have criticized the research for being too theoretical, a lot of the work has been implemented. Production control is what shapes the character of a plant. With the present thrust towards FMS, CIMS, and the "factory of the future", we can expect radical changes in the production control function. In the next section we examine some of these expected changes.

3.3. PRODUCTION CONTROL IN THE "FACTORY OF THE FUTURE"

In the literature review of CIMS a need to determine and investigate the decision making process which guides the operation and control of a CIMS facility was noted. A major element of this investigation would involve studying production control systems for CIMS and the "factory of the future." The nature of this futuristic function will depend on what our vision of the future factory is. Some descriptions are:

> "The production planning part of the system would use product information to set up an optimized production plan for the manufacture of the product, choosing proper equipment and processes, sequence of operations, operating conditions and so on. This numerical information is in turn used to to control the array of automatic machines and equipment that do the actual manufacture and assemble of the product. These machines are capable of automatically setting themselves up, handling parts, selecting tools, and carrying out automatically a variety of processes. Self-optimizing, feed back information to the control system. This system, as it constantly receives this information of the actual performance, compares this with ideal performance planned earlier. Then, as it finds performance beginning to depart from the planned optimum, overrides the original plan, performing dynamic scheduling, adjusting operating conditions to maintain optimum minimum cost performance." Merchant (1987)

> "In the factory of the future, automated systems will facilitate production at every step, beginning with electronic receipt of the customer order. The product will be designed uniquely for the customer on a CAD system, and routing will be created on a CAPP system in accordance with the resource capacities and workloads. Instructions will be given to the ASRS to pick materials and tools. An AGV will deliver these materials to robots and DNC machines, which will perform the correct processes. The vehicle will then deliver the products to the shipping dock. AI systems will tie all these systems together and make adjustments for any conflicts. Data will move from customer to supplier and through their respective facilities smoothly, without the stopping and starting that exists when people are the interface." Mather (1986)

Clearly, the development of production control methodologies for these futuristic systems will require a combination of both macro and micro approaches. Sadowski (1986) describes this as the ultimate control system and say's that though many of the necessary capabilities do exist such systems are yet a long way from being developed. Mather (1986) argues that the lack of an effective control system will impede progress towards the "factory of the future" and urges researchers to actively explore this area. Research should strive towards incorporating certain desirable features in future production control systems. It is these features which will make it possible to manage and control the complexity and dynamism of the "factory of the future."

The expression, "factory of the future", is usually synonymous with an automated manufacturing facility. O'Grady (1986) gives an overview of the latest developments in production control systems for automated manufacturing. O'Grady predicts such systems will be characterized by relatively very low lead times, and low WIP inventory levels. He gives two reasons for this. First, the time to manufacture a part on an automated machine is considerably less than that on a manual machine. The shorter production time will require a more careful monitoring of production activities. Second, the high capital investment in automated machinery will warrant a high rate of machine utilization. This will require a more integrated approach to production control and capacity balancing.

Another attribute commonly associated with the "factory of the future" is the aspect of flexibility. Achieving flexibility in all aspects of production operations is one of the primary goals of the future (Bullinger, 1986). Both Hayes and Wheelwright (1984) and Skinner (1985) describe production planning and control as a critical infrastructural element for the development of a competitive manufacturing strategy. Swamidass (1986) say's this is primarily because production control is the means for maximizing utilized flexibility in a system. Zelenovic (1982) defines flexibility of a production system as "a measure of its capacity to adapt to changing environmental conditions and process requirements." Based on this definition and the concepts introduced by Buzacott (1982), seven types of flexibility together define system flexibility. These are machine, product, process, routing, operation, volume, and expansion. The capability of a system to display these flexibilities is to a large degree dependent on the production control system. Recognizing the importance of flexibility several new flexible scheduling approaches have been developed (Kusiak, 1986, and Suri and Stecke, 1986). These techniques are primarily focussed on FMS applications. There does not appear to be much effort to introduce flexibility into large scale systems such as MRP as yet. One notable techniques in this vein is being developed by Parunak, et al (1986). They attempt to induce flexibility by moving decision making closer to the point of activity. This strategy imposes fewer constraints on the possible alternatives and reduces the reaction time in decision making.

Cellular manufacturing and group technology are also expected attributes of the"factory of the future." Greene and Sadowski (1984) list some of the advantages of cellular manufacturing as reduced material handling, reduced tooling, reduced setup time, reduced expediting, reduced WIP, and reduced part makespan. The attainment of these advantages is again dependent on the capability of the production control system. Ivanov (1968), reporting on Soviet industry, observed that the use of traditional production control approaches in a cellular manufacturing setup had disastrous results. What is needed are production control approaches which are tuned for cellular manufacturing. Sinha and Hollier (1984) review some of the production control problems associated with cellular manufacturing. They list recommendations for the development of effective future production control.

One factor often cited as being radically different in future manufacturing systems is the objective function. The primary strategy in designing future manufacturing systems and their associated sub-systems should be to enhance competitiveness. Traditionally, production control approaches have adopted a simple criterion as the objective function. Such approaches will not be suitable for future needs. Haas (1987) appropriately states the need for a change in objective functions:

> "Typically, manufacturing decisions are still taken in an operational framework defined by internal performance standards - machine downtime, scrap rate, work-in-process inventories, and the like. But the real test of manufacturing decisions is their impact on the company's performance in the dog-eat-dog world of global competition. A manufacturing decision that might be downright stupid in operational terms alone may look very different when seen from a strategic perspective."

Skinner (1974) found that the prevalent use of "cost" and "efficiency" as objective functions for planning and control of U.S. plants played a large part in their increasing inability to succeed competitively. Skinner (1985) recommends that the corporate objective and manufacturing strategy be translated into operational meanings for production control. Since strategies are typically broad based, the objective function of future production control systems can be expected to be of the multi-criteria type. There are already several approaches which exhibit this attribute. Lee and Moore (1984) describe the use of goal programming approaches to the multi-period scheduling problem. Masud and Hwang (1980) present a multi-objective decision making model for the aggregate production planning problem. O'Grady and Menon (1984) describe a multi-objective program for selection of prospective customer orders. These systems model the objective as a multi-dimensional vector of system characteristics. The problem in future systems will not be the ability to handle multidimensional vectors but the definition and aggregation of these vectors. The use of multi-criteria objectives matrices is a possible approach.

Sadowski (1986) discusses the aspect of automation and production control. Several characteristics of future systems are mentioned. These include control of production resources, real time simulation of decision alternatives, real time system control, and design as part of the physical system. Shunk (1984) defines four fundamental measures for the "factory of the future": EOQ's, inventory turns per day, key machine utilization, and product quality; and each of these must approach 1.0. The first three of these characteristics are also direct measures of production control and are desirable characteristics of future systems. Bedworth and Bailey (1987) identify three additional features: real time control, integrated decision making, and database orientation. A variety of other characteristics are mentioned in the literature. A list of desirable features of future production control systems can be assimilated from a review of the bibliographic literature and the above mentioned references (Table 3.1). Each of these features is briefly discussed here. The features which are directly related to integration are further discussed in the next section.

1. *Integrated Control of Production Resources*

   The execution of a production control operation usually requires a workable machine tool, the part(s) to be worked on, an operator, necessary tooling, and appropriate instructions. In addition, transportation resources are required to convey these resources to the site. Traditional approaches to production control typically control only a subset of these resources and, as a result are, often unable to meet the schedule due to constraints imposed by an unaccounted for resource. An effective technique should be able to control all required resources in an integrated fashion to ensure balanced utilization of resources, and avoid surprises.

2. *Low Work-in-Process (WIP) Inventory*

   Minimization of WIP inventory has always been a major objective of production control systems, but in future systems it will be almost imperative to maintain a very low WIP level. Reducing manufacturing leadtime is a must to be competitive, and leadtime is made up of processing time and queue time. Queue time translates into WIP inventory. The contradiction is that in assemble to order situations WIP translates into shorter leadtimes. But there are other disadvan-

Table 3.1. Features of Production Control in the "Factory of the Future"

1. Integrated control of production resources
2. Low work-in-process (WIP) inventory
3. Real time control
4. Short scheduling scope
5. Unit inventory turns per day
6. Unit EOQ's (batch size)
7. Unit key machine utilization
8. Exhibit system flexibility
9. Real time simulation of decision alternatives
10. Integrated with management and CAD/CAM
11. Integrated with corporate objective and manufacturing strategy
12. Suited for cellular manufacturing and group technology applications
13. Automated decision processing with database
14. Modularized
15. Finite capacity scheduling
16. Distributed decision making
17. Short production and procurement leadtimes
18. Using multiple decision making techniques
19. Incorporating artificial intelligence algorithms
20. Incorprate the use of statistical methods

tages associated with WIP, such as inflexibility, additional space, and part deterioration. These all have to be balanced to determine the optimal WIP. In the past, the practice has been to increase WIP to cover other more fundamental problems (as the Japanese have shown). Lower WIP will put a strain on production control, and Vollmann, et al. (1984) make a classical statement when they say we need to "substitute information for inventory." The intent of a CIPP&C system will be to use the prodigious amounts of data generated in CIMS to tackle production problems.

3. *Real Time Control*

CIMS promises the ability to communicate at any time between a production controller and any other resources within it's domain. This capability will enable the production control mechanism to ensure immediate transfer of directives, based on new information, for better performance. This capability is termed real time control. There are two possible interpretations of real time control. First, the scheduling interval is reduced to be equal to activity time so that the system schedules one activity at a time and actually schedules in real time. Second, whenever an unexpected, but relevant, event occurs in or outside the system, the controller immediately readjusts the schedule accordingly and conveys overriding directives to all resource nodes. Unexpected events would include equipment breakdowns, order changes, vendor failures and priority changes. Real time control also implies all future schedules are based on confirmed occurrence of past events and not on assumed occurrence.

Futuristic visions force us to achieve the first interpretation. Realistically, the second meaning is more achievable and beneficial (there is a lower bound to the optimal scheduling period). A few researchers have begun treating the subject of real time control in the event of disruptions (Akella, et al, 1984). The use of pertubation analysis approaches appear to be most promising in this area (Ho, 1985).

4. *Short Scheduling Scope*

The scheduling scope is the time interval after which the schedule is regenerated (also called time bucket or planning period). In current applications of MRP, the scheduling period is usually one week, and in applications of JIT it is usually one day. In the majority of other approaches, the scheduling period is usually about one month. In the future, scheduling periods can be expected to be in the one day to one week interval. But, in combination with real time capabilities, the effective scheduling period will actually be less, since disruptions occurring within the period will be accounted for. In effect, we will consider a medium scope schedule but actually implement a short-scope schedule only (Sadowski, 1986). The production control system will automatically release the short term schedule sequentially and reschedule at the end of the medium-term scope.

5. *Unit Daily Inventory Turns*

Inventory turnover is defined as the ratio between the average inventory value of a company and its total production value. Shunk (1986) assigns a daily turnover rate of 1.0 (approximately 250 annual turnover) as the goal of future production control. The best Japanese firms have as yet only achieved annual inventory turns of about 80-90. Inventory turns is a surrogate measure for the change rate of an organization. It is a well documented fact that the change rate of society increases with time. Achieving unit inventory turns will almost be mandatory by the end of this century[2]. Goldratt (1986) even envisions the situation

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[2] Inventory turns are a function of the physical size of the product being manufactured. Unit inventory

of "negative inventory turns." In such a situation a company will be able to turn around inventory so rapidly that they would be paid for the finished product before having to pay for the raw material. Thus, a negative inventory cost would be incurred.

6. *Unit EOQ (Batch Size)*

The EOQ is one of the earliest and most well-known results in inventory theory. It has been the basis for designing the bulk of the decision rules in inventory theory. Unfortunately, it molded managers into the "EOQ paradigm" who become overtly concerned with its derivation rather than with the management of the factors which control it (Hayes and Wheelwright, 1984). The Japanese were the first to get out of the paradigm and practically created a science of reducing setup times (Shingo, 1986). For instance, the time required to change over a heavy press in the hood and fender stamping department at a U.S. auto plant was about six hours, at Volvo about four hours, and at Toyota about twelve minutes (Monden, 1981). Viewed in isolation. setup times do not appear a strategic variable, but when translated into lower EOQ's and inventory cost and greater flexibility, they result in a competitive advantage.

Lower EOQ's increase the workload of a production control system since more units have to be controlled. Future systems must have the capability to track almost every part in the system. It is important to note that the production control system will strive to attain the EOQ but it cannot minimize the EOQ. Lowering the EOQ is a problem of setup costs and not of control.

7. *Unit Key Machine Utilization*

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turns will be expected for companies producing an average sized product (e.g. appliances, automobiles). For very large products we would expect lower inventory turns.

The capital cost of automated machinery is significantly higher than that of a traditional machine. In addition, there is the cost of the associated communication and computation equipment. Justification of these costs will imply a higher machine utilization rate. In future systems the pressure is going to be on "producing more with less." Clearly, all machines cannot have the same utilization rate due to the unavoidable imbalance in capacity. In any system there are certain key (bottleneck) machines whose production rate determines the production rate for the entire system. The production control system must focus on these machines first. As Goldratt (1980) has so aptly stated, "an hour lost at a bottleneck is an hour lost for the total system."

Future production control systems must first identify the primary key machines, then the secondary key machines and then ensure utilization rates of close to one for these machines.

8. *Exhibit System Flexibility*

A flexible system is created in two phases. First, it is designed to be flexible and then secondly, it is managed to exhibit that flexibility. FMSs and other individual machine tools make it possible to achieve the first phase. Achieving the second phase will depend primarily on the capability of the production control system. Specifically, process flexibility, operation flexibility, routing flexibility and volume flexibility capabilities need to be managed by the controller. The work in FMS scheduling has already made considerable progress in this direction (Kusiak, 1986, Stecke and Suri, 1984) and several applications are beginning to exhibit their flexibility.

9. *Real Time Simulation of Decision Alternatives*

Digital simulation is usually used in one of two modes: first, testing how a proposed system system will function, and secondly, how an existing system will function under a proposed control directive. The second of these modes is a common application in production control. The simulation model is used to estimate the operating performance of a proposed schedule. In real time simulation, this would be done immediately prior to schedule release. Further, simulation is an excellent tool for estimating performance variations due to changes in decision variables and system parameters. Two other desired feature listed here are real time control and short/medium term schedules. Real time simulation is a tool for achieving these features. For instance, if a disruption occurs in the middle of the term, the controller may either reschedule the system or use simulation to adapt the decision variables accordingly. Simulation would probably be a ~~more~~ faster and economical alternative. The adjustments could then be implemented in the next short term schedule.

Progress in the development of simulation tools has been phenomenal in recent years. A comprehensive treatment of simulation is provided by Shannon (1976). Several languages/packages have been developed. Pritsker (1984) has developed the SLAM language which is particularly applicable to production control. SIMAN, by Pegden (1985), is also becoming increasingly popular for simulation of material handling systems. Other example packages are GASP, GPSS, SIMON, SEE-WHY, FORSSIGHT, Q-GERT, SIMSCRIPT and SLAM-II (Carrie, 1985). These packages will usually require considerable effort in model building and learning. Several FMS specific simulators, which ease the modelling effort, have been developed. The best known are GCMS, MAST. and MUSIK (Carrie, 1985). A comparison of simulation packages is provided by Shannon and Philips (1983) in which they highlight the IDSS package as being most suitable for future applications. Future production control systems must be able to build simulation models and interface with the simulator.

10. *Integrated With Management and CAD/CAM*

Integration of CIPP&C with CAD/CAM and management corresponds to integrations #1 and #3 in the CIM model. The link between manufacturing and production control is not unidirectional. The bulk of the decisions made by the controller affects manufacturing and it needs feedback on these decisions. With increased automation, both CIPP&C and CAM will be "blind" to several operating problems. The tool room, maintenance, scrap removal, material supply, and floor operators need to inform CIPP&C with their suggestions and problems. Only then can continuous improvement become a reality. Unit product quality is one of the goals of the future and quality is often determined by the production schedule. Feedback on schedule/quality issues is a must.

There have been several new developments in the area of integrating CAD and CAM (integration #2). These include the Initial Graphic Exchange System (IGES) and Product Exchange System (PDES). Several other similar developments in Europe are reviewed by Kochan (1986). These developments are a step towards improving communication in a manufacturing system. Production control systems must be able to interface with these systems and effectively utilize the available data.

Production control is a function which is primarily managerial in nature. The decisions made by it need to be integrated with accounting, marketing, forecasting, and top management. Melynk, et al (1985) discuss each of these interfaces. Such integration is already practiced, but the tendency is for information to flow from management to control, and not the reverse. There is a lot of control information which can be beneficial to management.

11. *Integrated With Corporate Objectives and Manufacturing Strategy*

The concept of manufacturing strategy was first introduced by Skinner (1969, 1985). His thesis being that manufacturing must be linked to the corporate strategy if the corporation is to remain competitive in the long run, since manufacturing is the primary value adding function in the firm. A manufacturing strategy consists of a pattern of decisions affecting the element of manufacturing systems. Hayes and Wheelwright (1984) list eight decision categories that constitute a manufacturing strategy: capacity, facilities, technology, vertical integration, work force, quality, production control, and organization. The manufacturing strategy should be translated into a relevant strategy for each of these categories. An effective production control system is not one which maximizes efficiency or minimizes cost, but one which supports the manufacturing strategy. A hierarchical structure for operationalizing the production control strategy through the system needs to be an integral part of the controller.

12. *Suited for Cellular Manufacturing and Group Technology*

The concepts of cellular manufacturing and GT are particularly applicable in a medium volume, mixed product setup. The most common method for implementing these concepts is Production Flow Analysis-PFA (Burbidge, 1987, Ham, 1985). PFA divides the manufacturing resources into part families, machine cells, and tooling groups. Scheduling in these environments requires special algorithms. Mosier, et al (1984), analyzes some of the existing heuristics in this area. The development of more effective techniques and their integration with large scale controllers is needed.

13. *Distributed Decision Processing*

Technology is providing many data processing alternatives: minis, micros, and mainframes. The processing systems vary from being totally centralized to totally distributed. Distributed processing, with a high level of local intelligence, provides the data flexibility and reliability required for CIM systems. Ranky (1986) gives a summary of the principles of distributed processing, computer networks, and database management as applicable to CIMS. In a distributed system, each node executes specific tasks, and the tools required for executing those tasks are made available to that node. Architectures such as MAP enable the distributed nodes to interact closely with each other and access the required information. In effect, the managing and computing load is spread over all nodes which can work in parallel to solve problems faster.

The impact of Local Area Networks (LANS) and distributed processing on production control is beginning to be investigated. Shaw (1987) describes a distributed control approach based on a network bidding scheme. In his approach, a central cell announces a required task to all feasible cells. The cells, in turn, transmit their bids for production to their central cell. When all bids are received, the central cell selects the cell with the optimal bid for production. Shaw used the Augmented Petri Net (APN) technique to model the bidding scheme. In a simulation study, Shaw found the bidding mechanism to be significantly better than a centralized scheme. Future systems must move away from the centralized, single model approach and focus on a distributed approach with a mechanism for connecting the nodes.

14. *Automated Decision Processing With Database*

The control of a large system requires processing large amounts of data. This processing involves data storage, retrieval and transfer. To ensure that these activities are executed rapidly and efficiently requires a structured database. Sophisticated databases have already been developed for CAD and CAM applications. As of yet, there are no true databases for the CIPP&C function. Production control typically "piggy backs" off the CAD, CAM, and management databases. The argument being that the information used by the controller is also used for other activities, including accounting, marketing, engineering, etc. This problem of external and internal data has led to the development of distributed databases (DDBs) which are networked together. The MAP system provided specifications and a protocol for the development of DDBs for manufacturing. Future production control systems must have their own databases and be part of the DDB system and follow MAP guidelines. Ranky (1986) introduces some of the recent developments in database technology and discusses their application in CIMS.

Rolstadas (Kusiak, 1987) presents a first cut at defining data structures for a production control database. Two basic database structures are defined: one that describes the product structure, and the other that describes the resources needed to produce the product. Based on these two structures, several interactions in the control system are discussed.

15. *Finite Capacity Scheduling*

Capacity is a permanent constraint to production control. The problem of developing an optimal schedule within capacity is a difficult problem. Many of the frustrations and unreliabilities associated with production control stem from capacity constraints. Controllers are in the habit of transferring their overload problems to the shop floor by releasing an unachievable schedule. Prather (1983) identified seven sins of production control:

a. Not loading to the capacity of the shop's natural bottlenecks
b. Lack of schedule adherence and correction
c. Not rescheduling to current priorities
d. Increasing lead times on parts that have been late
e. Expediting only today's shortages
f. Pulling assembly kits too early

Of the seven sins, the first three are a direct consequence of the capacity constraint. These sins will be unacceptable in the future and must be accounted for by the controller.

The need for finite capacity scheduling has led to the development of several new approaches. Common practice is to develop a schedule and then create a corresponding capacity requirements plan. If the required capacity exceeds available capacity, then the load is trimmed and the schedule regenerated. This cycle is repeated until a feasible schedule is generated. The drawbacks in the approach are: (1) the capacity requirements routines are usually very rough cut and not always reliable, (2) the task of trimming the load requires an accompanying priorities scheme, and (3) the cycle involves significant amounts of computation time.

It is necessary that future systems consider schedule and capacity simultaneously. The OPT technique and FMS scheduling approaches follow this route. In the situation of tight capacity, the controller functions as a priority preserving mechanism (Gelders and Van Wassenhove, 1985). That is, it preserves those jobs with a higher priority. To execute this function, the controller must have an appropriate priority assignment system.

An interesting concept with reference to the relationship between capacity and other performance measures is introduced by Bitran, et al (1987). Analyzing production systems as networks of queues, they developed a performance trade-off curve (Figure 3.1) relating capacity, lead time, and WIP. From the curves it is possible to estimate the corresponding lead time and WIP for a given capacity. Earlier, we identified short lead times and low WIP as desirable features. Further, capacity flexibility was also described as a desirable attribute. In an FMS type environment where a facility can shut off part of its capacity, the x-axis in

Figure 3.1 can represent capacity flexibility. A controller can then on a real time basis, balance capacity, lead time, and WIP to determine the accessed capacity. Approaches similar to this for integrating capacity into the control function are needed.

We have identified and reviewed twenty desirable features for production control systems for the "factory of the future." These are neither exhaustive nor mandatory. They are in a sense a "wish list" and it is unlikely any one system will incorporate all the features. It is important the development of the features be approached in an integrated fashion. Further, in designing or formulating a production control system, attempts must be made to consider these features.

3.4. INTEGRATION IN PRODUCTION CONTROL SYSTEMS

Though numerous techniques and approaches have been developed in the area of production control, there has been limited work on developing macro systems which integrate the various activities constituting the production control function. In the absence of techniques which consider the total function, the other techniques are in reality ineffective. In this section, we will review approaches which have focussed on modeling the "big picture" of production control. To begin with we need to clarify our understanding of what is production control.

There is no standard definition of production control, and the operational meaning usually depends on the particular application. Some generic definitions are:

> "Production control is the function of management which plans, directs, and controls the materials supply and processing activities of an enterprise. Where, planning is the process of deciding what to do in the future, directing comprises the operation of issuing orders, and control can be described as the constraining of events to follow plans," - Burbidge (1978)

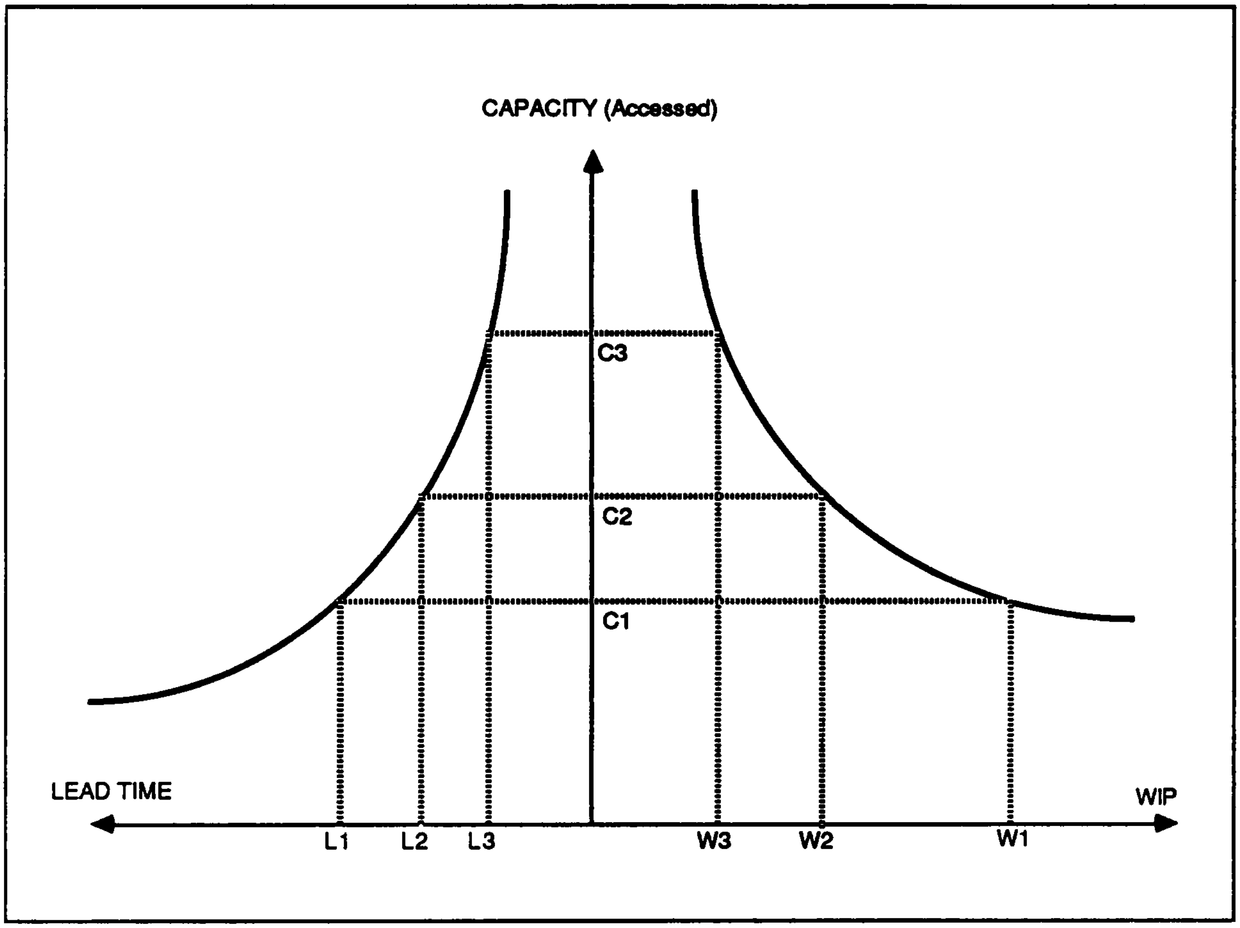

Figure 3.1. Trade off Curves For Capacity, Lead Times and WIP (Bitran et al, 1987)
a

"Controls the production of the necessary products in the necessary quantities at the necessary time in every process of a factory and also among companies," - Monden (1983)

Clearly, production control involves the making of certain decisions towards meeting a certain objective. It is how these decisions are made and their interrelationships considered that determines integration. One of the earliest works on integration in production control is by Holstein (1968). He presented an integrated view of the whole process. This view can be interpreted as a graphical definition of a production planning and control system (Figure 3.2). Eight classes of activities are identified in this definition:

1. Forecasting future demand
2. Order entry
3. Long term capacity plan
4. Master scheduling
5. Inventory planning and control
6. Short term scheduling
7. Short term capacity planning
8. Dispatching, releasing and shop floor control

Holstein's definition identifies the major information flows which connect these activities. The majority of current production control frameworks and flow charts are variations of this basic definition.

While Holstein defines integration within the controller, Harrington (1984) describes production control in the context of the manufacturing function. His de-

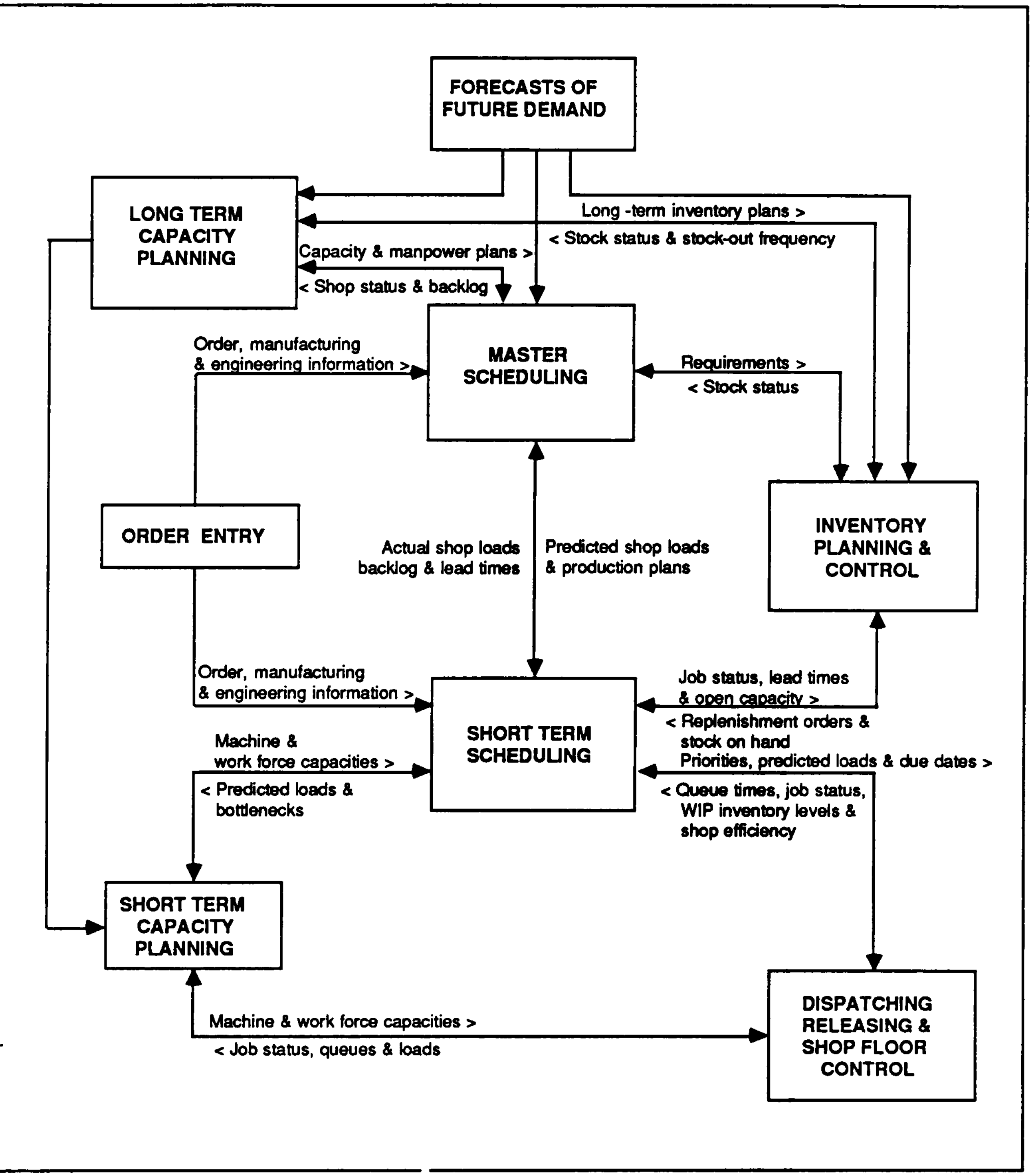

Figure 3.2. Graphical Definition of a Production Planning & Control System (Holstein, 1968)

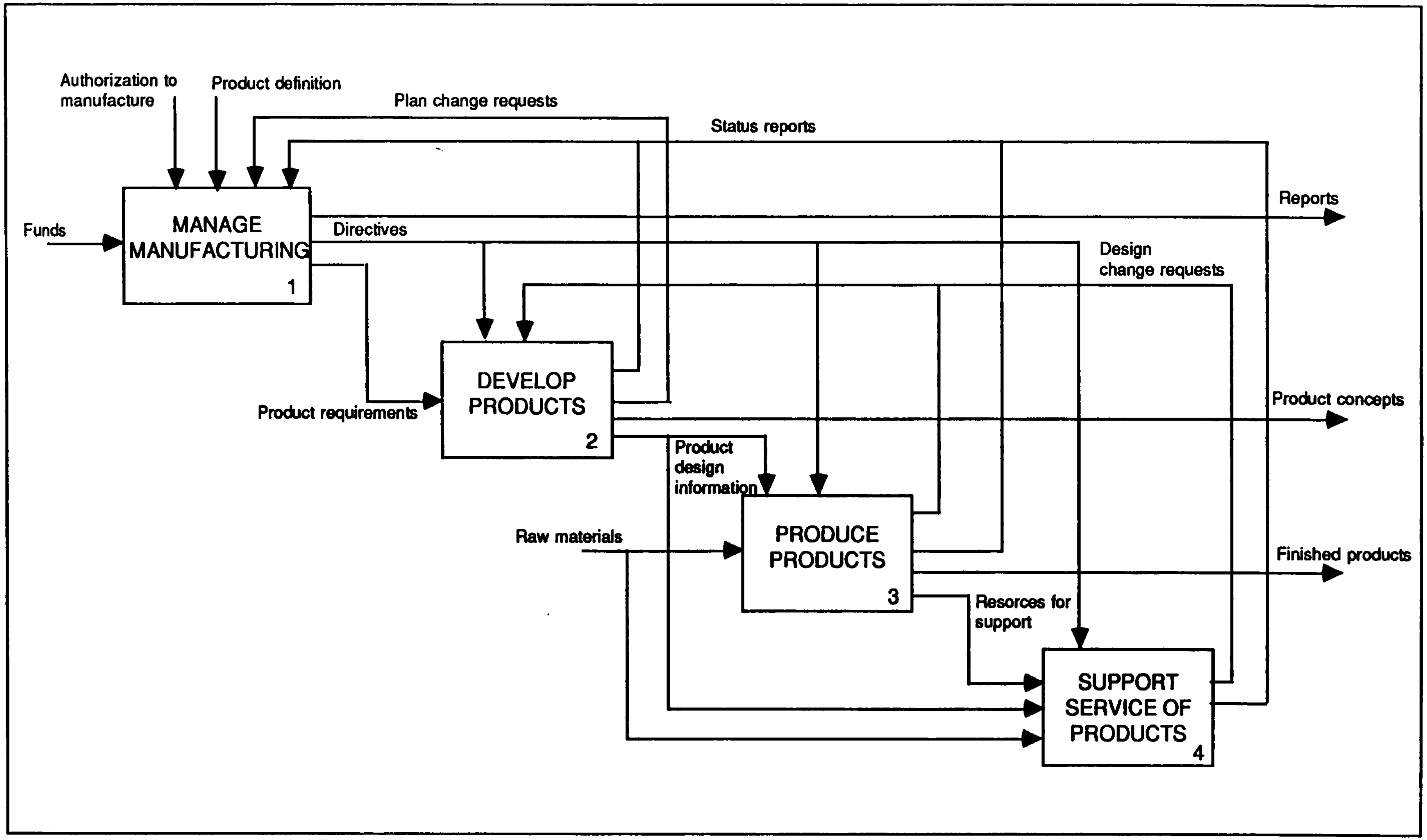

Figure 3.3. IDEF Definition of the Manufacturing Function (Harrington, 1984)

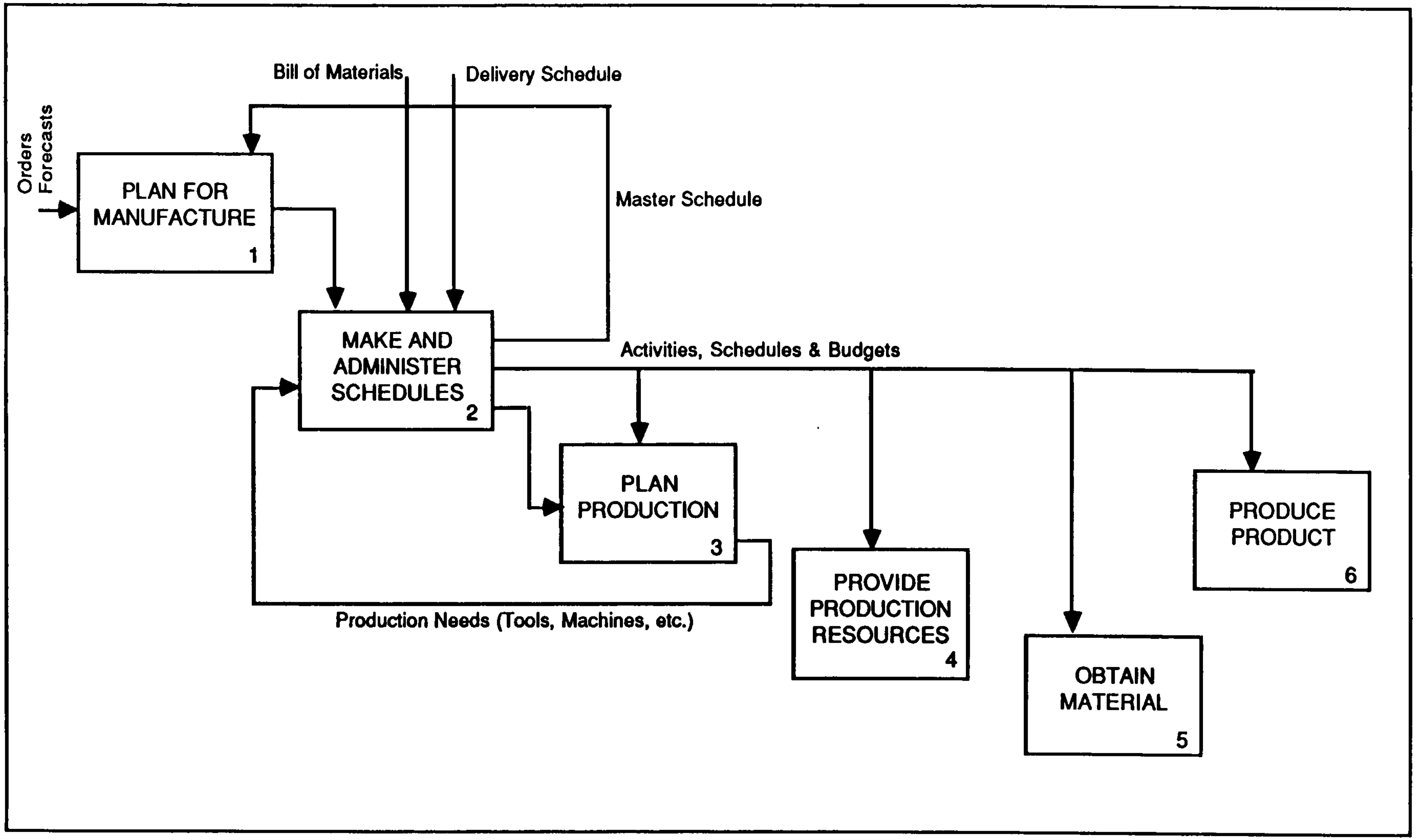

Figure 3.4. IDEF Definition of Produce Goods

scription is developed via the IDEF[3] technique. Figure 3.3 describes the manufacturing function, while Figure 3.4 describes the production function. Boxes 1 to 5 in Figure 3.4 define the production control function. Thus, box 3 places production control in the context of manufacturing. Both Holstein and Harrington provide detailed descriptions of the functions identified in Figures 3.2 to 3.4.

Several books and papers describe production control in general and these usually define the macro production control problem. But, in contrast, there is no comprehensive microscopic definition of the entire production control problem. Such a definition would list all the decisions to be made by this function. While a macro definition is explanatory, it is the microscopic definition which operationalizes the function. The lack of an overall microscopic definition is a roadblock to achieving integration. A starting point in this direction is execution of an input/output analysis. Parnaby (1979) reports the following inputs and outputs for the production control function:

Inputs	*Outputs*
1. Knowledge of present and planned state of production process	1. Raw materials ordering schedule
2. Detailed product design	2. Allocation of work by time to work centers
3. Order quantities	3. Listing of production procedures
4. Materials stock levels	4. Manpower utilization plan
5. Finished stock levels	5. Machinery utilization plan
6. Manpower availability	6. Performance checking procedures
7. Resource restrictions	7. Performance standards

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[3] IDEF is the ICAM Functional Definition Method. The method is further discussed in the next chapter.

Notice that all the inputs are data while the outputs are primarily decisions, implying production control is primarily a decision making system. The closest approximation to the overall microscopic definition of the production control problem is the composite function model of manufacturing developed in the ICAM program (ICAM Report, 1981 and 1983). This function model was developed using the IDEF methodology and documents , in network fashion, all functions occurring in manufacturing and their relevant inputs and outputs. The production control function is one of several functions modelled. In a subsequent project, the ICAM program developed the composite information model of manufacturing which documents current information flows in U.S. manufacturing (ICAM Report, 1983a). A major task of this dissertation will be to develop the definitive model of the production control function using the ICAM models as a starting point.

Traditionally, production control modelling has focussed on one or two of the functions identified by Holstein (1968). Seward, et al (1985) observe that in most companies these functions are executed separately and are loosely interfaced with minimal automatic data transfer. The most common interfaces being between master scheduling and short term scheduling. The majority of the functional developments are in the areas of inventory control and shop floor control. The developed models usually provide optimal solutions for their specific unit of analysis. But, they are not always compatible with models which focus on the larger system. In developing a subsystem model, the developer must always keep in mind the wider context of the system in which the subsystem operates. If a subsystem model is developed without relating back to the overall model from whence it came, then the new model will not be easily integrated into the overall system model (ICAM Report, 1981). One of the natural laws of systems integration is: if a subsystem procedure is not compatible with its parent system procedures, then the subsystem procedure will be overridden no matter how optimal a solution it may provide. Traditional approaches to production control tend to be a victim of this law, and this is a primary cause of the 'theory to practice' gap. The implication though is not that all research must be top down. Rather, integration should be an inherent goal in the development process, with validation checks to ensure that objectives, constraints, variables, assumptions, concepts and relevance are consistent with the parent system. Integration is a feature of design and not of consequence and must be approached as such. The dimensions identified earlier in the integration framework may be used as a guideline for the validation process.

To achieve integration in production control, we need a decision system which operationalizes the definitions of Holstein and Harrington. There are at least four modelling approaches for developing such a system:

1. Integration through a single mathematical model
2. Integration through a decision framework
3. Integration through a network model
4. Integration through a structured model

Each of these approaches attempts to optimize the whole rather than the parts. They all involve the handling of large scale models and are difficult to implement. The most common problems being the large data requirements, data accuracy and reliability, integration with related systems, and computer requirements.

3.4.1. Integration Through a Single Mathematical Model

The most obvious solution to integration is the development of a single model which represents the entire system. Assuming all decisions and their interrelationships can be quantified, a mathematical model can be designed. No such model for the entire control function exists. However, models which consider major portions of the function have been designed. The most common approach is the aggregate production planning problem (APPP), which consists of determining for each period the required labor, production rate, and inventory level. A variety of solution approaches for this problem have been presented (Bitran and Hax, 1984). The most well known approaches are by Dzielinski and Gomory (1965), Lasdon and Terjung (1975), and Newsom (1975). These approaches are LP based and, in addition, use decomposition or bounding methods.

The first problem with these methods is the difficulty in solving them. The resulting LP's are very large. A problem with 1000 items and twelve-period planning horizon has two million variables. Secondly, they consider only short term scheduling, short term capacity planning and shop floor control. Thirdly, they ignore the inherent uncertainties of the shop floor. In addition to these, there are other managerial problems. However, in certain cases these approaches provide significant benefits. King and Love (1980) report the implementation of the Lasdon and Terjung (1971) approach to a tire company. In association with other techniques, this approach resulted in significant benefits to the company.

3.4.2. Integration Through a Decision Framework

One approach to solving large complex problems is to partition them into manageable sub-problems and link these sub-problems to account for interrelationships. There are several strategies for this decomposition and subsequent linking. Possible strategies are hierarchy, decision scope, functional, or as needed in time. MRP, MRP-II, JIT, HPP, and OPT are production control frameworks of this type. In addition, several other frameworks of this type are reported in the literature. The frameworks are typically strong in one area and weak in others, and usually cover only a part of

Figure 3.2. Almost all are computer based, but vary in the amount of required environmental interaction. A brief review of the major approaches follows.

3.4.2.1. Materials Requirements Planning (MRP)

The earliest frameworks were of the functional, or decision scope type. These frameworks would begin with order entry and execute as many consecutive functions as possible. The bill of materials, Gantt chart, parts explosion, and Martino's (1972) PART system are examples. These early systems evolved into Orlicky's (1975) MRP system. MRP is designed to make purchased and in-house manufactured parts available before they are needed by the next stage of production or dispatch. MRP executes the following activities: short term scheduling, purchase order scheduling, part production ordering, shipping scheduling, and short term capacity planning (in the closed loop version). The linking or integrating mechanism is the dependent demand concept and the resulting time-phased requirements of materials and parts. MRP does not consider the time-phased requirements of machines, labor, tools and other resources. In reality, MRP is not a decision support system but more an activity support system. Its primary purpose being to organize the complex activities occurring on the plant floor through the use of database technology. The benefits of MRP are primarily due to this organization and resulting information flow.

Due to the ease of programming the MRP logic, and its natural database structure, several software packages for MRP are currently available. But, only 9.5% are class-A[4] users (Krajewski, et al, 1987). Criticisms of MRP are common in the literature (Mather, 1986). Mather even label's MRP's scheduling process as fundamentally illogical. The problems with MRP can be classified as relating to technical factors,

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[4] A 'class A' user is defined as one using closed loop MRP system for both priority planning and capacity planning.

process factors, and inner-environmental factors (Berry and Box, 1987). Some of these factors relate to the integrability of MRP, and these are of special interest here. MRP is primarily a mechanism for initiating production and assembly of parts. It is a "backward" scheduling method with a "push" type production. The start date is usually back calculated from a required delivery date on the basis of preset lead times. This back calculation is made without considering resource availability. Gelders and Van Wassenhove (1985) describe MRP as an infinite loader and emphasize the importance of simultaneously considering capacity and materials requirements. Another problem with MRP is its static nature. Lead times and schedules are intimately correlated, but MRP assumes that schedules are dependent on lead times and not the converse (Shivnan, et al, 1987). There is no feedback mechanism in MRP and it functions primarily as a planning methodology and not for controlling. MRP is a centralized planning system, and it attempts to integrate the plant through it's centralized plan.

To account for some of the above problems, MRP was enhanced by Wight (1984) to MRP-II. MRP-II includes all the functions identified by Holstein's (1968) definition and also considers integration #1 and #3. In addition to MRP, it consists of two additional subsystems. The first includes long range planning and master scheduling; the second focuses on shop floor control. MRP-II is described as being the total management system for integrating and coordinating the activities of all functions. There is, however, only limited documentation of MRP-II available.

The majority of manufacturing is managed in a functional manner, and hence naturally inclined to the application of MRP or MRP-II. This is one of the primary reasons of the high adoption rate for these systems. Functional frameworks are the easiest to implement. Their effectiveness, though, depends on the linking mechanism and the functional decision making process.

3.4.2.2. Hierarchical Production Planning (HPP)

Several frameworks for describing the structure of decision support systems have been proposed in the literature (Kurstedt, 1985). The framework most commonly applied to production control is by Anthony (1965), who provided a classification of managerial activity based upon the purpose of the decision making activity. Three levels of decision making are identified: strategic, tactical, and operational. Based on this framework, a problem may be hierarchically partitioned into subproblems. Each subproblem is constrained by the parameters of its lower problems and by the solution of its upper problem. Such a hierarchically integrated system for production planning was first developed by Hax and Meal (1975). They divided the problem into three distinct levels of aggregation: items, families, and types. The divided problem is solved by first solving an aggregate production planning problem and then two subsequent disaggregations. Several approaches for the disaggregation have been suggested (Hax and Golovin, 1978). The overall approach is equivalent to solving a single problem. Graves (1982) derived the Hax-Meal hierarchy as a natural decomposition of a primal optimization problem.

HPP overlaps the activities of long term capacity planning, master scheduling, short term scheduling, and short term capacity planning. The integrating mechanism is the disaggregation process which links the subproblems. HPP is a finite scheduler and focuses on the capacity constraint. It attempts to balance capacity so that demand is met. Thus, it is an effective planning method in situations of seasonal demand. The major problem with HPP is that it is an integrative approach for a partial problem. HPP cannot be run alone and has to be implemented in conjunction with other decision and information systems to provide it with the large amounts of data required. Meal, et al (1987), have proposed integrating HPP with MRP to overcome this problem.. They recommend the use of MRP to generate the master schedule and

HPP as the capacity planning module. They are currently researching the interfacing process.

HPP is a mechanism for hierarchical integration but does not consider lateral integration. Van Dierdonck and Miller (1980) define one measure of integrability as the frequency and intensity of lateral relations and communications. Lateral integration is primarily important from a control perspective. CIMS will provide the capability for extensive lateral communication, and the implementation success of a CIPP&C will depend on its ability to exploit this capability. Gelders and Van Wassenhove (1982) explore the problems created by hierarchical integration and discuss the issues of infeasibility, inconsistency, and sub-optimality. They describe two case studies where a HPP was implemented. They recommend the decision models at each level be carefully integrated, else we may create islands of decision making. They also emphasize the need for a cross-functional management team to oversee the implementation process.

Several other hierarchical control approaches are reported. Kimemia and Gershwin (1983) developed a hierarchical system for short term scheduling and shop floor control in an FMS. Their system is designed to minimize WIP and accounts for system uncertainties. Other approaches are based on the NBS-AMRF hierarchical control architecture for automated manufacturing. The architecture reported by McLean, et al (1983), is divided into five levels: facility, shop, cell, workstation, and equipment. Long term decisions are made at the facility level, coordination of resources and jobs at the shop level, the cell level schedules jobs through the cell, the work station level sequences operations within the cell, and the equipment level controls tools and materials. Parunak, et al (1986), propose a heuristic control approach based on this hierarchy. Their approach is different from the Hax-Meal approach in that machines are grouped together as opposed to grouping of items.

Parunak, et al, propose using the expert system scheduler ISIS (Fox, 1983) at the upper levels and other heuristics at the lower levels. Their approach is still at the experimental stage and it's integrability untested.

Hierarchical approaches are very effective means of achieving integration and can be expected to be a part of a CIPP&C system. But, they will have to be combined with lateral integration approaches to be successful. Hierarchical approaches are amenable to optimization modelling and are particularly useful in decomposing larger problems. Further, CIM systems are naturally inclined to hierarchical control as demonstrated at the NBS-AMRF.

3.4.2.3. Just-in-Time (JIT) Kanban

The concept of just in time manufacturing has been implemented by managers for years. One of the earliest practitioners being Henry Ford at the River Rouge plant (Halberstam, 1986). But the concept was first transformed into a science by Taiichi Ohno of the Toyota Motor Company (Sugimori, 1977). JIT-Kanban, as it is now called, is not only a means for production control but also a means for factory management. Our interest here is only on the production control element. However, from an integration perspective, it is important to note that several of the attributed benefits are due to the close communication between management and shop operations.

Two distinguishing features of JIT-Kanban are gleaned from Ohno's (1982) historical discourse. First, as opposed to other systems which emphasize inventory control more than shop floor control, JIT-Kanban emphasizes shop floor control more. Ohno observes that when we are weak in shop floor control, we tend to try to cover the defect with skills in inventory control. Second, while most systems consist only of a planning and scheduling mechanism, JIT-Kanban consists of both a planning mechanism and a controlling mechanism. It is this controlling mechanism which characterizes JIT-Kanban into a "pull" system, as opposed to a "push" system. In such a system, production is initiated by demand in a successive station and not be arrival of a part. Similar to other approaches, the JIT-Kanban system has an annual production schedule, a monthly master production schedule, and daily dispatching procedure. Relevant portions of these plans are communicated to individual workstations. But, whereas in other systems the workstations execute the plan independently, JIT-Kanban uses the kanban cards to trigger execution of the planned operations. That is, the kanban cards (or for that matter, actual demand) are the lateral integrating mechanism.

In JIT-Kanban, the shop floor boundaries extend to suppliers and customers. Hence, lateral integration crosses the organizational boundary. Several researchers are currently investigating the dynamics of kanban (Rees, et al, 1987, Lee, 1987). One of the critical factors is the number of kanban cards in the system since the number of cards puts an upper bound on the WIP. The number of cards is typically determined by the formula:

$$n = DL\,(1+I)/C$$

where, n is the number of cards, D is the average demand, L is the production lead time, I is a safety factor, and C is the container size. This formula is used only in situations where the setup time has been reduced to an almost negligible amount. In situations where the setup time is significant, the number of kanbans is a function of the traditional economic lot size (Monden, 1983). The calculated number of kanbans is really only a guideline. At Toyota, supervisors may adjust the number of kanbans on a real time basis. This enables the system to adjust to different situations.

Though the kanban cards are the primary integrating mechanism in JIT/kanban, there are several other lessons to be learned from it. Schonberger (1982) lists nine lessons to be learned. Some are especially important from an integration perspective. First, product quality is a function of production control and must be considered during CIPP&C design. Secondly, facilities are laid out not only to optimize production flow but also to facilitate production control. Thirdly, production control must exploit the intelligence and decision making capability of supervisors and line operators. JIT/kanban systems require a considerable degree of commitment on the part of workers who make the system run. In CIMS, the relative number of workers will be considerably less. Further, their responsibilities will also be more as a result of increased system complexity. Under these conditions, several of the JIT/kanban characteristics are inappropriate. Still, this approach exhibits the importance of a floor level control mechanism.

3.4.2.4. FMS Scheduling and Control

The new wave in production control is the scheduling of FMS facilities. It is also an area of extensive application of operations research methodologies. FMS scheduling tends to be closely integrated with CAM. Several fixed design attributes in traditional systems are flexible in FMSs and are modelled as control variables, thereby resulting in a dynamic system configuration. Buzacott and Yao (1986) review the development of FMS analytical models. They report the bulk of the development has occurred at five sites: Purdue, MIT-Draper Labs, MIT-LIDS, Harvard, and Toronto. Other reviews of FMS control are provided by Kalkunte, et al, (1986) and Kusiak (1986). Several FMS specific techniques have been developed and examples are reported in Kusiak (1986), and Stecke and Suri (1984). Control in a FMS is typically invoked directly from a computer and most techniques are mathematical programming based. In addition, the application of artificial intelligence methods is increasing. Current FMS scheduling and control approaches have achieved significant improvements in performance. Bessant and Haywood (1986), in a survey of fifty FMSs, report an average decrease of 74% in lead time and 68% in WIP, and a 63% increase in machine utilization. Each of these were listed earlier as desirable attributes of future production control. The bulk of these benefits are due to hard integration, but in the future we can expect greater benefits from soft integration.

At least five frameworks for the FMS production control problem can be identified. These are listed in Table 3.2. All the frameworks may be classified as hierarchical in nature. Almost all are accompanied by prescriptive algorithms which have been programmed and tested. Apart from the framework by Hildebrandt (1980), the others are considerably similar and make the same decisions in different procedures. Hildebrandt's approach is focused on FMSs in which machines are prone to failure. All the frameworks overlap short term scheduling and capacity planning, and shop floor control. One problem with these systems is they tend to be decoupled from the plant controller, and the approach by Kimemia and Gershwin (1983) even position incoming and outgoing buffers. There is thus a lack of integration between the FMS and the rest of the plant. Another problem is the exponentially increasing complexity with size (number of parts and machines). One solution to these problems is to model the plant as a set of small FMS susbsystems. A protocol of cooperation between the subsystems can then be implemented, as suggested by Berman and Maimon (1986). Their approach focuses on the transportation and distribution of parts and resources via the material handling system, which is the integrating mechanism. The integration of their approach with the five frameworks needs to be investigated.

FMS production control frameworks provide excellent approaches for integration within the FMS. But they are not good at integrating the total plant control function. The research groups have adopted a structured approach to the problem and several of the characteristics are applicable to CIPP&C design. The approaches also exhibit the capability of using mathematical models effectively and efficiently.

Table 3.2. FMS Production Control Decision Frameworks

RESEARCH GROUP	Purdue	MIT-LIDS	MIT-Draper Labs	Toronto	Carnegie-Mellon
REFERENCE	Stecke (1983)	Hildebrandt (1980)	Kimemia & Gershwin (1983)	Buzacott & Yao (1986)	Morton & Smunt (1986)
DECISION FRAMEWORK	FMS production control is divided into five subproblems: 1. Part type selection 2. Machine grouping 3. Production ratio 4. Resource allocation 5. Loading	FMS production control decisions are structured in three levels: *Level 1* - Find the mix of jobs entering the system and the machine assignement for each configuration of the working/failed condition, in order to minimize makespan *Level 2* - Find the sequence of jobs entering the system in each failure condition to maximize the average production rate *Level 3* - Find the input time for each job and the next operation for each job in each failure condition in order to minimize delay	FMS production control is decoupled from the plant master schedule and has a hierarchial structure: *Flow Control* - Regulates the production rate of each job type *Routing Control* - Determines the optimal routing of jobs *Sequence Control* - Determines the sequence and time to release an external job, and next operation on an internal job	FMS production control has the following basic hierarchial decision structure: *Pre-release Planning* - Deciding which jobs are to manufactured *Input Control* - Determining the sequence and timing of release of jobs to the system *Operational Control* - Ensuring movement between machines and deciding which is to be processed next by a machine	There are four levels in FMS production control: 1. Strategic planning 2. Capacity planning 3. Scheduling 4. Dispatching

3.4.2.5. Optimized Production Technology (OPT)

Of the five production control frameworks reviewed in this category, OPT is the newest and most controversial. Further, OPT is the only framework which is a specific product[5] and not a reported knowledge concept. Though the overall structure of the methodology is known, several of the control procedures use proprietary knowledge. A brief review of the methodology is reported by Jacobs (1984). The OPT technique includes both a control methodology and management philosophy. Users are required to implement both. In that regard, OPT achieves considerable integration #1 since management is sensitive to production control. Goldratt via his two books, "The Goal" and "The Race", is now shaping the approach into a total factory management system (Goldratt and Fox, 1986).

The foundations of the OPT approach are summarized in nine rules which are adopted by all users. The first rule is the most important and the essence of the approach. That is, balance flow and not capacity. The approach assumes imbalanced capacity is an unavoidable characteristic, and focuses instead on balancing the flow. The OPT scheduler identifies the bottleneck stations for a given order schedule. The bottleneck station and all stations downstream of it are scheduled forward. The upstream stations are scheduled backward. Thus, the interfacing mechanism is the bottleneck stations and the balanced flow the integrating mechanism. This concept is also called synchronized manufacturing (Goldratt and Fox, 1986). In such a system the flow rate of the plant is dictated by the bottleneck stations. In contrast, in a JIT-Kanban system, the flow rate is dictated by the last station.

It is not clear whether OPT covers long range capacity planning or inventory control. It is primarily an approach for minimizing WIP at the shop floor level. The

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[5] OPT is a product of Creative Output Inc., Milford, CT

approach is highly centralized and there is no control module since it assumes strict adherence to schedule.

3.4.2.6. Other Approaches

Five approaches to achieving production control integration via a decision framework were identified and discussed in the above review. These are the most commonly known. There are, in addition, some other approaches which are currently being developed. Villa, et al (1987), present a hierarchical decentralized architecture for production control. They propose a tailored optimization program for each stage in the process, with constraints coming from upstream and downstream stages and the hierarchical controller. Shaw (1987) also reports a distributed scheduling approach designed for CIM applications. His approach can be termed as "competitive scheduling" since the distributed nodes are allowed to submit bids for jobs. Though his approach is applied at the cell level, it could be applied for master schedule development.

Maxwell, et al (1983), developed a framework oriented towards discrete parts manufacturing. They propose a three phase approach: the creation of a master production plan, planning for uncertainty, and real time resources allocation. The first phase is similar to the traditional master schedule development; the second phase focuses on setting buffer levels and inventory levels. The third phase is the traditional shop floor control. No techniques are identified and Maxwell et al only propose a decision structure.

3.4.3. Integration Through a Network Model

Network modeling approaches are common and effective techniques in the analysis of complex interlinked systems. These models force a sequential analysis of the problem, which is their primary advantage from an integrative perspective. A drawback of these approaches is that they tend to be descriptive and are often difficult to evolve to the prescriptive stage. Often, simulation techniques are the only alternative. The other alternative is network programming techniques. This alternative, though, is not significantly different from the single mathematical model approach.

Zahorik, et al (1984), examine present network programming models for production control in multi-stage, multi-item systems. Network approaches are not very promising from an integration perspective. They tend to degenerate into mathematical problems and do not exhibit the intrinsic advantages of network analysis.

3.4.4. Integration Through a Structured Model

Production control is a complex activity and its complexity can be expected to increase in a CIM environment. The design of control methodologies for such complex systems requires a clear understanding of the system and the associated problem. All too often control approaches are developed without this understanding, resulting in poor system performance. One approach to understanding the problem is to structurally analyze it or model it. The word "structure" is defined in the dictionary as "the arrangement and interrelation of parts or elements in a complex entity". By "structurally analyze and model" we mean an examination and definition of this arrangement and interrelationship. None of the production control approaches reviewed here are based on such an analysis. Structural approaches help decompose the system into smaller subsystems. A suitable integrative framework for the control of this network of subsystems can then be developed.

The structural approach has resulted in the development of three specific techniques[6]. Ross (1977) developed the technique of Structured Analysis. The technique

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[6] The names of two of the techniques should not be confused with the ordinary usage of the expressions "structured analysis" and "structured modeling."

has been tested and applied to several problems and has now been extended to Structured Analysis and Design Technique - SADT (Connor, 1980, Ross, 1985). More recently, Geoffrion (1987) presented the structured modeling technique. The third structured approach is IDEF, which is based on the SADT methodology but oriented towards manufacturing applications (IDEF Manual, 1981). All three approaches are graphical in nature.

Structured approaches are useful in designing integrated systems. Shunk, et al (1986), describes three aspects of integration modeled by IDEF as: information, control, and material; all three are critical to CIPP&C systems. These approaches help define the architecture of a system, which in turn, identifies the required integration. Connor (1980) lists the characteristics of a structured approach as:

1. Bounding the context of the problem
2. Limited information portrayal
3. Merging of perspectives into a single viewpoint
4. Top-down decomposition
5. Levels of increasing detail
6. Levels of abstraction (i.e., from logical to physical)
7. Describe multiple hierarchies and networks
8. Emphasize both data and activities

Each characteristic describes a different aspect of systems development and integration. Clearly, an approach with the above characteristics will provide a rigorous and disciplined approach to problem solving.

There are no reported production control approaches based on structured modeling. The first effort in this direction is the Integrated Manufacturing Control project of the Air Force (ICAM Review, 1980). This project is focused on shop floor control and the results are not yet reported. The ultimate objective of the project is to develop a triple control system for the cell, center, and factory. Structural approaches appear to be a sound methodology for integrated efforts. The intent of this dissertation is to develop a production control system based on structured analysis and modeling. The system* is developed using the IDEF methodology and the manufacturing function model in the ICAM Report (1983). The system will attempt to cover all the functions identified in Holstein's (1968) definition. It is significantly different from existing approaches in that it is based on a structural definition of the problem, from which the required decisions and their interrelations are identified. The development of the methodology begins in the next chapter.

3.5. CONTROL ISSUES IN INTEGRATED MANUFACTURING

In any system there are characteristics which, if present, cause the system to behave as an integrated system. Several such characteristics and issues were evident in the review and analysis of production control methodologies reported in the previous section. Additional issues were identified in the earlier review of production control in the "factory of the future." These issues can be consolidated into the following distinctive integration issues for production control.

1. Dependent demand
2. Balanced Flow
3. Balanced Capacity
4. Flexibility (process routing and setups)
5. Common - interrelated objectives
6. Transportation and processing equipment coordination
7. Operation to tactical to strategic balance
8. Machine to cell to center to system balance
9. Proactively reactive
10. Appropriate data transfer
11. Effective data to information transfer
12. Guided intelligence based on feedback
13. Appropriate distributed decision making

Most of the issues are self explanatory and have been discussed earlier. The ninth issue implies that a system should react immediately to an event rather than when the effects of the event are experienced. For example, assume machine X is supplying machine Y and machine Y breaks down. Then, in a reactive mode, machine X stops supplying machine Y only when the buffer is blocked. In a proactively reactive mode, it stops supplying machine Y immediately and instead focuses on machine Z. The tenth issue refers to the earlier identified DRIP problem in computerized systems. One measure of this issue is:

Data Effectiveness = Data Available / Data Needed

A data effectiveness greater than unity implies a DRIP situation. The eleventh issue refers to the ability of a decision support system to fully utilize the available data. One measure of this issue is:

Information Effectiveness = Data Utilized / Data Available

Notice the product of the above two measures is a surrogate measure for the reliability of decisions made by the system. The twelfth issue advocates the need for effective feedback mechanisms. Current production control systems do not fully utilize the feedback information available to them.

Table 3.3 is an audit of the presence of these issues in some of the approaches reviewed earlier. It is not advocated that a successful production control system display all of these characteristics; neither are all the issues relevant to all applications. For different scenarios, the thirteen issues will have to have different priorities. But together, they do describe a desirable set of characteristics.

3.6. SUMMARY

The objective of this chapter was to review production control in general, with a specific emphasis on the issues of integration. We found that production control is an area of extensive research, dominated by the application of mathematical models

Table 3.3. Integration Issues Considered in Common Production Control Approaches

	INTEGRATION ISSUES	MRP	JIT	HPP	OPT	FMS
1.	Dependent demand	√	√			
2.	Balanced flow		√		√	
3.	Balanced capacity			√		
4.	Flexibility (process routing and setups)					√
5.	Common - interrelated objectives		√			
6.	Transportation and processing equipment coordination					√
7.	Operation to tactical to strategic balance			√		
8.	Machine to cell to center to system balance					√
9.	Proactively reactive		√			
10.	Appropriate data transfer	√				
11.	Effective data to information transfer					
12.	Guided intelligence based on feedback		√			√
13.	Appropriate distributed decision making		√	√		

and procedures. The research was described by some practitioners as being strongly theoretical. An emphasis on the practicality and applicability issues in the future is recommended by most practitioners and researchers. Of the four components of CIM systems, CIPP&C was found to be the least developed from an automation perspective. To guide future work in the development of CIPP&C systems and production control in general, twenty desirable features of production control were identified and analyzed.

Integration is an issue of interrelationships which are best described graphically. Two such graphical definitions of production control are reported by Holstein (1968) and Harrington (1984). These are shown in Figures 3.2 and 3.4. Future production control systems can be modeled on the basis of these definitions to ensure integrability. In this vein, four modeling approaches with an integration focus were identified. These were via a single mathematical model, a decision framework, a network model, and a structured model. Each of these were reviewed and analyzed. Most currently used large scale systems are of the decision framework type. The focus of this dissertation is on the fourth type, that is, a structured modeling approach. There is currently only limited research in this area but it appears to be the most promising.

Based on the above reviews, thirteen control issues in integrated manufacturing were identified. Thus, in this chapter, the stage was set for the development of production control systems for the "factory of the future", or more specifically CIPP&C systems. Most current systems cover portions of CIPP&C but none can substitute for it totally in CIMS. The majority of systems were developed to solve problems, rather than improve the system. Contrarily, the structured approach proposed here develops the control mechanism based on a definitive model of the system and problem.

This approach ensures the consideration of the interfacing, integrating, and networking issues which are so critical to the success of CIPP&C and CIM systems.

CHAPTER FOUR

DEVELOPMENT OF THE CIPP&C PLAN

4.1. INTRODUCTION

In describing the structure of a system, Nadler (1981) noted that a system consists of elements and dimensions, each of which is in turn a system within itself. In addition, there is a system of interfaces which relates the various elements to one another. This hierarchy of systems is what differentiates a "mess" from an " ordered" system. The hierarchy is an architecture or "blue print" for bringing together the various pieces that constitute the system. Thus, the first step in the design and building of a system is the formulation of the architecture from which the system is to be built. There are various levels of detail to which this architecture could be built. One classification of details is : a "city plan", an architecture, and a detailed modeling. This research is based on the premise that a plan, or scheme, for executing production control in a manufacturing facility can be developed. In this chapter, the focus is on the design of such a plan.

In the preceding chapters the importance of building a system of production control was highlighted and discussed. A primary objective of this dissertation is to design the "city plan" of such a system. This is not to imply that such systems have not been built in the past. In the second half of Chapter Three several such plans and approaches were reviewed and discussed. A common problem with these is that they are methodology oriented, by which it is meant they evolved from a methodology to a system. Again, this is not to imply the resulting system is not worthwhile, but that it may not be the best solution. The process of building a system will need to evolve from a plan, to individual methodologies, and then to an overall architecture. This is equivalent to going from a macro, to micro, to a medium perspective. Such a process ensures that the system is well balanced and feasible. It is the intent of this dissertation to follow a similar path. In this chapter a plan is developed, while in the next chapter individual methodologies for specific modules are formulated. In developing the plan for a building, the process is usually unstructured and depends to a large extent on the creativity of the architect who creates what is termed a"bubble diagram." Contrarily, the plan for an operating system is primarily functional in nature (ICAM Report, 1983) and needs to be developed in a more structured manner. Similarly, here it is proposed the CIPP&C plan be developed via a structured analysis technique. Such a technique identifies the inputs, outputs, and activities of each individual element comprising the system. Identification of these sub-elements increases the understanding of the system and hence, helps improve the quality of the developed plan. A system is only as good as the method used to design it, and structured methods have been proved to be effective methods in several applications.

In this chapter, a description of the general manufacturing environment for which the plan is designed is described. A list of assumptions about the operations is also introduced. The method of structured analysis is briefly reviewed. Finally, the ICAM definition model from which the plan is to be generated is also introduced.

4.1.1. General Manufacturing Setup

There are several configurations by which a manufacturing facility can be setup. As such, it is difficult to to describe a truly general setup, but there are some salient features common to most facilities. The focus here is on CIM systems and the setup adopted here reflects the characteristics of a CIM system.

The general structure of the manufacturing system modeled in this dissertation is shown in Figure 4.1. The production facilities are divided into two categories, one manufacturing products for finished products inventory; the other parts and compo-

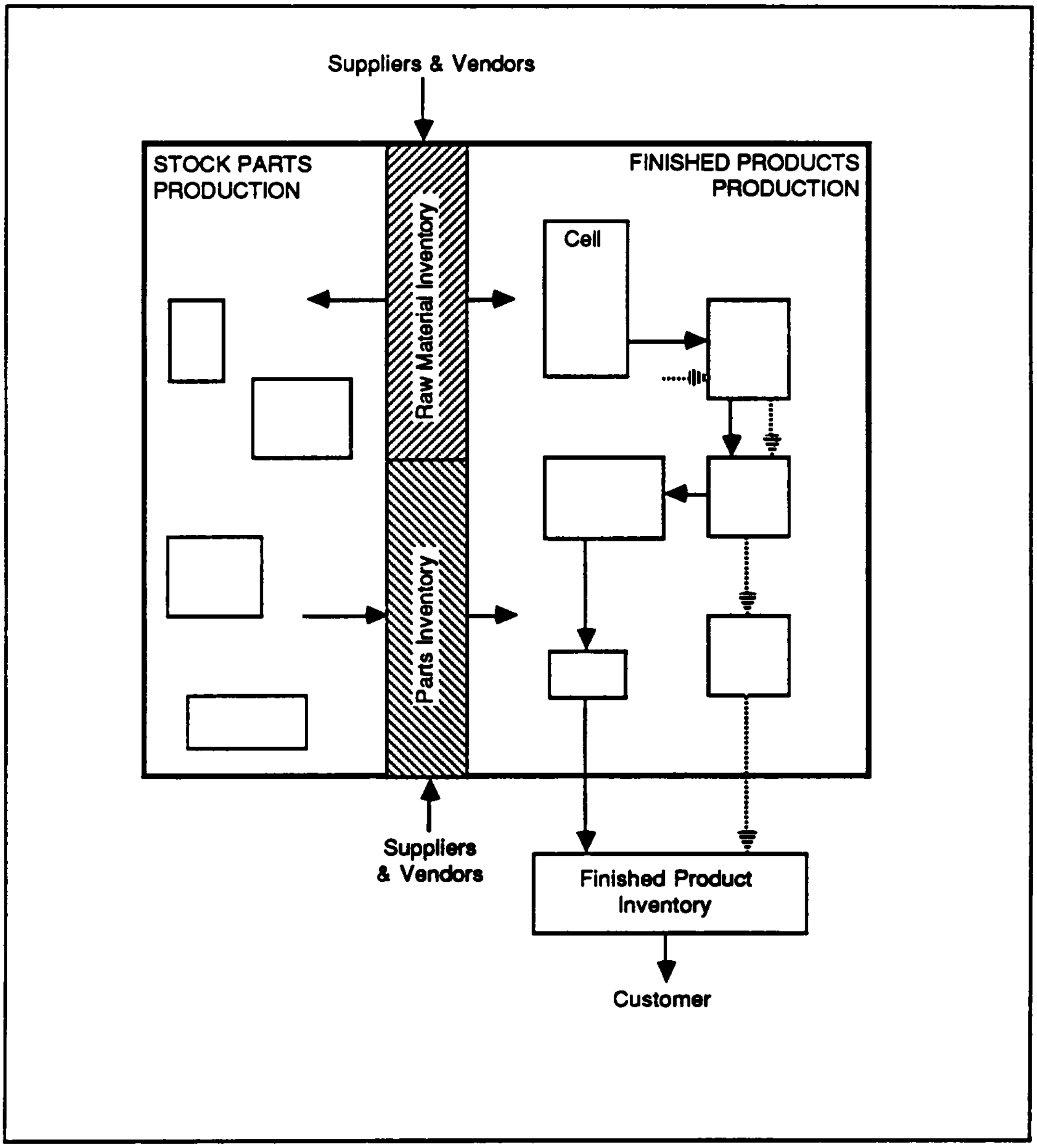

Figure 4.1. General Setup of a Manufacturing Facility

nents for stock inventory which, in turn, are used in the manufacture of finished products. From a production control perspective, stock production is driven by finished production, which, in turn, is driven by customer demand. If inventory levels for stock items are predetermined, then at the higher levels of CIPP&C the controller is primarily concerned with finished products. The production facility has a cellular manufacturing/group technology layout. That is, product items are grouped into types, and machines are clustered into cells. These are defined as follows:

Product Type	Group of products having similar production processes and requirements. They are analogous to "part families" in group technology; the only major difference being that families typically have a similar seasonal demand, but this is not assumed here.
Production Cells	Group of machines which can perform a defined set of operations. They do not necessarily have to perform all the operations on a product. They do not have to be all similar machines, and may actually have all dissimilar machines.

Both of the above definitions are adapted from Ham, et al (1985). Next, the list of assumptions made about the operations of this general setup are introduced.

4.1.2. Modeling Assumptions

The major assumptions made regarding the facility are listed below, other assumptions are listed in Chapter Five.

1. Production control in manufacturing facility is executed by a central controller which has the capability to direct activities in all parts of the facility. Specifically,

all decisions associated with the eight functions identified by Holstein (1968) are made by the central controller.

2. All information regarding production capability and performance are available to the controller on a real time basis.
3. All production is discrete and occurs in batches, and the schedule is in time buckets (typically, one week). The developed plan could be applied to a discrete environment, but the later developed methods are designed strictly for a discrete environment.
4. The flow of materials, parts, and products through the facility is described by Figure 4.1.
5. The various sub-methodologies to be used in production control will be networked via a LAN or other effective and efficient method.
6. Products can be aggregated into types, machines can be aggregated into cells, and time buckets can be aggregated into time periods.

4.2. REVIEW OF STRUCTURED ANALYSIS

The structured modeling approach used in this research is a simplification of the SADT technique (Ross, 1977) and IDEF methodology (IDEF Manual, 1980). Structured analysis of manufacturing was done in great detail by the ICAM program. The output of the program is synthesized here to create the CIPP&C plan. Thus, it is necessary only to further apply the structured analysis to those portions of the plan which are formulated here. For which purpose, a simplified analysis will suffice.

The underlying concept of structured analysis is that, for any system, it is possible to create a graphical model which is representative of the structure of the system. This structure could be function, decision, information, element, or event based. At any time, the model displays only that portion of the system which is relevant to the current perspective. The simplest type of structured model is a flow chart which describes process structure. Clearly, structural analysis does not solve problems, but helps better understand the system. Techniques have been developed for creating this type of graphical model in a stepwise fashion. The two best known approaches are SADT and IDEF. SADT has been used mainly in modeling of computer systems and IDEF in the modeling of manufacturing systems. Both these techniques generate a model consisting of a series of hierarchically and laterally interrelated graphs. Detailed description of the two techniques may be found in Ross (1977 and 1985), Connor (1980), IDEF Manual (1981), Harrington (1984), and Shunk (1986).

4.3. ICAM OUTPUT AND DEVELOPMENT OF THE CIPP&C PLAN

Currently, the most extensive project on developing a plan, for manufacturing in general, is the "composite function model of manufacturing" (ICAM Report, 1983). This composite model is a representation of manufacturing as it exists in the general aerospace industry. The motivation for this project was the need for an integration umbrella under which all future computer-aided technologies could be tucked. The DoD felt that continued development in the current fragmented way would result in the continued proliferation of disjointed and disintegrated technologies. Thus, the composite function model provides a common baseline definition and understanding of the manufacturing process. It is hoped this definition will be used by researchers in their model building efforts, hence ensuring a common integration base. The definition was developed by the staff at Wright-Patterson AFB and several major aerospace manufacturers and is well validated. The ICAM definition is based on aerospace manufacturing, but Harrington (1984) made the necessary changes to generalize the definition to all batch manufacturing. Extensive documentation on the definition is available in the ICAM Reports (1983, 1983a).

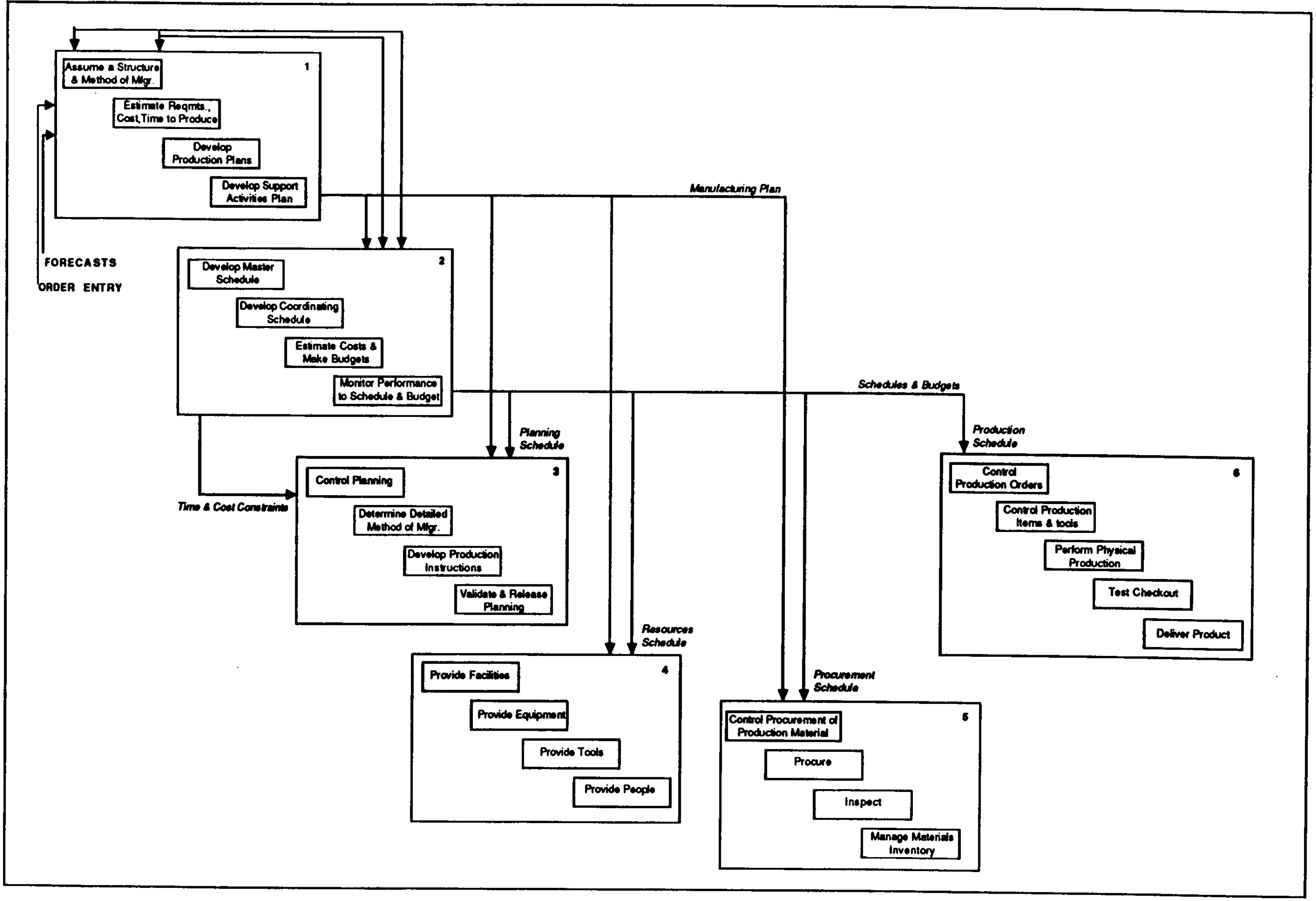

FIGURE 4.2. Two Level Graphical Definition of Production Control

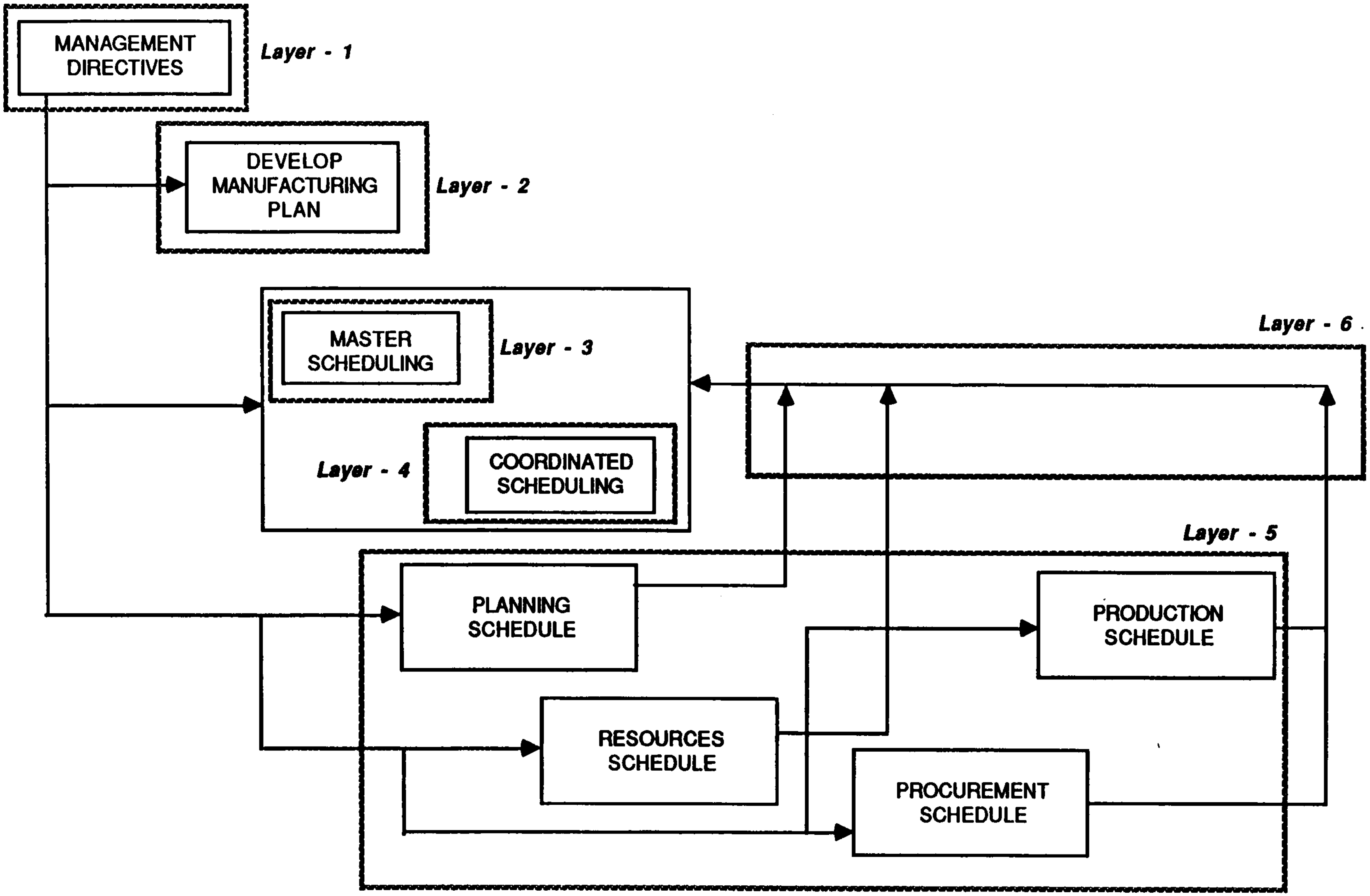

Figure 4.3. There Are Six Decision Layers in the CIPP&C Plan

The ICAM definition has been referenced in this research from the initial stages. It provides a validated picture of manufacturing and is a logical starting point for this research. The definition is arranged in levels, with increasing level number indicating increasing detail. The level '0' function is "manufacture product". Figure 4.2 is adapted from the definition and displays level 2 and 3 together. The 25 functions together define the process and management of manufacturing. The ringed boxes indicate functions which are part of the CIPP&C system. Clearly, the majority of the functions are CIPP&C functions. This validates the importance of production control to CIMS. The functions in box 1 are primarily static in nature, while the decision making occurs in box 2 onwards. Analysis of this definition, and comparisons with other control systems were used to transform Figure 4.2 to the CIPP&C city plan.

4.3.1. Outlining the CIPP&C "City Plan"

Figure 4.2 represents a network of decisions. To better model this network, it was decided to search for a hierarchy within the network. The hierarchy would be such that decision modules at the same level would have similar impact on performance, and would be constrained by similar higher level decisions. The search resulted in a six layer hierarchical structure. The layers of this structure are superimposed on the ICAM definition in Figure 4.3. Notice that, while all modules of the ICAM definition are used, the six layers do not totally correspond with the definition.

The layers were selected from studies of the IDEF reports on each function in the definition. In these studies it was noticed there is minimal information transfer between the planning, production, resources, and procurement schedules. Further, these schedules communicated primarily with the coordinating schedule module rather than the master scheduling module. In most existing systems the master schedule drives the production schedule, which in turn, drives the other schedules. Introduction of the coordinating module makes it possible to bring the four lower schedules into one layer. Additionally, this layer communicates with the coordinating layer and not the master layer. To distinguish between master and coordinating layers consider the following definitions:

Master Schedule	Establishes major milestones/goals and paths to meet demand
Coordinated Schedules	Schedules which generate and show information that is required to coordinate several major activities within the system

Which implies that all decisions that are required by several schedules should be made at the coordinating level. If the layers were to be divided via Anthony's (1965) hierarchy then, layers 1,2, and 3 would be strategic, layer 4 would be tactical, and layer 5 would be operational. Layer 6 is the feedback loop between layer 5 and layers 3 and 4. Its primary function is to alert the master aggregate and coordinating schedules of any schedule variances. Based on the above discussions, a "city plan" for the CIPP&C system was developed (Figure 1.1).

4.3.2. Structural Analysis of the MA-Schedule and CP-Schedule

One of the inferences from studies of the ICAM output was that while most of the CIPP&C inputs are of the macro type (months, batches, cells, etc.), the majority of the outputs are of the micro type (minutes, units, machines, etc.). Thus, the first modules in the plan must focus on the macro level. There are two possible methods which are appropriate for these modules: master scheduling and aggregate planning. Here, the two are combined to create a master aggregate schedule (MA-Schedule) module. The MA-Schedule will serve as the driver for the next layer of coordinated schedules.

Structural analysis of the MA-Schedule involved developing an IDEF diagram, followed by a question-directed design process. Questions answered in the design process were:

1. What are the decisions to be made ?
2. Where are the decisions to be sent ?
3. What are the horizontal and vertical integration issues ?
4. What dimensions of horizontal integration are dominant ?
5. What information is required by the coordinating schedules ?
6. Which dimensions of flexibility are to be exhibited ?
7. What are the quantifiable objectives ?
8. How is the manufacturing strategy operationalized ?
9. What are the implications of real-time control ?

The answers obtained in this analysis are reflected in the formulations presented in the next chapter. Sample answers to questions 1 and 2 are shown in Table 4.1.

The coordinating schedule is sub-divided into four sub-schedules. Of these, the coordinating production schedule (CP-Schedule) is addressed here, and was structurally analyzed.

4.4. SUMMARY

In this chapter, a "city plan" for CIPP&C systems is provided. Though major modules are identified, the plan is far from complete. It is hoped the plan will evolve with future research. The overall CIPP&C plan is designed to permeate throughout the entire production control function and hence will accommodate several modules.

Table 4.1. Sample Structural Analysis of the MA-Schedule

QUESTION	ANSWER
What are the decisions to be made ? (P = Primary) (S = Secondary)	P1 What quantity of each product group is to be produced to meet the demand?
	S1 Which cells will be accessed to produce the scheduled quantity? (capacity flexibility)
	S2 What flow routing among the cells will be used for each product type? (routing flexibility)
	S3 What is the required regular and overtime capacity?
	S4 What amount of the expected demand is tardy?
	S5 What is the total required material handling load/period?
	S6 What is the anticipated process quality level?
Where are the decisions sent ?	P1 To the four coordinating schedules To marketing and product delivery To senior management
	S1 To the four coordinating schedules To CAM Tolong term capacity planning
	S2 To the CP, CTRNS, and CTOOL-Schedules To CAPP To CAM To CAD
	S3 To personnel management To the four coordinating schedules To CAM To middle management
	S4 To middle management To customer service
	S5 To the CTRANS-Schedule
	S6 To customer service To middle and senior management

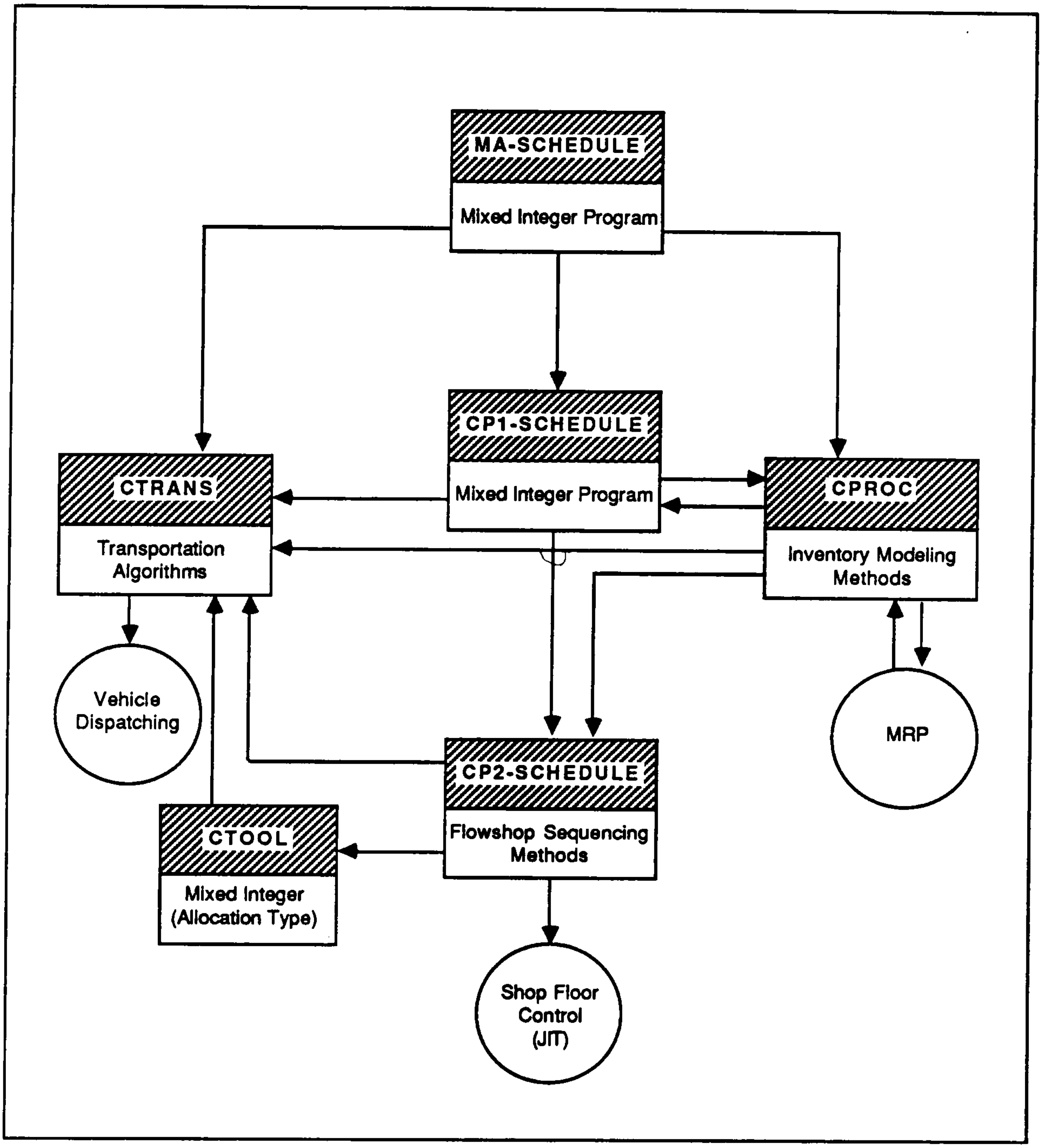

Figure 4.4. Module Integration and Solution Techniques in the CIPP&C Plan

Figure 4.4 is an attempt to illustrate the integrative nature of this plan. This schematic focuses on the master and coordinated levels of the plan. We envision each module using an individual solution method. But, the parameters and decisions of each module will be appropriately interfaced. Structured analysis can be used to develop each module in detail. Once decision requirements and the basic structure of each module has been identified, an appropriate method of decision making can be selected. This selection will be based on expertise with operations research and other techniques. In the next chapter such techniques are selected for the MA-Schedule and CP-Schedule. Probable techniques for some of the modules are indicated in Figure 4.4. Figure 4.4 also shows the sequential relationship between the coordinating schedules. It is expected that CP1 will be solved first, followed by CP2, CPROC, CTOOL, and CTRANS.

CHAPTER FIVE

FORMULATION OF THE MA-SCHEDULE AND CP-SCHEDULE

5.1. INTRODUCTION

In the previous chapter a "city plan" for a CIPP&C system was developed. Within this plan a structured analysis of the MA-Schedule and CP1-Schedule was done. This analysis identified the decisions to be made by these scheduling modules. In this chapter, mathematical models for determining these decisions are formulated. In the general master scheduling problem, the primary decision variable is $X_{i,t}$ where:

i represents what to produce
t represents when to produce
and X represents how much to produce

The process of determining $X_{i,t}$ is very amenable to the linear programming method of solution, with resources availability being modeled as a set of inequality constraints, and demand requirements being modeled as a set of equality constraints. When solved as an aggregate planning problem, the subscript 'i' denotes a family of products. Solution methodologies for determining $X_{i,t}$ are well documented in the literature and briefly reviewed later. These methods do not provide all the secondary decisions and additional information required by the CIPP&C plan. Thus, a new methodology to fit the needs of the plan is developed here. This new methodology consists of three separate modules for the MA-Schedule, CP1-Schedule, and CP2-Schedule problems. The respective decisions to be made by these three modules are (notation defined in Section 5.1.3.):

MA-Schedule - $X_{i,t}, Z_{k,t}, O_{k,t}, W_{k,t}, h_{k,t}, y_{i,r,t}, H_{i,r}$

CP1-Schedule - $Y_{q,\tau,i,t,}$

CP2-Schedule - $S^k_{q,\tau,l,t}$, $F^k_{q,\tau,l,t}$

This dissertation is concerned with developing solution methods only for the MA-Schedule and CP1-Schedule modules. Solution methods for the CP2-Schedule are briefly explored only in the context of the MA-Schedule and CP1-Schedule modules.

The two module formulations developed here can be described as large-scale problems. The solution of large-scale problems is typically very different from the solution of small-scale problems. In the course of this research it was observed that the actual solution methodology tends to dominate the formulation, whereas the converse is true in small scale-problems. This is primarily due to the exponential increase in computational time with problem size. The formulations presented in this chapter were developed after extensive experimentation with both methodology and formulation. The formulations are designed to complement the solution methods and capture the desired system characteristics.

The formulation of the MA-Schedule problem developed here is an enhancement of the combined aggregate planning and master scheduling problem. These enhancements are:

1. The simultaneous modeling of three aggregations - capacity[1], products, and time.
2. The modeling of the facility as a group technology/cellular manufacturing layout.
3. The modeling of capacity flexibility[2].

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[1] There is a distinct difference between "lumping" and "aggregating" an element. General master scheduling models "lump" capacity into a single element, while in the approach adopted here capacity is "aggregated" into cells.

[2] Capacity flexibility is the ability of the system to economically start and shut production units from period to period

4. The modeling of routing flexibility[3].
5. The modeling of material transporter availability as a resource.
6. The inclusion of expected quality as an objective.
7. The modeling of orders with dual delivery priority.

The modeling of the above flexibilities introduces 0-1 variables in the formulation. The problem therefore has to be solved using 0-1 Mixed Integer Programming (MIP) methods. Further, nonlinearities are introduced due to cross products between the 0-1 variables and continuous variables. These nonlinearities are removable using existing procedures, enabling a linear programming formulation. The resulting formulation can then be solved as a linear MIP.

The MA-Schedule and CP1-Schedule are linked by an aggregation/disaggregation of products, capacity and time. The CP1-Schedule and CP2-Schedule are linked by an aggregation/disaggregation of capacity through an iterative procedure. There are several approaches to disaggregating the decisions of the MA-Schedule. Where the disaggregation is one dimensional, rule-based procedures can be used (Hax and Golovin, 1978), but where there is more than one dimension, the combinatorial problem requires an optimizing algorithm. Thus, the CP1-Schedule sub-methodology developed here is modeled as an optimizing algorithm and formulated as a 0-1 MIP, which disaggregates the families into products and the time period 't' into the time bucket 'τ'. That is, the decision $X_{l,t}$ is exploded into a set of $Y_{q,\tau,l,t}$ decisions. The CP2-Schedule sub-methodology raises the sequencing question and is actually equivalent to the flowshop problem. It involves setting a corresponding set of $S^{*}_{q,\tau,l,t}$ decisions for each $Y_{q,\tau,l,t}$. A common assumption made by aggregate and master scheduling models is that the entire capacity assigned to a product is accessed in the scheduled period. The sequential nature of

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[3] Routing flexibility is the ability of the system to vary the production route from period to period (Zelenovic, 1982)

production invalidates this assumption and causes schedule interferences. This is discussed further in section 5.8.1. Clearly, the objective of the CP2-Schedule is to minimize the probability of schedule interference from bucket to bucket, which implies minimizing makespan. The CP2-Schedule is therefore solvable using existing group sequencing algorithms for minimizing makespan. The solution methods for the three modules are summarized as:

MA-Schedule - 0-1 Mixed Integer Programming
CP1-Schedule - 0-1 Mixed Integer Programming
CP2-Schedule - Group Scheduling Heuristic (Ham & Hitomi, 1985)
(n-cell m-group flowshop problem)

Further, the progressive disaggregation between the three modules is:

MA-Schedule	***CP1-Schedule***	***CP2-Schedule***
Cells	Cells	Machines
Periods	Buckets	Real time
Groups	Items	Items

Note that all three problems have been individually studied. The uniqueness of the formulations here stems from first, the linked solutions, and secondly, the enhancements made based on the structural analysis. The interrelationship of the three modules is shown in Figure 5.1. The origins of the overall methodology are from the HPP method, and this formulation can be considered an extension of the HPP method. A comparison of the two methods is shown in Figure 5.2. The similarity of the two methods stems from their hierarchical processing of separate mathematical programs. All the objectives and constraints of HPP are included in MA-Schedule. In addition, the MA-Schedule models CIM characteristics and has a wider decision domain. Further, the overall CIPP&C system is designed to permeate throughout the entire production control function and hence accommodates several methodologies.

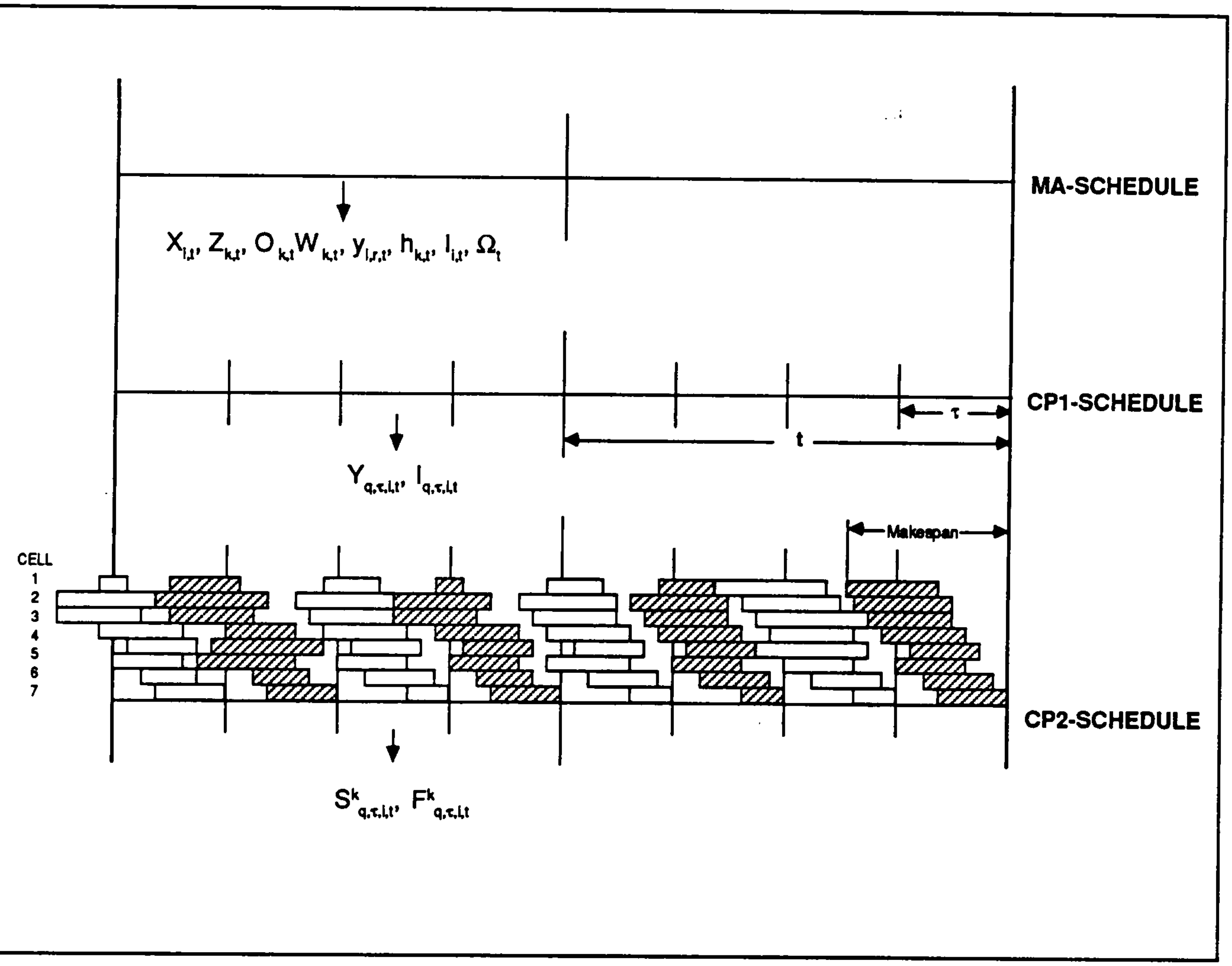

Figure 5.1. Mathematical Relationships Between The MA-Schedule and CP-Schedules

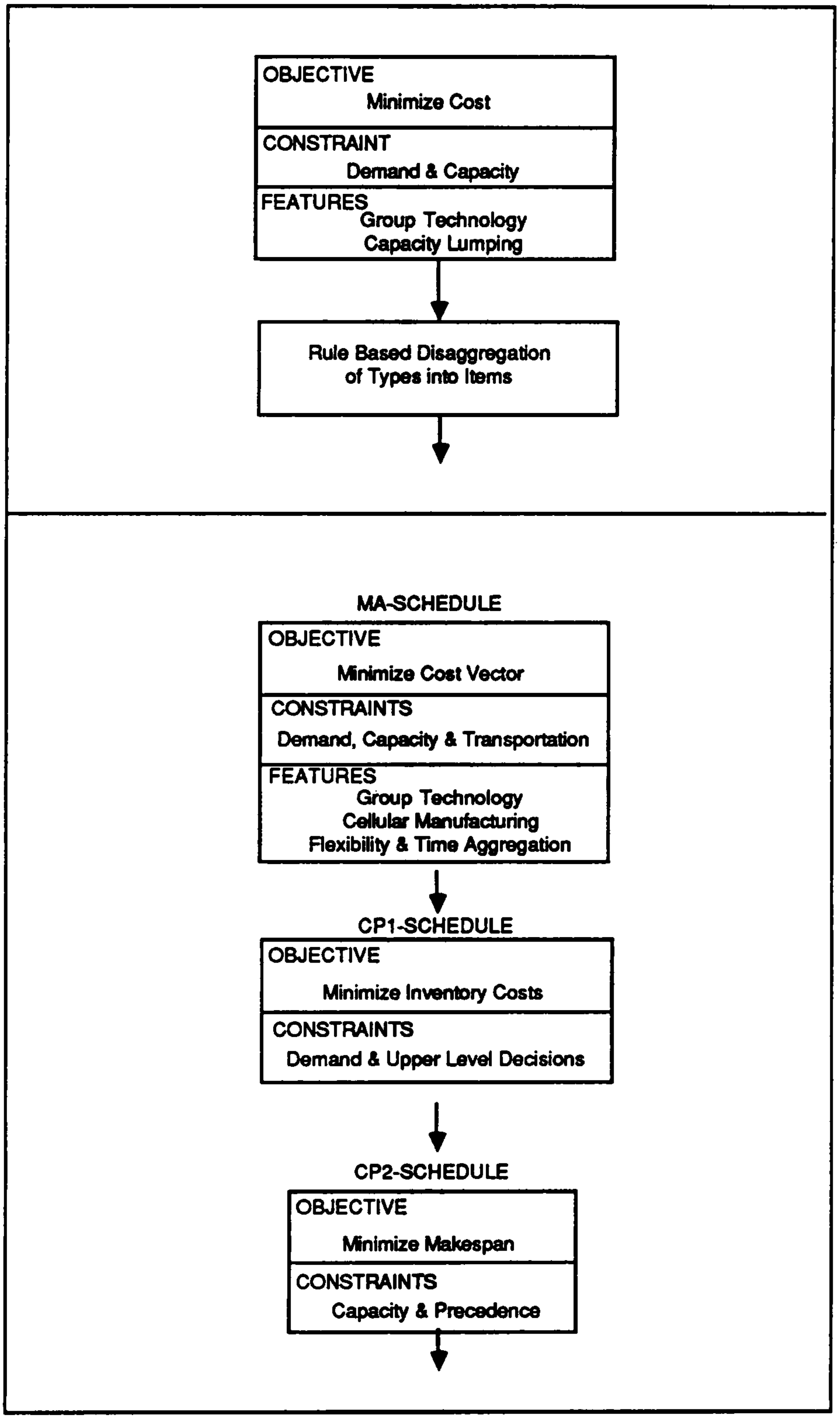

Figure 5.2. Evolution From HPP to CIPP&C Methdologies

The feasibility of decisions made by the MA-Schedule will be considerably more than those of HPP due to the new constraints added.

5.1.1. Brief Review of Master Scheduling Practice

The subject of master scheduling is a traditional area of industrial engineering and has been well studied in the past. Traditionally, the master schedule disaggregates the overall production plan into what to make and when to make decisions. Most of the current approaches are graphical or tabular in nature and are typically executed by the "chief scheduler" in a facility. Gessner (1986) and Vollmann, et al (1984), provide a detailed description of the major methods and their use. With the graphical methods, the scheduler uses visual tools to ensure that demand is met while creating a feasible schedule. Such methods are popular in smaller facilities with a steady production volume, but, they are not efficient in a larger or more complex facility.

There are only a handful of approaches for solving the master schedule problem mathematically. There are two reasons for this. First, the problem is difficult to solve due to its combinatorial nature. Secondly, it involves a multi-criteria objective function. Most of the approaches identified in Section 3.4.1 may be used to solve the master schedule problem. These approaches, however, focus on a single criterion objective. To solve the multi-criteria problem, one good approach is goal programming (Lee and Moore, 1984). Gonzalez and Reeves (1983) have developed a methodology based on this approach. The recent emphasis in master scheduling research is the combined solution of master and aggregate scheduling models. The most well known combined solution was developed by Hax and Meal (1975) in which they disaggregated product types. Following their work, the solution of hierarchical models has been the general methodology for master aggregate scheduling. Chung and

Krajweski (1987) extended the Hax and Meal methods to disaggregate both product type and time. Their approach is the first to involve an optimization procedure at both levels.

The intelligence of a solution method is determined by the modeling of constraints which define the solution space, in which the method searches for the best solution. Current master scheduling methods have very few constraints, and as a result, tend to make unintelligent decisions. Consequently, there has been a revival in the building of more detailed and intelligent models. This research proposes a new approach to master scheduling for CIM systems. The approach is more detailed and intelligent than existing approaches and is closely integrated with other scheduling activities in the CIPP&C system.

5.1.2. Basic Features of Linear and Mixed Integer Programming

In this section, the basic features of linear and mixed integer programming are presented. There are three basic elements which constitute a linear program (Ravindran, et al, 1987):

1. A set of non-negative continuous decision variables
2. A linear objective function which defines the criterion for selecting the optimal values of the decision variables
3. A set of linear constraints describing the operations and limitations of the system

A large variety of problems in diverse fields can be formulated as a linear program and solved. Linear programs can be solved via the simplex method, an iterative procedure for moving the current solution from corner to corner of the convex polytope that defines the feasible solution space. The simplex method has been the backbone for the several commercial codes available. These codes usually contain built-in heuristic algorithms that assist the simplex method in its quest for the optimal point.

MIPs differ from linear programs in that a subset of the decision variables are constrained to being integers. A special case of the MIP is the 0-1 MIP in which the integer variables are either zero or one. The current state-of-the-art in solution of MIPs is less sophisticated than linear programs and pure integer programs. For the last 25 years, the only general approaches for solving this class of NP-hard problems have been (Van Roy and Wolsey, 1987):

1. Branch and bound, based upon the simplex method
2. Bender's decomposition
3. Lagrangian relaxation
4. Cutting planes

Several commercial codes based on these approaches are available and are reported to be efficient. MIPs are particularly applicable in the modeling of manufacturing systems, since they enable the simultaneous modeling of both binary and numerical decision variables in the program. The best solution method will depend on the nature of the specific problem. Mixed integer programming is the chosen method of solution for the MA-Schedule module. The intent of this dissertation is not to research the solution of MIPs. The intent is to effectively integrate the best available solution method into the CIPP&C system.

5.1.3. Definition of Notation

In this section the mathematical notation used in the formulation of the MA-Schedule and CP-Schedule is introduced.

Decision Variables

$X_{i,t}$ = Number of product type 'i' produced in period 't'

$Z_{k,t}$ = Operating status of cell 'k' in time period 't'
(0 = shut-down, 1 = operating)

$O_{k,t}$ = Overtime hours worked by cell 'k' in time period 't'

$W_{k,t}$ = Regular time hours worked by cell 'k' in time period 't'

$Y_{q,\tau,i,t}$ = Number of product 'q' of type 'i' produced in bucket 'τ' of period 't'

$S^k_{q,\tau,i,t}$ = Production start time of batch $Y_{q,\tau,i,t,}$

$F^k_{q,\tau,i,t}$ = Production finish time of batch $Y_{q,\tau,i,t,}$

$y_{i,r,t}$ = Indicates which production routing 'r' is being followed by product type 'i' in time period 't' (1 = selected route)

$R_{i,r,t}$ = Number of product type 'i' produced via route 'r' in period 't'

$h_{k,t}$ = Transportation resource from the pool assigned to cell 'k' in period 't'

Ω_t = Total transportation resource needed for inter-cell movement in time 't'

$I_{i,t}$ = Positive inventory level of type 'i' at end of period 't'

$L_{i,t}$ = Negative inventory level of type 'i' at end of period 't'

$I_{q,\tau,i,t}$ = Positive Inventory level of product 'q,i' at end of period 'τ,t'

$L_{q,\tau,i,t}$ = Negative Inventory level of product 'q,i' at end of period 'τ,t'

$IC_{i,t}$ = Total unassigned (item) group quantity available at end of period 't'

$YP_{q,\tau,i,t}$ = Previous group production assigned to item 'q,i' in period 'τ,t'

$YG_{\tau,i,t}$ = Unassigned (item) group production in period 'τ,t'

$\rho_{\tau,i,t}$ = Indicates whether group 'i' batch is produced (0-1 variable)

$\Delta P_{\tau,k,t}$ = Positive variation in CP1-Schedule from $W_{k,t} + O_{k,t}$

$\Delta N_{\tau,k,t}$ = Negative variation in CP1-Schedule from $W_{k,t} + O_{k,t}$

$\delta_{i,t}$ = Variation in CP1-Schedule from $X_{i,t}$

$ZS_{k,t}$ = Starting up cell 'k' in time period 't' (1 = start)

$ZD_{k,t}$ = Shut-down cell 'k' in time period 't' (1 = shut-down)

System Parameters

$P_{i,r,k}$ = Process structure matrix for product type 'i', where $P_{i,k}$ represents a feasible production route for 'i' and denotes the processing time required at cell 'k'

$F_{i,t}$ = Firm orders for type 'i' in period 't'

$E_{i,t}$ = Expected orders for type 'i' in period 't'

$d_{q,\tau,i,t}$ = Firm delivery of product 'q,i' in period 'τ,t'

$e_{q,\tau,i,t}$ = Expected delivery of product 'q,i' in period 'τ,t'

θ_k = Maximum regular time capacity available in cell 'k' in any period

C_k = Maximum time cell 'k' can operate in any period

$I_{D,i}$ = Desired inventory level for type 'i'

$H_{i,r}$ = Transportation resource required for inter-cell movement per unit of type 'i' produced in route 'r'

A_k = Dedicated transportation resource in cell 'k'

v_k = Required transportation resource per unit utilization

L = Makespan or length of production lead time

q_t = Expected lost quality as a function of utilization

Ψ = The total transportation resource available in the central pool

B = Set of key utilization cells

EPQ_i = Economic production batch size for product group i

Π = A large number

Cost Parameters

β_i = Finished product inventory holding cost per unit per period (group) (All inventory costs constant for all periods)

$\beta_{D,i}$ = Type 'i' penalty cost per unit variation about desired inventory level

$\beta_{q,i}$ = Positive inventory holding cost per unit per bucket 'τ' (item)

α_i = Negative inventory holding cost per unit per period (group)

$\alpha_{q,i}$ = Negative inventory holding cost per unit per bucket 'τ' (item)

ϕ_i = WIP inventory cost per unit per period

S_k = Start-up cost for cell 'k'

D_k = Shut-down cost for cell 'k'

$Q_{f,k}$ = Fixed operating cost for cell 'k'

$Q_{r,k}$ = Regular time varying operating cost for cell 'k' per unit time

$Q_{o,k}$ = Overtime varying operating cost for cell 'k' per unit time

$Q_{q,k}$ = Expected cost of lost quality due to cell 'k'

$Q_{u,k}$ = Cost for under utilization of capacity in cell 'k'
(Utilization of started-up cells only considered)

QD_i = Penalty for unit variation in $X_{i,t}$

QV_k = Penalty for unit variation in $w_{k,t} + O_{k,t}$

Summation Parameters

N = Total number of product types (subscript 'i')

M = Total number of cells (subscript 'k')

T = Total number of periods in planning horizon (subscript 't')

R = Maximum number of process routes (subscript 'r')

G = Maximum number of items in a product type (subscript 'q')

5.1.4. Modeling Assumptions

In the previous chapter, a set of assumptions were listed prior to the development of the CIPP&C "city plan". These assumptions are also in effect for the formulation of the MA-Schedule and CP-Schedule. In addition, the following specific assumptions are made:

1. The production facility is modeled as a cellular manufacturing facility. In the context of the MA-Schedule and CP1-Schedule, production may behave as either

a job shop or flow shop. For the CP2-Schedule it is assumed that production occurs in the form of an ordered flow shop[4]. That is,

- A product may visit a cell only once.
- The cells are ordered such that if a product visits cells 'i' and 'j' sequentially, then j>i always. The specified flexible routes are also designed with this assumption.

2. All production occurs in a straight line flow. There is no converging or diverging flow of products.
3. All processing times are known and deterministic.
4. Products are due at the end of the due period.
5. Products are produced in batches of at least EPQ size. A batch consists of identical type items only, and is transferred to the next cell only on completion of the entire batch.
6. The time to transport a product between processors is included into the processing times.
7. Parts and raw materials needed for a current period's production are available at the beginning of that period.
8. There is a set of routes associated with each product group. The process structure matrix identifies the cells visited in a route and the corresponding processing times at these cells.

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[4] The proposed incorporation of the Ham-Hitomi algorithm causes this restriction. Currently, research is underway at several sites on new methods which may make it possible to remove this assumption.

5.2. OBJECTIVE FUNCTION FORMULATION FOR THE MA-SCHEDULE

The primary decision variable for the MA-Schedule is $X_{i,t}$. In addition, there are six secondary decision variables: $Z_{k,t}$, $y_{i,r,t}$, $W_{k,t}$, $O_{k,t}$, $I_{i,t}$, and $h_{k,t}$. Of these, $Z_{k,t}$ and $y_{i,r,t}$ are flexibility variables in that they represent the operating status of a cell and the selected processing route, respectively. $W_{k,t}$ and $O_{k,t}$ are capacity variables and denote the regular and overtime capacity used. $I_{i,t}$ is an inventory variable and represents units in stock. $h_{k,t}$ is a transportation resource variable and represents the amount of resource assigned to each cell. Together, the objective of these decision variables is to ensure the facility is operating at an optimal rate.

Most master scheduling and aggregate approaches model the objective function as the minimization of a sum of costs (Bowman, 1956, Hax and Golovin, 1975, Buffa and Miller, 1979, Bedworth and Bailey, 1987). These costs typically include production cost, labor cost, overtime cost, stockout cost, hiring and firing costs, and inventory carrying cost. Earlier, the drawbacks of this approach was discussed. Skinner (1974 and 1985), Haas (1987), and Hayes and Wheelwright (1984) have all recommended the development of objective functions which are a reflection of the facilities and operations impact on the organization's overall competitiveness. Further, one of the earlier identified issues of integration was the need to balance strategic, tactical, and operational objectives. Considering master and coordinating schedules as being tactical decisions, then current approaches achieve only a tactical to operational balance. The aim of this formulation is to emphasize strategic to tactical balance.

The manufacturing strategic plan represents the role of production activities in the strategic business plan of the organization; the master and coordinating schedules are responsible for integrating this plan with actual operations. O'Grady and Menon (1984) developed a multi-objective function for production planning in FMSs. Their plan is focused at the shop floor level, but introduces some interesting uses of the goal programming technique. Rather than incorporate strategic dimensions in the objectives, they prescribe introducing preset parameters which reflect management strategy. A similar approach is adopted here by developing a multi-dimensional vector to model the MA-Schedule objective. The terms in this vector have different measures. In order to bring all the terms to a common scale, a parametric cost measure is used and all terms are scaled to this measure. The following categories constitute the objective function:

1. Minimize inventory costs (finished product & WIP)
2. Minimize system operating costs
3. Maximize expected quality level
4. Minimize variation about a desired inventory level
5. Minimize underutilization of capacity
6. Minimize lost sales due to negative inventory

Of the six categories listed here, the first two are common in the literature. Objective categories 4 and 5 were used by Gonzalez and Reeves (1983) in their formulation of the master scheduling problem and is incorporated here. Haas (1987), in discussing strategic objectives for manufacturing control, identified quality and responsiveness as key dimensions. Objective categories 3 and 4 are representative of these two dimensions, respectively. Each of the objective categories is now individually developed.

5.2.1. Development of the Objective Function Terms

The first objective category is finished and WIP inventory cost. The finished product inventory cost is simply the cost of holding the ending inventory till the end of the next period, and is given by

$$\sum_t \sum_i (\beta_i \max(0, I_{i,t})) \qquad (5.1)$$

where β_i is the holding cost per unit per period, and since negative inventory is permissible $I_{i,t}$ is unrestricted[5]. While most approaches (Hax and Meal, 1975) consider only the finished product inventory cost, it is important that WIP inventory also be included in the objective function. Goldratt (1987) and Schonberger (1985), and the JIT method in particular, have indicated and demonstrated the importance of controlling WIP. Surveys have shown that a part spends 60-80% of its inprocess life in the idle mode and this is a reflection of WIP. WIP is defined as all materials which have entered the production floor. Assuming that all parts are available at the beginning of a period, the WIP level is given by $X_{i,t}$. Later, the CP2-Schedule will provide start times, and a more accurate estimate of WIP can be computed. Let 'L' be the length of the makespan or production lead time, where 'L' is typically greater than 't' and therefore measured in multiples of 't'. Then, the WIP cost is given by

$$L \sum_t \sum_i X_{i,t} \phi_i \qquad (5.2)$$

where ϕ_i is the WIP inventory cost per period per item 'i'.

The second objective category is system operating cost. This cost is made up of the start-up and shut-down costs, and the facility operating cost. In a CIMS environment the facility is expected to have capacity flexibility and, as a result will be able to start-up and shut-down cells on an as-needed basis. The associated start-up and shut-down cost are modeled as follows:

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[5] In Section 5.4 the current formulation will be modified. Following this modification $I_{i,t}$ will be restricted to positive values only.

$$\sum_t \sum_k [\{S_k \max(0, Z_{k,t} - Z_{k,t-1})\} + \{D_k \max(0, Z_{k,t-1} - Z_{k,t})\}] \tag{5.3}$$

The equipment operating cost includes a fixed initial cost and a utilization varying cost. There is therefore a piecewise linear operating cost as described in Figure 5.3a. $Q_{f,k}$ is the fixed cost and $Q_{r,k}$ and $Q_{o,k}$ are the varying cost per unit time for regular and overtime, respectively. The operating cost is then given by:

$$\sum_t \sum_k [W_{k,t} Q_{r,k} + O_{k,t} Q_{o,k} + Z_{k,t} Q_{f,k}] \tag{5.4}$$

The third category is the level of expected quality. The issue of quality is not usually discussed in conjunction with production control. However, there are certain decisions of production control which are determinants of product quality. It is well known that as the pressure to produce increases, the possibly of a defect occurring during the production process increases. Thus, there is an inverse relationship between expected quality and capacity utilization. This relationship between quality and capacity utilization is not well researched. Garvin (1988), though, has done some exploratory studies in this direction. In an analysis of the U.S. air conditioning industry he found a positive correlation between cycle times and quality, and decreasing product quality with an increasing capacity utilization. Nonetheless the data is not significant enough to estimate the graphical relationship between the two factors. In this formulation, it is assumed expected loss of quality in each cell in a period ($q_{k,t}$) is a function of capacity utilization, and, is given by:

$$q_{k,t} = f\left[\frac{\{W_{k,t} + O_{k,t}\}}{\theta_k} \right] \tag{5.5}$$

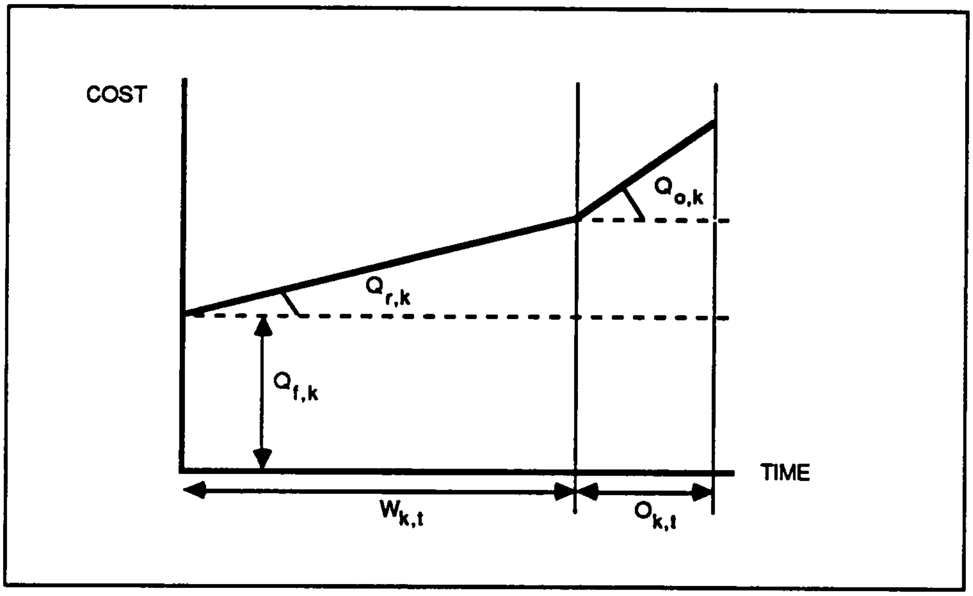

Figure 5.3A. Equipment Operating Cost

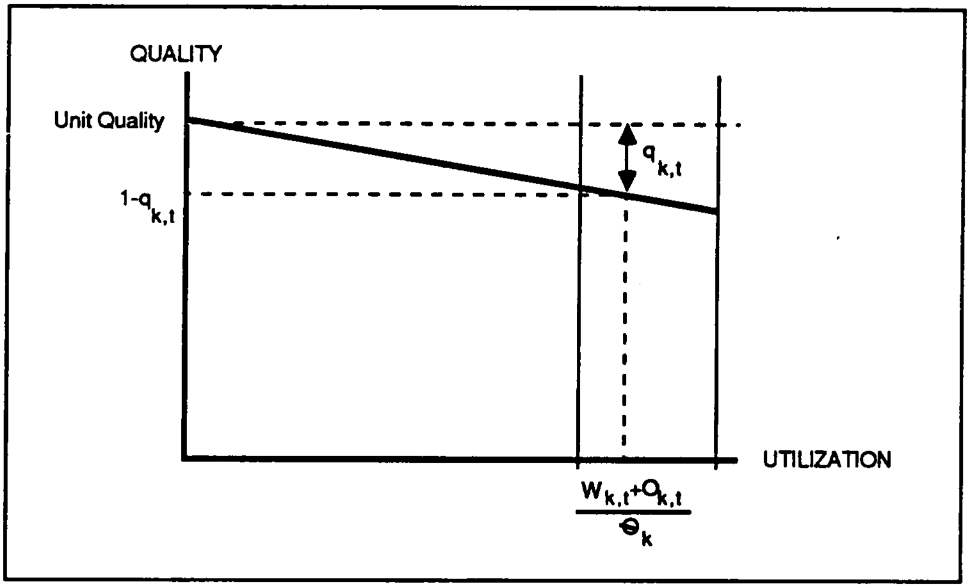

Figure 5.3B. Expected Loss of Quality

where 'f' is a linear function as shown in Figure 5.3b. The expected quality is an indicator which needs to be parametrically transformed into a cost function. Several books discuss methods for computing the expected cost of quality, and these can be used to obtain $Q_{q,k}$. Letting Q_q be the expected cost of lost quality per unit utilization, then the quality term in the objective function is

$$\sum_k\sum_t\{Q_{q,k}q_{k,t}\} = \sum_k\sum_t Q_{q,k}\left[\frac{\{W_{k,t}+O_{k,t}\}}{\theta_k}\right] \tag{5.6}$$

The fourth objective category is the variation about a desired level of finished goods inventory. In most organizations, senior management sets a desired level of inventory on the basis of strategic considerations. For instance, in the auto industry it is common to prescribe a 10-20 day production inventory, depending on the time of the year. The objective is to minimize variation about this desired level $I_{d,i}$. The parameter β_D represents the unit cost of variation. The cost is then given by

$$\sum_i\sum_t \beta_{D,i}[\max(0, I_{D,i} - I_{i,t}) + \max(0, I_{i,t} - I_{D,i})] \tag{5.7}$$

Note that the above equation automatically accounts for negative valued $I_{i,t}$. The fifth objective category focuses on the underutilization of capacity. The OPT procedure emphasized the importance of achieving unit utilization rates for key machines. Similarly, the intent of a master schedule is to achieve unit utilization for key cells. Let 'B' be the set of key cells, then the objective function is:

$$\sum_t\sum_{k\epsilon B} Q_{u,k}Z_{k,t}(\theta_k - W_{k,t}) \tag{5.8}$$

The sixth objective category focuses on lost sales or customer dissatisfaction. This occurs whenever there is a negative inventory. The MA-Schedule guarantees delivery of "firm order"s, but schedules "expected orders" as needed to optimize the schedule[6]. As a result, every time there is a negative inventory there is a possibility a sale is delayed, and a cost is incurred. Let this cost be α_i per unit of negative inventory, then the objective expression is,

$$\sum_{t}\sum_{i}\alpha_i \max(0, 0 - I_{i,t}) \tag{5.9}$$

Expressions 5.1, 5.2, 5.3, 5.4, 5.6, 5.8, and 5.9 together define the objective function, which is written as:

Minimize:

$$\begin{aligned}
&\sum_{t=1}^{T}\sum_{i=1}^{N}\{(\beta_i I_{i,t}) + (LX_{i,t}\phi_i) + (\alpha_i \max(0, 0 - I_{i,t}))\} \\
&+ \sum_{t=1}^{T}\sum_{k=1}^{M}\{(S_k \max(0, Z_{k,t} - Z_{k,t-1})) + (D_k \max(0, Z_{k,t-1} - Z_{k,t})) + (W_{k,t}Q_{r,k} + O_{k,t}Q_{o,k} + Z_{k,t}Q_{f,k})\} \\
&+ \sum_{k=1}^{M}\sum_{t=1}^{T}\{Q_{q,k}q_{k,t}\} + \sum_{t=1}^{T}\sum_{i=1}^{N}\beta_{D,i}\{\max(0, I_{D,i} - I_{i,t}) + \max(0, I_{i,t} - I_{D,i})\} \\
&\sum_{t=1}^{T}\sum_{k \in B}Q_{u,k}Z_{k,t}(\theta_k - W_{k,t})
\end{aligned} \tag{5.10}$$

The objective function consists of both pure cost terms and cost equivalent terms. Several of the terms are nonlinear due to a maximization operator. These nonlinearities will be removed in Section 5.4. In the next section, the constraints which define the solution space for this objective function are developed.

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[6] Firm and expected orders are two priority levels assigned to orders. See Section 5.3.1 for more description.

5.3. CONSTRAINT FORMULATION FOR THE MA-SCHEDULE

Constraints define the feasible decision space of a problem. Constraints may define system limitations, in which case, they are of the inequality type. Else they may be of the requirement type, in which case, they are of the equality type. For instance, demand satisfaction constitutes a requirement constraint, whereas available machine capacity is a limiting constraint. The more constraints there are in a model, the more intelligent it is, since it considers more of the world interrelated to its decision domain. In the formulation of the MA-Schedule, there are three types of constraints. Each type is individually developed in the sections to follow.

5.3.1. Demand-Supply Constraints

This is primarily a requirements constraint and ensures that all firm orders are delivered in the promised/expected period. Constraints of this type are fundamental to master scheduling practice. Bowman (1956) in his transportation formulation of the aggregate problem, and Hax and Golovin (1975) in their formulation of the HPP, among others, ensured that current demand is met by available inventory and current production. But in these formulations, it was assumed all orders must be met in the demand period. In many situations orders are of two types, firm or expected. Further, in situations where all demand is based on forecasts, the company policy may require that certain orders be filled upon receipt (equivalent to firm), while some be subject to tardiness (equivalent to expected) at an additional cost. Also it may be considered as a two priority level ordering system like an ABC inventory system. An expected order that is tardy appears as negative inventory in the records. Therefore, the inventory in any period 't' is given by:

$$I_{i,t} = X_{i,t} + I_{i,t-1} - F_{i,t} - E_{i,t} \qquad (5.11)$$

Further, it is assumed that all orders, firm or expected, are filled within the current planning scope. Therefore, there is no negative inventory at the end of period T:

$$I_{i,T} \geq 0 \tag{5.12}$$

Further, to ensure that all firm orders are met in the current period the constraint is:

$$X_{i,t} + \max(0, I_{i,t-1}) \geq F_{i,t} \tag{5.13}$$

where the maximization operator ensures that only positive inventory is used to meet $F_{i,t}$. Considering that constraint 5.12 is the nonegativity constraint, constraint 5.13 is the only additional constraint introduced over the formulations of Bowman (1956) and Hax and Golovin (1975). Thus, the effective number of constraints doubles due to the modeling of firm/expected orders. However, considerable benefits are gained by this structure. The ABC system of classification has long been used in the design of decision models for purchased items. The classifications typically being based on the annual dollar usage (Silver and Peterson, 1985). Similarly, the categorization of orders based on delivery priority incorporates a significant increase in flexibility in decision making for scheduling purposes.

5.3.2. Capacity Constraints

Capacity is a resource, and this is primarily a limitation constraint. Finite capacity scheduling will be a critical feature of CIPP&C, and the MA-Schedule must act as a finite capacity planning model. In its simplest form, the capacity constraint is written as:

$$\sum_i P_i X_{i,t} \leq O_t + W_t \tag{5.14}$$

However, this constraint is inadequate for a CIM setup since it does not consider capacity aggregation, routing flexibility, or capacity flexibility. Capacity aggregation implies that there must be a constraint 5.14 for each production cell. Therefore, the subscript 'k' is introduced and 5.14 is rewritten as:

$$\sum_i P_{i,k} X_{i,t} \leq O_{k,t} + W_{k,t} \tag{5.15}$$

The introduction of routing flexibility implies there is no unique processing time ($P_{i,k}$) for an item ($X_{i,t}$). Since every product can be processed by more than one route through the cells, and it is assumed the entire product group batch is processed by the same route in a period, the quantity produced in a route is given by:

$$R_{i,r,t} = y_{i,r,t} X_{i,t} \tag{5.16}$$

where $y_{i,r,t}$ is restricted by:

$$\sum_r y_{i,r,t} \leq 1 \tag{5.17}$$

Constraint 5.17 is not an equality constraint since it is possible $X_{i,t} = 0$ and all $y_{i,r,t} = 0$. From constraints 5.16 and 5.17 it is implied that, if $y_{i,g,t} = 1$, then $R_{i,g,t} = X_{i,t}$, and $R_{i,r,t} = 0$ for $r \neq g$. Thus, in a particular period the capacity requirements of a product type is given by:

$$\text{Capacity required for type 'i'} = \sum_r R_{i,r,t} P_{i,r,k} \tag{5.18}$$

Now that capacity requirements are specifically known for a period, $P_{i,k}$ is substituted by expression 5.18 and constraint 5.15 is rewritten as:

$$\sum_i \sum_r R_{i,r,t} P_{i,r,k} \leq O_{k,t} + W_{k,t} \tag{5.19}$$

where the variables $O_{k,t}$ and $W_{k,t}$ represent the total operating time of cell 'k' in period 't', and are constrained by the physical capability of the cell equipment. That is,

$$O_{k,t} + W_{k,t} \leq C_k \tag{5.20}$$

But CIM systems incorporate capacity flexibility, and have the capability to shut cells down for one or more periods. This will require that products only be processed by cell 'k' if it is operating in time 't', implying:

$$O_{k,t} + W_{k,t} \leq C_k Z_{k,t} \tag{5.21}$$

Further, there is a limitation on regular processing time:

$$W_{k,t,} \leq \theta_k \tag{5.22}$$

Thus, constraints 5.16, 5.17, 5.19, 5.21, and 5.22 together form the set of capacity constraints. In the earlier formulations by Bowman (1956) and Hax and Golovin (1975), there was only one constraint; there are now five constraints. The additional constraints are due to the seven enhancements identified earlier and are necessary for CIMS modeling.

5.3.3. Material Transportation Constraints

In the process of manufacturing, there are several resources in addition to capacity which are consumed. The integrated control of these resources was identified as one of the features of production control in the "factory of the future." Ideally, all of these resources should appear in the formulation of the scheduling model. The development of such models is often referred to as the Resource Constrained Scheduling Problem (RCSP). Even when developed for small problems, the solution of the RCSP is very complex and known to be NP-Complete (Norbis and Smith, 1988). Of the several resources considered in the RCSP, the resource of material transportation is especially critical since it forms the linking medium between cells and machines. Consequently, it is the only resource modeled in the MA-Schedule. The other resources will be modeled at the coordinating schedule level. In the modeling approach adopted here, it is assumed that there are two classes of material transporters in the facility: those for inter-cell movements, and those for intra-cell movement. Typically, a manufacturing facility will have a central pool of material transporters, which may be used for either inter or intra-cell movement. Also, some cells may have dedicated transporters (for example, an FMS-AGVS). Thus a cell may use either it's own resource or that from the central pool for material transport.

The demand on transportation resources is proportional to the processing load, or for that matter, the capacity utilization. The capacity utilization for a cell is given by:

$$\text{Cell Capacity Utilization} = \frac{W_{k,t} + O_{k,t}}{\theta_k} \tag{5.23}$$

where utilization will likely exceed unity when overtime is used. Let ν_k be the required transportation resource per unit cell capacity utilization. Though there are no standard measures for material handling as a "lumped" resource, several utilization measures are listed by Apple and Rickles (1987). These measures are ratios of time, volume, weight, or units. Pending the selection of a more specific measure for transportation resource, it is assumed to be a discrete measure combining time and capacity. Therefore, letting $h_{k,t}$ be the resources accessed from the central pool, and A_k the cell's own resource, the cell transportation resource constraint is:

$$v_k \left[\frac{W_{k,t} + O_{k,t}}{\theta_k} \right] \leq A_k + h_{k,t} \tag{5.24}$$

The inter-cell transportation load, on the other hand, is dependent on the selected processing route for each product type. The more cells a route visits, the more the transportation load. Thus, for every feasible route, there is an associated required material transportation load per unit produced, given by $H_{i,r}$. Letting Ω_t be the total resource required for inter-cell movement, the constraint is:

$$\sum_i \sum_r H_{i,r} R_{i,r,t} \leq \Omega_t \tag{5.25}$$

Since there is a limitation on the amount of resource in the central pool, the above constraint is rewritten as:

$$\sum_k h_{k,t} + \sum_i \sum_r H_{i,r} R_{i,r,t} \leq \Psi \tag{5.26}$$

where Ψ is the total available central resource. Constraints 5.24 and 5.26 together constitute the set of transportation constraints. This completes the constraints for the MA-Schedule. There are eleven constraint sets which are presented in Table 5.1. The number of constraints in each set and their nature is also listed.

Table 5.1. Constraints in the Initial MA-Schedule Formulation

#	DESCRIPTION	EQUATION	# OF	TYPE
1.	Defines processing quantity for each possible route	$R_{i,r,t} = y_{i,r,t} X_{i,t}$	N R T	Linear
2.	Ensures that at most only one route is selected in each period	$\sum_{r} y_{i,r,t} \leq 1$	N T	Linear
3.	Ensures production is within cell capacity	$\sum_{i} R_{i,k,t} P_{i,r,k} \leq O_{k,t} + W_{k,t}$	M T	Non Linear
4.	Ensures production is routed to cell only if it is operating	$O_{k,t} + W_{k,t} \leq C_k Z_{k,t}$	M T	Linear
5.	Defines limit on regular time capacity	$W_{k,t} \leq \theta_k$	M T	Linear
6.	Calculates inventory at end of each time period	$I_{i,t} = X_{i,t,} + I_{i,t-1} - F_{i,t} - E_{i,t}$	N T	Linear
7.	Ensures that all firm orders are filled in the demand period	$X_{i,t} + \mathrm{Max}(0, I_{i,t-1}) \geq F_{i,t}$	N T	Non Linear
8.	Ensures there is no negative inventory at the end of period T	$I_{i,T} \geq 0$	N	Linear
9.	Ensures that transportation load assigned to cell can handle intra-cell movement	$\frac{v_k}{\theta_k} (O_{k,t} + W_{k,t}) \leq A_k + h_{k,t}$	M T	Linear
10.	Ensures that inter-cell movement can be handled by available resources	$\sum_{k} h_{k,t} + \sum_{i}\sum_{r} H_{i,r} y_{i,r,t} X_{i,t} \leq \Psi$	T	Non Linear

5.4. MODIFICATION OF PROGRAM FOR SOLUTION EASE

The above formulation has two drawbacks with respect to solvability. First, it has several expressions of the non-linear type. Secondly, the number of integer variables is significantly large. In order to improve the solvability of the MA-Scheduler, both of these drawbacks were addressed. The methods employed are described in the next two sections.

5.4.1. Linearization of Nonlinear Terms

The nonlinearities are of two types: those due to the presence of a maximization operator, and those due to the cross-product of a 0-1 variable and a continuous variable. While nonlinearities due to the maximization operator are easily removable, those due to the cross-product require considerable manipulation of the terms. There are several approaches for directly solving MIPs of the nonlinear type (Cooper, 1981). These methods are not as convenient to solve as linear programming methods. An alternative approximate method to the solution of nonlinear MIPs is the use of piecewise linear approximations (Watters, 1967). Another method, which is exact, involves linearizing the nonlinear terms and then solving the resultant linearized 0-1 problem directly. This method is especially viable when the cross products involve 0-1 variables, as in this case, and is therefore applicable here.

5.4.1.1. Linearization of Cross-Product Terms

Several linearization methods have been proposed for 0-1 cross product terms in the literature. These usually involve rewriting the nonlinear term as a multilinear function (Balas and Mazzola, 1984). The methods often encounter a severe shortcoming in that they result in a radical increase in the number of problem constraints and variables. As a result, they have not been very popular in the past. But, in the modeling of CIM systems, where flexibility is an intrinsic system characteristic, cross-products involving 0-1 variables are bound to appear. Thus, linearization methods are an important tool in CIM and FMS modeling. Of the known methods, the more economical approaches are those by Balas (1965), Peterson, (1970), and Glover (1975). Stecke (1983) applied several of these methods to a machine loading formulation for FMSs with considerable success.

The cross product term in the current formulation is of the form $y_{i,r,t}X_{i,t}$ and it appears in equation 5.16. Several methods can be applied to linearize this cross product term. The method adopted here is a variation of Peterson's method. To illustrate Peterson's original method, consider the cross product $x_r y_r$, where x_r is continuous and y_r is a 0-1 variable, and the nonlinear constraint is:

$$x_r y_r \leq k_r \tag{5.27}$$

Then, Peterson's method requires the substitution $z_r = x_r y_r$. If x_r is bounded above by a constant Π (large number), then Peterson proposes the following new constraints:

$$\Pi y_r \geq z_r \geq x_r + \Pi y_r - \Pi \text{ and } x_r \geq z_r \tag{5.28}$$

Thus, three new constraints and one new variable are added. Therefore, if there were 'n' cross product terms, there would be '3n' new constraints and 'n' new variables. But in the MA-Schedule formulation, there are certain special properties which could reduce the number of new constraints and variables. The equivalent nonlinear substitution in the MA-Schedule is $R_{i,r,t} = y_{i,r,t}X_{i,t}$, as given by expression 5.16. One special property of this substitution, using Peterson's notation, is that there is always a unique $y_r = 1$, for each set of 'r' cross product terms. That is, if $x_r y_r = z_r$ then, $y_r = 1$ for r=g and $y_r=0$ for r≠g or $\sum_r y_r=1$, which implies that $z_r=x_r$ for r=g and $z_r=0$ for r≠g. From equation 5.28 the upper bound on z_r is given by $\Pi y_r \geq z_r$, where for $r \neq g$ this expression defines $z_r=0$. Another special property of the MA-Schedule substitution is that all the x_r variables are the same, or $x_r=x$. Since at most one y_r is non-zero, there is at most one $z_r=x_r=x$. Further, there is at most one non-zero z_r. Therefore, it is proposed $x=\max(z_r)$, and $x=\sum_r z_r$. These propositions not valid only when all $y_r=0$, in which case x_r and x are unrestricted. In Peterson's method it is assumed x_r is not constrained by z_r, hence, x_r may take on any value when $z_r=0$. In the MA-Schedule this assumption does not hold, and it is required x=0 if all $z_r=0$. This condition is imposed by the above propositions, and hence they are valid applications to the Ma-Schedule. Removing redundancies between propositions and expressions relationship $x=\sum_i z_i$, the two new constraints which then define all z_r, are:

$$z_r \leq \Pi y_r \qquad \text{for all r} \quad (5.29)$$

$$\sum_r z_r = x \qquad (5.30)$$

For 'm' sets of cross products with 'n' terms each, Peterson's method would have required '3mn' new constraints. The new method adds 'mn+m' new constraints. For a problem with m=10 and n=10 this results in a 63% reduction in the number of constraints. Applying this method to the equivalent MA-Schedule substitution, equation 5.16 is transformed into the following two constraints:

$$R_{i,r,t} - \Pi y_{i,r,t} \leq 0 \qquad (5.31)$$

$$\sum_r R_{i,r,t} - x_{i,t} = 0 \qquad (5.32)$$

This eliminates all cross-products of the non-linear type from the formulation.

5.4.1.2. Removal of Maximization Operators

The maximization function occurs in three different cases. These are: modeling the negative inventory situation, modeling the start-up/shut-down of a cell, and modeling the variation about a desired inventory level.

To account for the negative inventory a new variable $L_{i,t}$ is introduced. This variable represents the amount of negative inventory at the end of a period. Integrating $L_{i,t}$ into the formulation, constraints 5.11 and 5.13 are rewritten as:

$$I_{i,t} - L_{i,t} = X_{i,t} + I_{i,t-1} - L_{i,t-1} - F_{i,t} - E_{i,t} \tag{5.33}$$

$$X_{i,t} + I_{i,t-1} - I_{i,t} \geq F_{i,t} \tag{5.34}$$

This lets all $I_{i,t}$ be positive. In addition, if all negative inventory is to be cleared at the end of the last period:

$$L_{i,T} \geq 0 \tag{5.35}$$

Expressions 5.1 and 5.9 in the objective are then rewritten as:

$$\sum_{i}\sum_{t}(\beta_i I_{i,t} + \alpha_i L_{i,t}) \tag{5.36}$$

To remove the start/shut maximization, two new variables and two new constraints are introduced. The new variables are $ZS_{k,t}$ and $ZD_{k,t}$, which represent the starting and shutting down of a cell. The additional constraints then are:

$$ZS_{k,t} - Z_{k,t} + Z_{k,t-1} \geq 0 \tag{5.37}$$

$$ZD_{k,t} + Z_{k,t} - Z_{k,t-1} \geq 0 \tag{5.38}$$

Expression 5.3 in the objective is then rewritten as:

$$\sum_{t}\sum_{k}(S_k ZS_{k,t} + D_k ZD_{k,t}) \tag{5.39}$$

Observe that, though $ZS_{k,t}$ and $ZD_{k,t}$ are required to be integer, they are not modeled as such, since, integer $Z_{k,t}$ ensures integer $ZS_{k,t}$ and $ZD_{k,t}$. To remodel the inventory variation, two new variables and one new constraint is introduced. The new constraint is:

$$I_{i,t} - IY_{i,t} + IZ_{i,t} - I_{d,i} = 0 \tag{5.40}$$

Where, $IY_{i,t}$ is positive variation, and $IZ_{i,t}$ is negative variation. Expression 5.7 in the objective function is then rewritten as:

$$\sum_{t}\sum_{i}\beta_{o,i}(IY_{i,t} + IZ_{i,t}) \tag{5.41}$$

Integration of the expressions 5.31 to 5.41, in the formulation, removes all nonlinearities due to a maximization operator.

5.4.2. Remodelling of Integer Variables

The presence of integer variables greatly increases the solution time of a linear program. This is because of the fact that in all the known Integer Program (IP) solution methods the program iteratively searches for an optimal integer. The solution method used here is the branch and bound method. In this approach, the search efficiency is dependent on the integer infeasibility[7] of the integer variables in the intermediate LPs. Clearly, if the LP was modeled such that integer variables had smaller infeasibilities, the solution efficiency would greatly improve. This can be done by introducing additional constraints which "fool" the program into lower infeasibilities. This approach is especially effective for integer variables which do not appear in the objective function.

There are two sets of integer variables, $Z_{i,t}$ and $y_{i,r,t}$, in the MA-Schedule formulation. After much effort, it was concluded the $Z_{i,t}$ variable could not be further remodeled. In contrast, considerable success was achieved with the $y_{i,r,t}$ variable. The remodeling introduced one new variable and one additional constraint. The new constraint which "fools" the program into smaller infeasibilities, is:

$$V_{i,t} + \sum_r y_{i,r,t} \geq \sum_r R_{i,r,t} \qquad (5.42)$$

Note that, whenever $R_{i,r,t} > 0$, then $y_{i,r,t} > 0$. In the case that $\sum_r R_{i,r,t} \geq 1$, it follows that $V_{i,t} + \sum_r y_{i,r,t}$ must be greater than '1' if any $y_{i,r,t}$ is to assume a non-zero value. Further, $V_{i,t}$ is introduced in the objective with the coefficient '0.001'. Therefore, when $\sum_r R_{i,r,t} \geq 1$, then $\sum_r y_{i,r,t} = 1$ and $V_{i,t} = \sum_r R_{i,r,t} - 1$. Now, the mechanisms of the simplex method are such that, if $y_{i,g,t} \neq 0$ and $y_{i,r,t} = 0$ for $r \neq g$, then introduction of constraint 5.42 would result in $y_{i,g,t} = 1$, though it is feasible another $y_{i,r,t}$ be non-zero. The variable $y_{i,r,t}$ appears in constraints 5.17. 5.31, and 5.42, observe that none of these restricts $y_{i,r,t} = 0$ when $R_{i,r,t} = 0$ or $X_{i,t} = 0$, though this is a modeling neccessity. Thus, a feasible solution could have $y_{i,r,t} > 0$ and $R_{i,r,t} = X_{i,t} = 0$. But, the mechansims of the

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[7] Integer infeasibility is defined as the amount by which an integer variable is off from it's closest integer value.

simplex method as applied to this problem are such that, $y_{i,r,t}$ does not enter the basis unless required to do so by one of the constraints. Therefore, in all generated solutions $y_{i,r,t} = 0$, if $R_{i,r,t} = X_{i,t} = 0$. Constraint 5.42, thus, removes the integer infeasibility associated with $y_{i,r,t}$ in most cases. The two exceptions are, first, when capacity is constrained such that more than one $y_{i,g,t} \neq 0$ for a unique i,t, in which case there will be residual infeasibility. Secondly, in the unlikely case when $0 < \sum_r R_{i,r,t} < 1$, in which case constraint 5.42 is ineffective. Experimentation with and without constraint 5.42 indicates a 40-60% reduction in solution time due to remodeling.

The formulation of the MA-Schedule is now complete. Table 5.2 displays the final formulation. Each constraint is also assigned a name. The names are used in Chapter six to develop the solution method. The total number of constraints is NRT + 6NT + 6MT + T + N, the number of integer variables is NRT + MT, and the number of continuous variables is NRT + 6NT + 5MT + T.

5.5. OBJECTIVE FUNCTION FORMULATION FOR THE CP1-SCHEDULE

The objective of the CP-Schedule module is to appropriately disaggregate the master schedule into an operating schedule. The three aggregating dimensions being capacity, time, and product. While most previous approaches have handled primarily one (Hax and Golovin, 1978) or two (Chung and Krajweski, 1986) dimensions, the triple aggregation model is new. Several approaches for disaggregating the aggregate schedule have been proposed; these approaches are of two kinds: rule based and optimizing. The double disaggregation requires an optimizing routine, while the single disaggregation is usually rule based. The triple disaggregation here is an optimizing approach and makes the following two decisions:

1. The quantities of an item to be made in time bucket τ, and

Table 5.2. Final Linearized Formulation of the MA-Schedule

OBJECTIVE TERM	MATHEMATICAL FORM
Inventory & WIP Cost	$\sum_{i} \{ (\alpha_i \sum_{t} L_{i,t}) + (\beta_i \sum_{t} I_{i,t}) + (L\phi_i \sum_{t} X_{i,t}) \}$
Inventory Variation Penalty	$\sum_{i} \beta_{D,i} \{ \sum_{t} (IY_{i,t} + IZ_{i,t}) \}$
Start-up/Shut-Down Cost	$\sum_{k} \{ (S_k \sum_{t} ZS_{k,t}) + (D_k \sum_{t} ZD_{k,t}) \}$
Cell Operating Cost	$\sum_{k} \{ (Q_{r,k} \sum_{t} W_{k,t}) + (Q_{o,k} \sum_{t} O_{k,t}) + (Q_{f,k} \sum_{t} Z_{k,t}) \}$
Lost Quality Penalty	$\sum_{k} Q_{q,k} \{ \sum_{t} (W_{k,t} + O_{k,t}) / \theta_k \}$
Under Utilization Loss	$\sum_{k \varepsilon B} Q_{u,k} \{ \sum_{t} Z_{k,t} (\theta_k - W_{k,t}) \}$
Dummy Costs	$0.001 \sum_{t} (\sum_{i} V_{i,t} + \sum h_{k,t})$

#	CONSTRAINT NAME	MATHEMATICAL FORM	NUMBER OF
1	TIM.i.r.t	$R_{i,r,t} - \Pi y_{i,r,t} \leq 0$	NRT
2	REQ.i.t	$\sum_{r} R_{i,r,t} - X_{i,t} = 0$	NT
3	DUM.i.t	$\sum_{r} y_{i,r,t} + V_{i,t} - \sum_{r} R_{i,r,t} \geq 0$	NT
4	CAP.k.t	$\sum_{i} \sum_{r} R_{i,r,t} P_{i,r,k} - O_{k,t} - W_{k,t} \leq 0$	MT
5.	FXR.i.t	$\sum_{r} y_{i,r,t} \leq 1$	NT
6.	FXC.k.t	$O_{k,t} + W_{k,t} - C_k Z_{k,t} \leq 0$	MT
7.	REGT.k.t	$W_{k,t} \leq \theta_k$	M
8.	INV.i.t	$I_{i,t-1} - I_{i,t} + L_{i,t} - L_{i,t-1} + X_{i,t} = F_{i,t} + E_{i,t}$	NT
9.	PIV.i.t	$X_{i,t} + I_{i,t-1} - I_{i,t} \geq F_{i,t}$	NT
10.	NINV.i.t	$L_{i,T} = 0$	N
11.	TRC.k.t	$(\eta_k / \theta_k)(W_{k,t} + O_{k,t}) - h_{k,t} \leq A_k$	MT
12.	TRAP.t	$\sum_{i} \sum_{r} H_{i,r} R_{i,r,t} + \sum h_{k,t} \leq \Psi$	T
13.	IND.i.t	$I_{i,t} - IY_{i,t} + IZ_{i,t} - ID_i = 0$	NT
14.	SRT.k.t	$ZS_{k,t} - Z_{k,t} + Z_{k,t-1} \geq 0$	MT
15.	DWN.k.t	$ZD_{k,t} + Z_{k,t} - Z_{k,t-1} \geq 0$	MT

2. When the processing of a batch type is to start at a cell.

It is not feasible to have the above two decisions made by the same model. Rather two separate models, CP1 and CP2, need to be developed. Only the CP1-Schedule is modeled in this dissertation. The CP1-Schedule uses integer variables to indicate when a product batch is being produced, and is formulated as a mixed integer program. The two primary decision variables for this module being $Y_{q,\tau,i,t,}$ and $I_{q,\tau,i,t}$. These are a disaggregation of production quantity ($X_{i,t}$) from group 'i' to item 'q' and from period 't' to bucket 'τ'. Perfect disaggregation is not possible since the CP1-Schedule assumes production occurs in batches of at least EPQ size. This in combination with the smaller time unit causes a MA-CP1 variation.

The CP1-Schedule is solved as a series of 'T' MIPs. Each of these programs makes the corresponding decisions for that period. Due to MA-Schedule directives, there may be an inventory at the end of each period for group 'i'. But, the CP1-Schedule at period 't' does not know the itemized breakup of this ending inventory. This inventory, designated as $IC_{i,t}$, is not assigned an item number until actual consumption occurs in the schedule. Ideally, $IC_{i,t}$ should be equal to $I_{i,t}$, but due to the variations this is not so. There are three production/consumption decisions to be made in each period, these are:

$Y_{q,\tau,i,t}$ = Item 'q,i' produced in bucket τ,t for consumption in the same period

$YG_{\tau,i,t}$ = Type 'i' produced in bucket τ,t for consumption in a following period

$YP_{q,\tau,i,t}$ = Item 'q,i' consumed in bucket τ,t from production in an earlier period

Over all periods $\sum_{t}\sum_{\tau} YP_{q,\tau,i,t} \leq YG_{\tau,i,t}$, the inequality arises due to the inability to compensate the variations over the horizon.

The CP1-Schedule objective function consists of three terms, these are:

1. Minimize the inventory cost within period 't'.
2. Minimize the production variation about $X_{i,t}$.
3. Minimize cell activity about $W_{k,t} + O_{k,t}$, and the imbalance between buckets in the period.

The MA-Schedule assumes inventory is constant across a period 't', but in reality deliveries are made at the end of time bucket 'τ', thereby implying inventory levels change from bucket to bucket, as shown in Figure 5.4. The MA-Schedule minimizes the area under the dashed line, whereas the CP1-Schedule minimizes the area under the solid line, which is given by:

$$\sum_{i}\sum_{\tau}\{[YG_{\tau,i,t}\beta_i(4-\tau)] + [\sum_{q}(\beta_{q,i}I_{q,\tau,i,t} + \alpha_{q,i}L_{q,\tau,i,t})]\} \tag{5.43}$$

Each $YG_{\tau,i,t}$ is certain to remain in inventory for the remainder of the period, and hence is multipyed by 4-τ. The second objective is a measure of how closely the CP1-Schedule matches the MA-Schedule. Letting $\delta_{i,t}$ be the difference between total CP1-Scheduled production and MA-Scheduled production, and QD_i be the penalty for unit variation, then the objective term is:

$$\sum_{i}\delta_{i,t}QD_i \tag{5.44}$$

The third objective combines two sub-objectives, namely, balancing the workload across the buckets in a period, and, minimizing variation about $W_{k,t} + O_{k,t}$. Letting QV_k be the combined imbalance and variation penalty, then the objective term is:

$$\sum_{k}(\Delta P_{k,t} + \Delta N_{k,t})QV_k \tag{5.45}$$

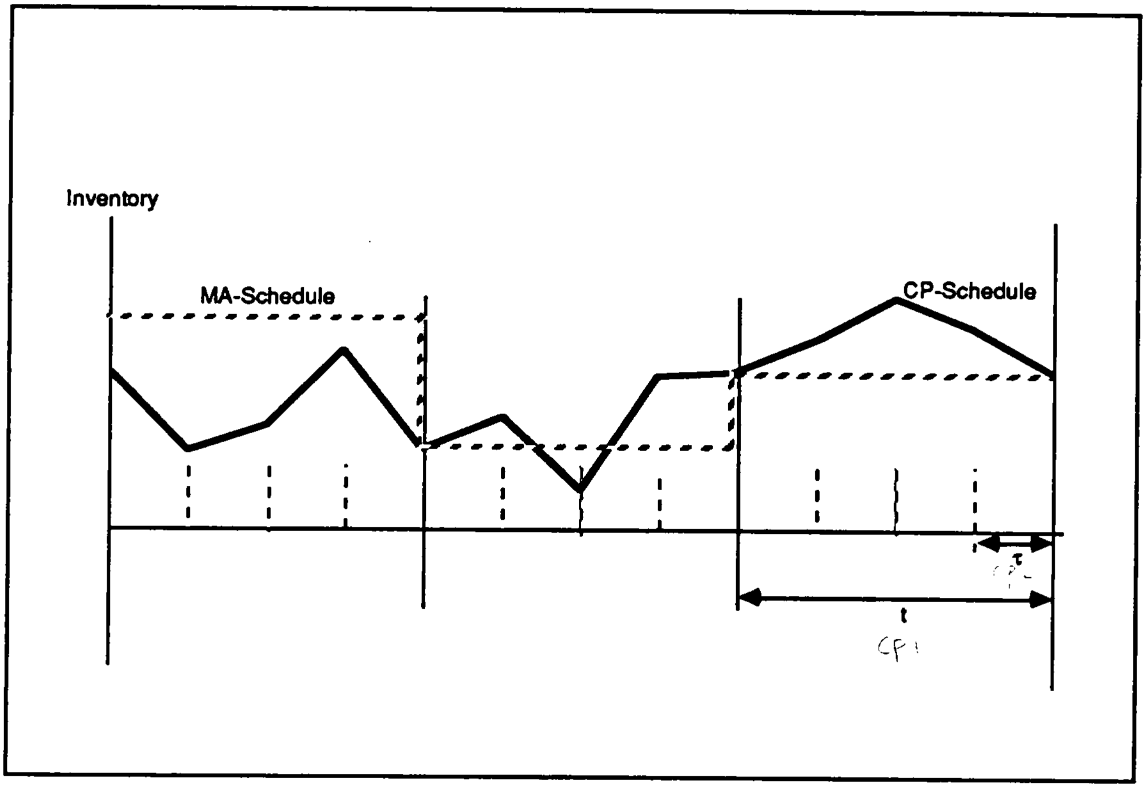

Figure 5.4. Inventory levels in the MA-Schedule and CP-Schedules

Where, ΔP and ΔN represent the positive and negative variation. Expressions 5.43, 5.44 and 5.45 together define the objective for the CP1-Schedule which is written as:

Minimize

$$\sum_{i=1}^{N}\sum_{\tau}^{4}\{[YG_{\tau,i,t}\beta_i(G-T)]+[\sum_{q=1}^{G}(\beta_{q,i}I_{q,\tau,i,t}+\alpha_{q,i}L_{q,\tau,i,t})]\}$$
$$\sum_{i=1}^{N}\delta_{i,t}QD_i+\sum_{k=1}^{M}(\Delta P_{k,t}+\Delta N_{k,t})QV_k \tag{5.46}$$

The above objective function contains only linear terms and is much simpler than that for the MA-Schedule. In the next section, the constraints which define the solution space for this objective function are developed.

5.6. CONSTRAINT FORMULATION FOR THE CP1-SCHEDULE

The primary constraint from the MA-Schedule that reappears in the CP1-Schedule is the demand-supply constraint. In the CP1-Schedule, production is processed in batches which are delivered at the end of a time bucket 'τ'. To ensure coordination between production and delivery, three sets of constraints are introduced. The first set ensures that all firm orders are met from either current period production or accrued inventory. This is ensured by:

$$Y_{q,\tau,i,t}+I_{q,\tau-1,i,t}-I_{q,\tau,i,t}\geq d_{q,\tau,i,t}-YP_{q,\tau,i,t} \tag{5.47}$$

where $YP_{q,\tau,i,t}$ is previous production now designated as item 'q,i'. Also $I_{q,0,i,t}=I_{q,4,i,t-1}=0$. The inventory at the end of any bucket is then given by,

$$I_{q,\tau,i,t}=I_{q,\tau-1,i,t}+Y_{q,\tau,i,t}-d_{q,\tau,i,t}-e_{q,\tau,i,t}+YP_{q,\tau,i,t}-L_{q,\tau-1,i,t}+L_{q,\tau,i,t} \tag{5.48}$$

where $L_{q,0,i,t} = L_{q,4,i,t-1}$. Note that constraint 5.48 only defines item designated inventory. The assignment of previous production, f.YP sub q, sub tau sub ,i,t, is constrained by the entering inventory. That is,

$$\sum_{\tau}\sum_{q} YP_{q,\tau,i,t} \leq IC_{i,t-1} \tag{5.49}$$

where

$$IC_{i,t} = IC_{i,t-1} + \sum_{\tau} YG_{\tau i,t} - \sum_{\tau}\sum_{q} YP_{q,\tau,i,t} \tag{5.50}$$

The next set of constraints ensures that production occurs in economic quantities. The EPQ model defines a minimum batch size for economic production. Production quantities need to be adjusted from bucket to bucket to ensure that all group batches are of EPQ size at least. Letting $\rho_{\tau,i,t}$ indicate whether a group batch is produced or not, then the constraint is:

$$YG_{\tau,i,t} + \sum_{q} Y_{q,\tau,i,t} \geq \rho_{\tau,i,t} EPQ_{i} \tag{5.51}$$

Further, $\rho_{\tau,i,t}$ is such that it constrains YG and Y to zero when there is no production. This gives the constraint:

$$YG_{\tau,i,t} + \sum_{q} Y_{q,\tau,i,t} \leq \Pi \rho_{\tau,i,t} \tag{5.52}$$

The third constraint set concerns capacity. Capacity as a resource was modeled in the MA-Schedule, and is not modeled in the CP1-Schedule. Rather, to minimize the possibility of infeasibility, the scheduled production is balanced over the buckets within a period. Clearly, perfect balance will not always be possible. The imbalance is defined as $\Delta P_{\tau,k,t}$ and $\Delta N_{\tau,k,t}$, and the constraint is:

$$\sum_{i} P_{i,g,k}(YG_{\tau,i,t} + \sum_{q} Y_{q,\tau,i,t}) + \Delta P_{\tau,k,t} - \Delta N_{\tau,k,t} = \left[\frac{(W_{k,t} + O_{k,t})}{4} \right] \tag{5.53}$$

where g is such that $y_{i,g,t} = 1$

The final constraint set models variation about $X_{i,t}$. The sum of the bucket production quantities from a period may not match $X_{i,t}$. This occurs due to the minimum batch size constraint, but there is no limitation on maximum batch size. In any case, there is a difference in actual and prescribed $X_{i,t}$, which is given by:

$$\sum_{\tau}(YG_{\tau,i,t} + \sum_{q} Y_{q,\tau,i,t}) - \delta_{i,t} = X_{i,t} - IC_{i,t-1} + I_{i,t-1} + LC_{i,t-1} - L_{i,t-1} \tag{5.54}$$

The $X_{i,t}$ value is adjusted on the RHS for variation which has occurred in an earlier period. Such variance has already been accounted for in the objective function.

The constraints 5.47, 5.48, 5.49, 5.51, 5.52, 5.53, and 5.54 together constitute the set of constraints for the CP1-Schedule. This completes the CP1-Schedule formulation. The final model is displayed in Table 5.2. In Section 6.5, the solution procedure for this model is developed.

5.7. SOLUTION METHODOLOGIES FOR THE CP2-SCHEDULE

In Figure 5.1, the three levels of modeling being formulated in this chapter were illustrated. Formulations for the upper two levels have now been developed. The third level disaggregates the decision of these higher levels to the final level to provide shop floor level directions. The primary decisions of the CP2-Schedule are $S^{k}_{q,\tau,i,t}$ and $F^{k}_{q,\tau,i,t}$, the start and finish times of a production batch at each cell in its route. A solution model for this module is not developed here; however a discussion of existing models which can be integrated into the CIPP&C plan is relevant. The problem of determining the CP2-Schedule decisions is equivalent to the traditional flowshop

Table 5.3. Final Formulation of the CP1-Schedule

OBJECTIVE TERM	MATHEMATICAL FORM
Inventory Cost	$\sum_i \sum_t \{ (\beta_i YG_{\tau,i,t}(4-\tau)) + \sum_q(\alpha_{q,i} L_{q,\tau,i,t} + \beta_{q,i} I_{q,\tau,i,t}) \}$
Quantity Variation Penalty	$\sum_i \sum_t QD_i \, \delta_{i,t}$
Processing Variation Penalty	$\sum_k \sum_t QV_k \, (\Delta P_{k,t} + \Delta N_{k,t})$

#	CONSTRAINT NAME	MATHEMATICAL FORM	NUMBER of / Period
1	A.q.τ.i.t	$Y_{q,\tau,i,t} + I_{q,\tau-1,i,t} - I_{q,\tau,i,t} + YP_{q,\tau,i,t} \geq d_{q,\tau,i,t}$	$4(\Sigma G)$
2	B.q.τ.i.t	$Y_{q,\tau,i,t} + I_{q,\tau-1,i,t} - I_{q,\tau,i,t} - L_{q,\tau-1,i,t} + L_{q,\tau,i,t} + YP_{q,\tau,i,t} \geq d_{q,\tau,i,t} + e_{q,\tau,i,t}$	$4(\Sigma G)$
3	CUMI.i.t	$\sum_q \sum_\tau YP_{q,\tau,i,t} \leq IC_{i,t-1}$	N
4	EPQ.τ.i.t	$YG_{\tau,i,t} + \sum_q Y_{q,\tau,i,t} \geq \rho_{\tau,i,t} EPQ_i$	4N
5.	DIF.i.t	$\sum_\tau (YG_{\tau,i,t} + \sum_q Y_{q,\tau,i,t}) - \delta_{i,t} = X_{i,t} - IC_{i,t-1} + I_{i,t-1} + LC_{i,t-1} - L_{i,t-1}$	N
6.	DELP.τ.k.t	$\sum_i P_{i,g,k}(YG_{\tau,i,t} + \sum_q Y_{q,\tau,i,t}) + \Delta P_{\tau,k,t} - \Delta N_{\tau,k,t} = (W_{k,t} + O_{k,t})/4$	4M
7.	BAT.τ.i.t	$YG_{\tau,i,t} + \sum_q Y_{q,\tau,i,t} \leq \rho_{\tau,i,t} \Pi$	4N

problem. There are several approaches for solving the flowshop problem and, it is proposed that one of these be incorporated in the CP2-Schedule methodology. A brief review of the flowshop problem follows in order to identify the available techniques. Further, there are several objectives for which the flowshop problem can be solved. The objective of focus here is the minimization of makespan. The reason for this objective is explained in the next section.

5.7.1. Schedule Interferences in the MA-Schedule

Most approaches to aggregate and master scheduling are modeled such that it is assumed that all the assigned resource is consumed in the same period of production. This assumption will often lead to an infeasible schedule, even though the schedule is capacity constrained. The reasons for this are:

1. Sequence constraints will cause jobs to attempt to simultaneously access the same resource, resulting in queue time and lengthening the production lead time.
2. With decreasing scheduling scope, the production lead time is going to be longer than the length of the period τ.

The implications of these two reasons is that the production Gantt chart for two adjacent time buckets would be as shown in Figure 5.5a. While most approaches assume schedule A°, the actual schedule is given by A. Notice that A does not violate the capacity constraint, since its width is the same as A°. Figure 5.5b depicts the schedules for three successive buckets. Should schedules A,B, and C all be inclined at the same angle, then there would be no interference. This is usually not the case and schedule B interferes with schedule A. The probability of this interference is minimized if the makespan for the individual buckets is minimized. Notice that the smaller the makespan, the closer schedule A comes to becoming A°. Therefore, the

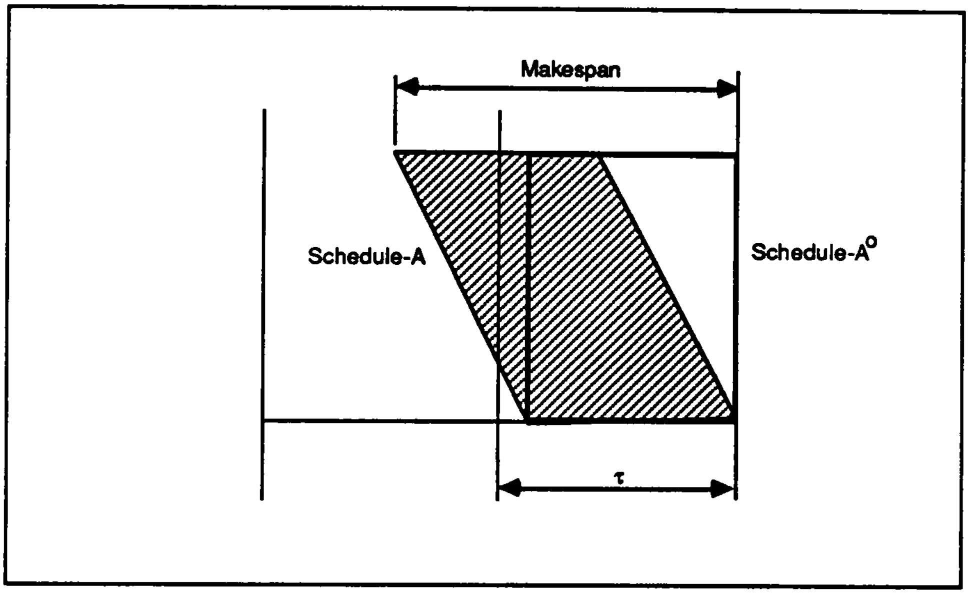

Figure 5.5A. Gantt Charts Showing Inclination of Actual Schedule

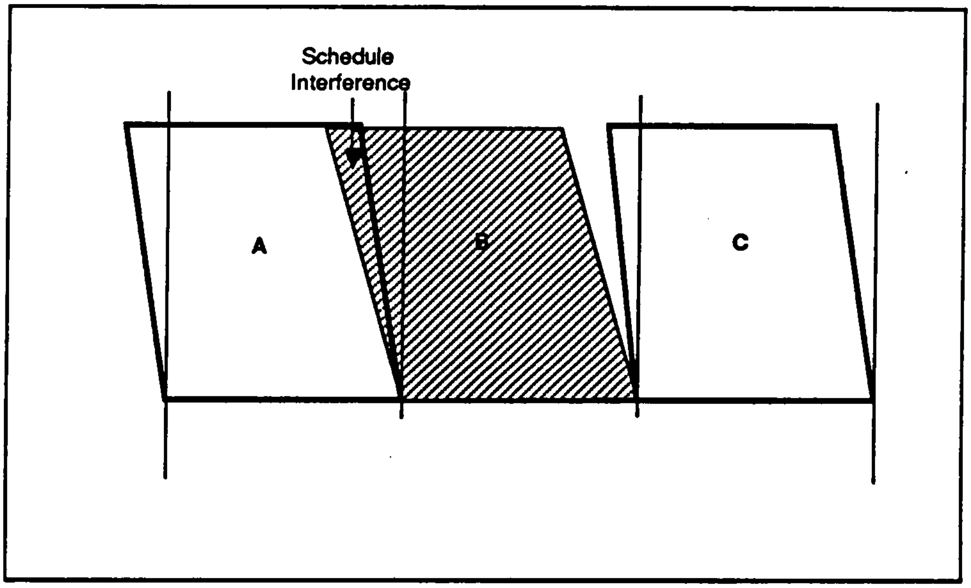

Figure 5.5B. Gantt Charts Showing Schedule Interferences Between Adjacent Periods

objective function of the CP2-Schedule is to minimize makespan within each bucket 'τ'.

5.7.2. Review of the Flow Shop Problem

The minimum makespan flow shop problem is a classical area of research in production scheduling. A detailed description of the problem and its characteristics is provided by Baker (1974). A wide variety of methodologies have been proposed for solving this problem; an excellent review and listing of these methodologies is provided by McHale (1983). The flow shop problem is NP-complete for three or more machines, and the only constructive algorithm is due to Johnson (1954) for the two machine problem. The bulk of the other methodologies are either branch-and-bound based or heuristics. Several of these are known to provide very good solutions for medium size problems.

This research is interested in a special class of the flow shop problem termed the "group scheduling" problem. While the general flow shop problem considers the scheduling of N jobs on M machines/cells, the group scheduling problem is concerned with the scheduling of N groups, each of which is made up of G jobs, through M cells. The group scheduling problem is relatively difficult to solve and most of the available approaches are restricted to assuming a special structure sequence. That is, the processing of jobs and groups is the same through each cell. Clearly, this assumption will detract from the performance of a CIM facility's desired characteristics, but pending the availability of flow shop algorithms which are more flexible, this assumption has to be in effect.

Ham, et al. (1985) and Hitomi (1979) describe the available group scheduling techniques in detail. The technique which is best suited for the CIPP&C plan was developed by Taylor and Ham (1981). This approach uses a heuristic algorithm based on Petrov's algorithm (Hitomi, 1979). Initial investigations indicate this approach can be integrated with the MA-Schedule and CP1-Schedule. Other methods using artificial intelligence approaches (Sarin and Salgame, 1989) have recently been developed. These, and other methods, are potential candidates for the CP2-Schedule. The ability to integrate these methods into the plan exhibits the desired CIPP&C characteristics of modularity and flexibility.

5.8. ANALYTICAL SUMMARY

In this chapter two MIP formulations were developed, one for the MA-Schedule module, and one for the CP1-Schedule module. As observed earlier, existing formulations closest to the MA-Schedule are those by Bowman (1956), the upper layers of the Hax and Meal (1975) heirarchy, Gonzalez and Reeves (1983), and Chung and Krajweski (1987). All of these considered the demand-supply constraints while some also considered the capacity constraints, in their formulations. The MA-Scheduler goes beyond this and includes transportation resource in the formulation. This is represented by constraints TRC and TRAP. In order to model CIM facilities several other enhancements were included. The earlier works considered all demand to be of the same priority. The MA-Scheduler has a two-level order prioritization. One subject to tardiness ($E_{i,t}$) and the other not ($F_{i,t}$). This resulted in the modeling of negative inventory (;f.L sub i,t). Further, in addition to the inventory balance constraint (INV), two more constraints, PIV and NINV, were necessary. The MA-Scheduler is also a candidate for CRP methods. Most CRP methods use "what if analyses" or "alterations planning" to adjust for overloading (Vollmann, et al., 1984). These methods are cumbersome, and an exact method such as the MA-scheduler could be very effective for CRP in CIMS.

The majority of FMS scheduling methods are focussed at the machine or cell level. In Section 3.4.2.4 several prescriptive models and frameworks were reviewed. The framework closest to the CIPP&C heirarchy is that by Morton and Smunt (1986). The MA-Scheduler would fit very well into their "strategic planning" layer. This is the FMS decision layer interfacing with CIMS. As of now there are no strong algorithms in this layer which could be applicable to both FMS and CIMS. The MA-Scheduler appears to be the first to fit in this role.

The solution of non-linear MIPs is expected to be a common solution method in the mathematical modeling of CIMS and FMS. Stecke (1983) was one of the first to model and solve MIPs in FMS for loading problems. The linearization methods used here were influenced by her work. This linearization and solution of LS-MIPs demonstrates their feasible application in CIMS modeling. The two flexibilities modeled here are capacity and routing. In typical FMS models routing flexibility is achieved by the allocation of parts to cells, since most cells can produce most parts. For a general manufacturing environment, specific routes are pre specified, and the MA-Schedule provides an effective means for route slection for this scenario. Further, capacity flexibility is decided simultaneously in the same model. The flexibilities introduce constraints TIM, REQ, FXC, FXR, SRT, and DWN in the formulation.

Earlier in Section 5.1 and Figure 5.2 the projected extensions to the hierarchical scheduling methodology, by the MA and CP1-Schedules were noted. These extensions have been made in the formulations. The CP1-Schedule is one of the first second level HPP models to consider batch size. Chung and Krajweski (1987) used LP methods in the second level models to consider setup costs and capacity overload. The CP1-Schedule does not consider setup costs, but will account for overload. The use of Y, YP, and YG variables is a new feature. This enables the piecewise solution of the disaggregated model, resulting in faster solution times.

Two weaknesses of the model stem from the modeling of expected quality and transportation resource. It is assumed there is a linear relationship between lost quality and capacity utilization. In reality this relationship may be curvilinear, further, quality is dependent on other factors in addition to capacity utilization. Four instance, product routings, inventory life, start times, etc. are possible factors. It is expected the linearity assumption will not have large impacts on the decision policies, but future research should focus on the derivation of a more consolidated quality expression in the objective.

In the developed models, transportation resource is measured in continuous units which are a combination of time and capacity. This may be difficult to implement in practice. Transporters typically are counted in discrete units representing vehicles. The current model will split assign these vehicles to different cells. At times this may work, but there is a possibility of infeasibility.

Another minor weakness stems from the modeling of production quantities as continuous variables. Modeling $X_{i,t}$ as an integer variable would greatly increase the solution time. Since the schedulers are intended for mid to large volume production, the loss due to rounding off will be low and the approach adopted acceptable. Future research should investigate the round off loss. Overall the formulations have met the CIPP&C design objectives, and are an improvement on existing methods.

CHAPTER SIX

SOLUTION METHODS FOR THE MA-SCHEDULE AND CP1-SCHEDULE

6.1. SOLVING MIXED INTEGER PROGRAMS

In the previous chapter, the mathematical formulations for the MA-Schedule and CP1-Schedule were developed. In this chapter, solution procedures are developed for the two schedules. Both the MA-Schedule and CP1-Schedule solution methods involve a Mixed Integer Programming (MIP) approach. Earlier, in Section 5.1.2, the basic features of MIPs were reviewed. Four general methods of MIP solution were identified. These methods are known to be effective in the solution of small size problems, but no technically strong algorithms are as yet available for the solution of Large Scale MIPs (LS-MIPs). In the past, it was assumed that LS-MIPs were not amenable to solution by exact methods. The two primary reasons for this assumption were the excessively large memory requirements and, the lengthy CPU processing time. Recently, there have been significant developments in commercial codes for MIPs as a result of considerable direct research in the LS-MIP area. These developments are making it possible to solve several real world problems and this has new research implications for the production control discipline.

Crowder, et al (1983) and Johnson, et al (1986) have extensively researched the solution of large scale 0-1 MIPs. Their research concluded "that a combination of problem preprocessing, cutting planes, and clever branch-and-bound techniques" permit the solution of LS-MIPs in reasonable computation times. Their work prescribes several steps to take in the solution of LS-MIPs. Their research, along with those by Brearly, et al (1975), Spielberg (1979), and Van Roy and Wolsey (1987), were used as the basis for developing the solution methods in this chapter. In addition, the classical works by Garfinkel and Nemhauser (1972) and Geoffrion and Marsten (1972) were reviewed.

6.1.1. The MPS-III Mathematical System

Almost all solutions of LS-MIPs, discussed in the literature, involve the use of a commercial mathematical programming system. The majority of such systems have been refined over several years and incorporate state-of-the-art methods. Selecting the best system for a particular application is typically a judgmental decision since performance is difficult to estimate upfront. In most cases, availability is the deciding factor. There are primarily three commercial systems which dominate the large scale math programming market. These are APEX, MPSX, and MPS-III[1]. Of these, MPSX and MPS-III are more popular and considered better solvers. Both these systems were available at the Virginia Tech computing facility. After much deliberation, the MPS-III system was selected for the purposes of this research. The selection was based on reported computing superiority and the relatively better failure rate of MPS-III. Selection of MPS-III does not restrict the applicability of other developed methods. Any comparable commercial or noncommercial system could be used in lieu of MPS-III.

MPS-III is designed to run on IBM computer systems 360 and 370; all the programming in this research was done on such systems. The modules of MPS-III used were:

WHIZARD	In-Core Optimizer - Solves LP models entirely within main or virtual memory storage
MISTIC	Mixed Integer Optimizer - A branch and bound procedure for solving MIPs

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[1] APEX is a product of Control Data Corporation, MPSX is a product of IBM Corporation, and MPS-III is a product of Management Sciences Corporation.

WHIZARD has performed very well on problems similar in size to the MA-Schedule. For instance, a 1084x1129 (rows x columns) problem was solved in about 9.9 seconds, and a 4426x10918 problem in about 27.5 seconds[2] (MPS Manual,1984). Data is input into the system in the form of a rows and column matrix. WHIZARD then generates the simplex iterations to continuous optimality. For a MIP solution, MISTIC combines with WHIZARD to execute a branch-and-bound search process.

6.1.2. Branch and Bound in MIP solution

Branch and bound (B-B) is a time tested method of solution for MIPs. A general description of the methodology can be found in any integer programming text. The basic method may be augmented by the addition of decompositions, cutting planes, node selection strategies, etc.. MISTIC begins B-B by determining the relaxed optimal solution. Then, based on a predefined search strategy, nodes are selected for branching and integer variables selected for bounding. One of the most important elements in a B-B method is the node selection criteria. In MISTIC, this is done on the basis of the best projection criteria. To better understand this, some key MPS-III terminology is introduced.

BOUND	The predefined upper bound on the all integer solution
PROJFAC	Projection factor, the amount by which the continuous solution is degraded for each unit of integer infeasibility
COPT	Continuous (relaxed) optimal solution
NCOST	Continuous optimal solution at an intermediate node
BINT	Best available integer solution
INFE	Integer infeasibility of a node

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[2] The comparable times for MPSX are 35.4 seconds and 109.9 seconds.

For each active node in the tree, a projection factor and projected cost are computed from the above terms, as follows:

$$PROJFAC = \frac{BOUND - COPT}{INFE_{atCOPT}} \quad \text{or} \quad \frac{BINT - COPT}{INFE_{atCOPT}} \tag{6.1}$$

$$\text{Projected Cost} = \text{NCOST} + (\text{PROJFAC} * \text{INFE}) \tag{6.2}$$

The first expression for PROJFAC, is used until the first integer solution is found. The node with the lowest projected cost is selected for branching, and the integer variable with the largest infeasibility is chosen for bounding. The process continues until the tree is exhausted or the user-specified number of nodes have been generated.

Whereas branching in MISTIC is done on the basis of projected cost, fathoming of nodes is only done on the basis of actual cost. That is, a node is fathomed only if $NCOST \geq BINT$. This summarizes the basic operations of MISTIC. Several additional features are available which the user may control and accordingly adjust the search strategy. Some of these features have been incorporated here and discussed are later.

6.2. PREPROCESSING THE MA-SCHEDULE FORMULATION

Preprocessing of MIPs is very effective in reducing computation time. Brearly, et al (1975), and Crowder, et al (1983), recommend six preprocessing strategies: constraint classification into special ordered sets, variable presetting, blatant infeasibility check, coefficient reduction, constraint reduction, and upper bounding. Of these at least three are implemented in the MA-Schedule solution strategy.

The variable $y_{i,r,t}$ is the only candidate for a Special Ordered Set (SOS). Attempts to model $y_{i,r,t}$ as an SOS were not successful. This is because the introduction of a

$y_{i,r,t}$ SOS requires removal of the constraint DUM (for references to constraints see Table 5.2). In a comparative test between the two options, constraint DUM performed better than the SOS. Explorations with coefficient reduction and constraint reduction did not reveal any effective methods and were not considered further. Possibly, later investigations may be able to exploit these strategies. Also, MISTIC automatically removes redundant constraints.[3]

6.2.1. Presetting Flexibility Variables

The preprocessing strategy having the greatest impact on the solution of MIPs is the presetting of integer variables, since this strategy can significantly decrease the size of the search tree. Of the two MA-Schedule integer variables, presetting of only $Z_{k,t}$ is attempted here. The variable $y_{i,r,t}$ behaves rather well after introduction of the constraint DUM and it was felt presetting was not necessary. On the other hand, presetting the variable $Z_{k,t}$ greatly improves solution time.

$Z_{k,t}$ appears in constraints FXC, SRT, and DWN. It also appears in the objective function with a positive coefficient. The program therefore attempts to minimize the

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[3] In the context of preprocessing strategies, a discussion of special structures is appropriate. Special structures are defined as the distinctive pattern in which non-zero coefficients appear in the constraint matrix (Hillier and Liebermann, 1974). Customized versions of the simplex method are able to exploit these special structures resulting in faster solutions. The most common type of special structure is the transportation problem. While special structures are easily identifiable and exploitable in small-medium size LPs, this is not the case with LS-MIPs. In Crowder, et al's (1983) study of ten real world problems, they were unable to identify any apparent special structure in half the problems and for the remainder, were unable to exploit the identified structure. This is not to imply that special structures are not useful, but rather indicates their rarity in large-scale problems. Special structure identification is beyond the scope of this research, but it is hoped future activity will address this issue, in the context of the developed models.

value of $Z_{k,t}$. Now, $Z_{k,t}$ indicates whether a cell is active or not. Further, cell activity is dependent on the work load assigned to the facility. Given a particular loading, it is thus possible to estimate whether a $Z_{k,t}$ variable should have the value '1'. Based on this fact, two rules were developed for presetting $Z_{k,t}$.

Rule #1: Fixing $Z_{k,t}$ Based on Loading

At the end of any period 't', it is possible to estimate the workload that passed through a cell 'k'. From this estimation, a loading is calculated. Let the variable $PROCS_{i,k}$ be defined as the minimum time product 'i' will spend in cell 'k' irrespective of routing. That is,

$$PROCS_{i,k} = \min P_{i,r,k} \tag{6.3}$$

Since $PROCS_{i,k}$ is used in all loading calculations, the uncertainty of flexible routing is removed. On the other hand, it also reduces the effectiveness of the developed rules since $\sum_k PROCS_{i,k} \le \sum_k P_{i,r,k}$ for all r. Now, five different sets of loadings are calculated for each MA-Schedule. These are:

$$LOAD1_{i,k,t} = PROCS_{i,k} F_{i,t} / C_k \tag{6.4}$$

$$LOAD2_{k,t} = \sum_i LOAD1_{i,k,t} \tag{6.5}$$

$$LOAD3_{k,t} = \sum_{ti=1}^{t} LOAD2_{k,ti} \tag{6.6}$$

$$LOAD4_k = \sum_i \sum_t PROCS_{i,k} E_{i,t} / C_k \tag{6.7}$$

$$LOAD5_k = LOAD3_{k,T} + LOAD4_k \tag{6.8}$$

Where LOAD1 is the capacity required to produce $F_{i,t}$ in period 't'; LOAD2 is the capacity required to produce $\sum_i F_{i,t}$ in period 't'; LOAD3 is the capacity required to produce $\sum_{t=1}^{tt}\sum_{i} F_{i,t}$; LOAD4 is the total capacity required to produce the expected demand; LOAD5 is the total capacity required to produce the scheduled demand (firm + expected). Based on these five loadings, four separate rules for presetting $Z_{k,t}$ were developed. These rules are:

Rule #1A: If $LOAD1_{i,k,t} \geq 0.60$, then set $Z_{k,t} = 1$

Rule #1B: If $LOAD2_{k,t} \geq 0.75$, then set $Z_{k,t} = 1$

Rule #1C: If $LOAD3_{k,tt} \geq tt - 1$, then set $Z_{k,t} = 1$ for $t \leq tt$

Rule #1D: If $LOAD5_{k} \geq T - 1$, then set $Z_{k,t} = 1$ for $t \leq T$

If the period demand for a product requires at least 60% of that periods capacity then Rule #1A sets the cell to active, while Rule #1B sets the cell to active if at least 75% capacity is required across all products. The rational is that, if loading is high in period 't', it will be relatively high in periods immediately preceding 't'. This would make it difficult to schedule all current demand in earlier periods. Note that Rules #1A and #1B are stochastic rules, since they are based on expectation, while Rules #1C and #1D are deterministic. If Rules #1A or #1B set $Z_{k,t} = 1$, then any schedule with $Z_{k,t} = 0$ is infeasible. Clearly, the reliability of Rules #1A and #1B is dependent on the percentages. The values, 60% and 70% were selected after experimentation and our knowledge in scheduling, but they are easily modified. In many settings, the scheduler is able to use his "expert" knowledge to create a schedule. Given a particular application, expert system rules could be used to capture this knowledge and integrated in Rules #1A and #1B percentages.

While rules #1A and #1B are based on period loading, rules #1C and #1D are based on cumulative loading. If, at the end of period 't', the total capacity required is at least $(t-1)C_k$, then the cell would have to be active continuously. Rule #1D is similar to rule #1C, but includes expected demand and is applicable on the last period. Figure 6.1 shows a sample loading graph for a cell. In this case, $LOAD3_{k,6} \geq 5$ hence rule #1C would set $Z_{k,t \leq 6} = 1$, but rule #1D would not be activated since $LOAD5_k \leq 7$. Thus, $Z_{k,7}$ and $Z_{k,8}$ enter the B-B as variables.

Rule #1 also does a blatant infeasibility check on the problem. Infeasibility occurs whenever one of the following two situations arises:

$$LOAD3_{k,tt} \geq tt \tag{6.9}$$

$$LOAD5_k \geq T \tag{6.10}$$

When this happens, problem solution ceases. Since this implies overloading of the cell. Appropriate adjustments can then be made to the overloaded cell.

Rule #2: Fixing $Z_{k,t}$ Based on Routing

Since it is assumed a product group may be produced by one of several routes, it is possible a cell is bypassed by all production in a given period. The probability that a product will bypass a cell is determined by its routing matrix. For instance, if all product 'i' routes visit cell 'k', then cell 'k' will certainly be active if 'i' is produced. Let the variable $SEE_{i,r,k}$ be defined as:

$$SEE_{i,r,k} = 1 \text{ if } P_{i,r,k} \geq 0$$

$$SEE_{i,r,k} = 0 \text{ otherwise}$$

Let it be assumed that at least one product is produced in a period. Note that, if no product is produced, it implies the entire facility was shut down for that period. Such an event is not improbable but highly unlikely. Now, if at least one product is

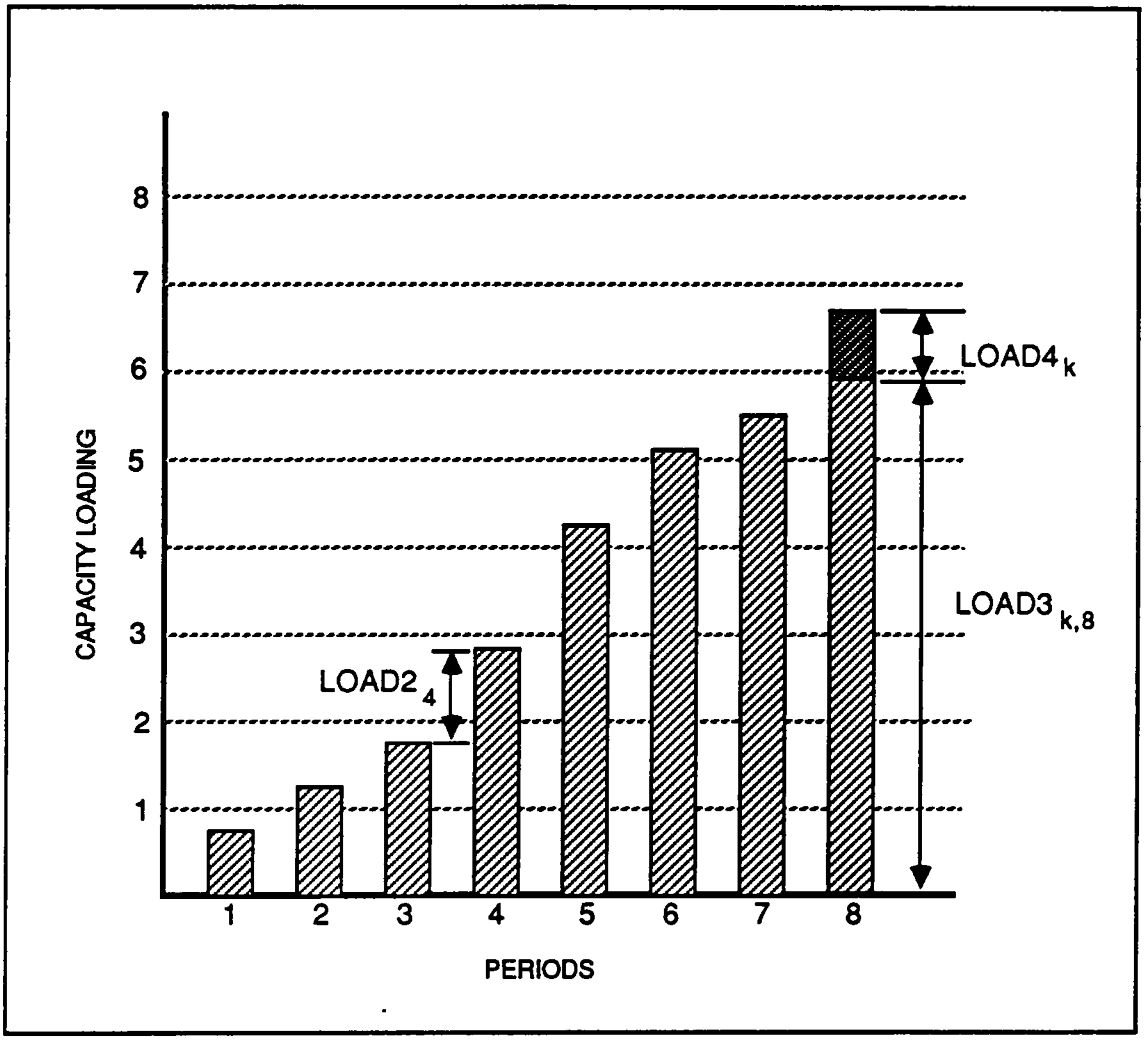

Figure 6.1. Cumulative Loading on a Cell

produced, then the probability that cell 'k' is visited is determined by the number of routes passing through it. That is,

$$\text{Probability cell 'k' is visited} = \frac{\sum_i \sum_r SEE_{i,r,k}}{RxN} \tag{6.11}$$

This probability is also the probability cell 'k' is active, if there is any production. An indication of when there will be no production is got from the period loading, as given by $LOAD2_{k,t}$. If LOAD2 is very low, then there may be no production. Based on this fact, the following rule was developed:

Rule #2: If $\left[\frac{\sum_i \sum_r SEE_{i,r,k}}{RxN}\right] \geq 0.80$ and $LOAD2_{k,t} \geq 0.30$, then set $Z_{k,t} = 1$

This implies that if 80% of the routes visit cell 'k' and the period loading for the cell is at least 30%, the cell is activated. Rule #2 is a stochastic rule and the percentages can be adjusted on the basis of expert knowledge. This concludes the development of preprocessing rules. All the rules performed well. The later experiments showed rules #1C and #2 to be most oftenly activated. Tests with three of the experiments showed a 20-45% reduction in solution time to the best integer solution, as a result of the rules.

6.2.2. Pruning the Search Tree

Upper bounding a B-B search will decrease unproductive branching in many cases, since nodes with $NCOST \geq BOUND$ will be fathomed. MISTIC allows the user to prescribe a bound in the source program. The user may opt to set BOUND as a percentage of COPT or as a constant. One of the rules developed by Crowder, et al (1983), was to set $BOUND = GAP \times COPT$, where GAP is a parameter greater than 1.1.

They would then rerun the problem increasing GAP in increments of 0.1 until an optimal solution was found. Following experimentation and analysis of this rule, it was felt it would not be beneficial to the MA-Schedule procedure. This is because the MA-Schedule solution varies greatly with loading and cost structure and in a low loading problem could be as much as 50% away from the COPT.

Setting BOUND to the best available integer solution is another approach. This was the approach adopted. From the continuous optimal solution, all nonzero $Z_{k,t}$ variables were bounded at '1'. This does not violate any of the constraints. The objective function was recalculated and this was set as the BOUND value. The adjusted solution is not necessarily integer, since there will be some residual infeasibility from the $y_{i,r,t}$ variables. But this infeasibility, typically is low in the COPT solution, and is ignored. Later experiments showed a 0-15% reduction in solution time to the best integer solution, as a result of bounding.

6.3. SOLUTION PROCEDURE FOR THE MA-SCHEDULE

The solution procedure for the MA-Schedule combines the formulation, preprocessors, and search strategy. The search strategy specified to the MPS-III program can be described as follows:

1. For the 50 most recently created active nodes, compute the projected cost. PROJFAC is determined via equation 6.1, but if $PROJFAC \leq 0.08$, set PROJFAC = 0.08.
2. Select the node with the lowest projected cost for bounding and select the variable, at that node, with the highest integer infeasibility for bounding.
3. Create two new nodes, one with the selected variable bounded at '0', and the other with it bounded at '1'. Solve for the relaxed solution at the two nodes.
4. Fathom any node with $NCOST \geq BOUND$.
5. Continue steps 1-4 till first integer solution is found. Then recalculate PROJFAC using Equation 6.1.
6. Fathom all nodes with $NCOST \geq BINT$.

7. Compute projected cost for all active nodes and repeat steps 2 and 3. Repeat steps 6 and 7 till search is exhausted (or aborted).

Initially limiting the search to the most recent 50 active nodes, and restricting PROJFAC, ensures a quick generation of the first integer solution. Once that is determined, tree wide search is resumed and PROJFAC recalculated from BINT.

Computer programming of the solution procedures along with the preprocessors was done in FORTRAN[4]. The entire solution system (including CP1-Scheduler and test routines) consists of ten programs. The programs are designed to run in a VM/XA operating system but can be adapted for most other environments. Figure 6.2 shows the network of programs developed. Linking of the programs was done manually within the VM environment, though automatic linkage is possible. IBM's REXX execution language has been used for such linkage in the past.

The four programs constituting the MA-Schedule solver are MSCHED, GUB, MIPROG, and RESULT-1. The MSCHED program has two functions, preprocessing the application problem and converting data into the formulation matrix to be input to MPS-III. MSCHED and CSCHED are the only programs requiring data input directly from the user. All other programs use transfer data. MSCHED executes preprocessing rules #1 and #2. Then, it generates the equivalent matrix consisting of rows and variables as listed in Table 5.2. The matrix is then transferred to MIPROG. MIPROG is the interface program between the MA-Scheduler and MPS-III. MIPROG is first executed with no BOUND to find COPT. The COPT solution is transferred to GUB which bounds all nonzero $Z_{k,t}$ at '1' and computes the problem BOUND. BOUND and the appropriate PROJFAC are transferred to MIPROG. The search is then started by MIPROG and continues for a prespecified number of nodes. Once the search is concluded, the

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[4] All programs were executed on an IBM 3090 processor complex using the WATFIV compiler

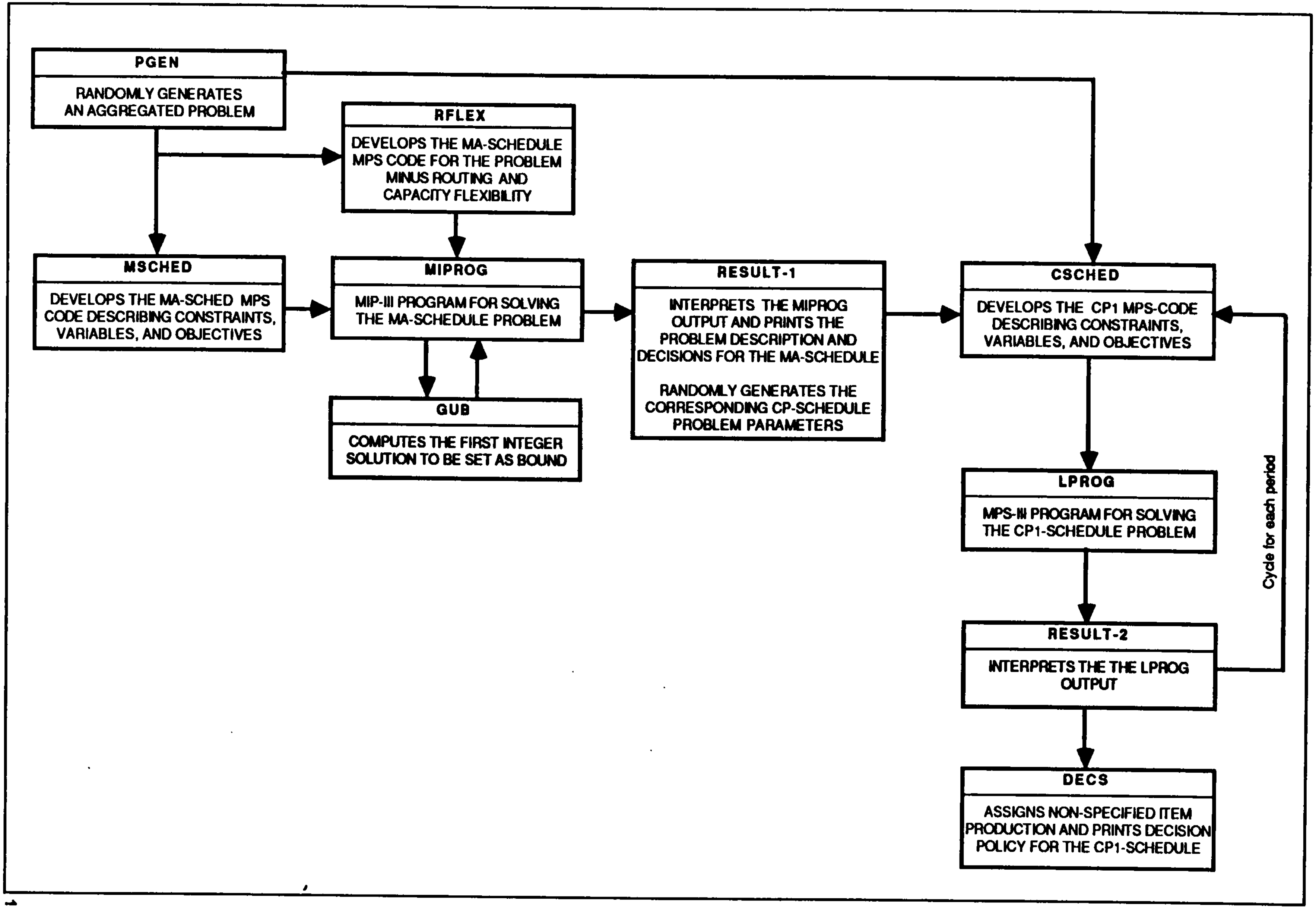

Figure 6.2. Network of Computer Programs Used to Execute the MA-Schedule and CP1-Schedule

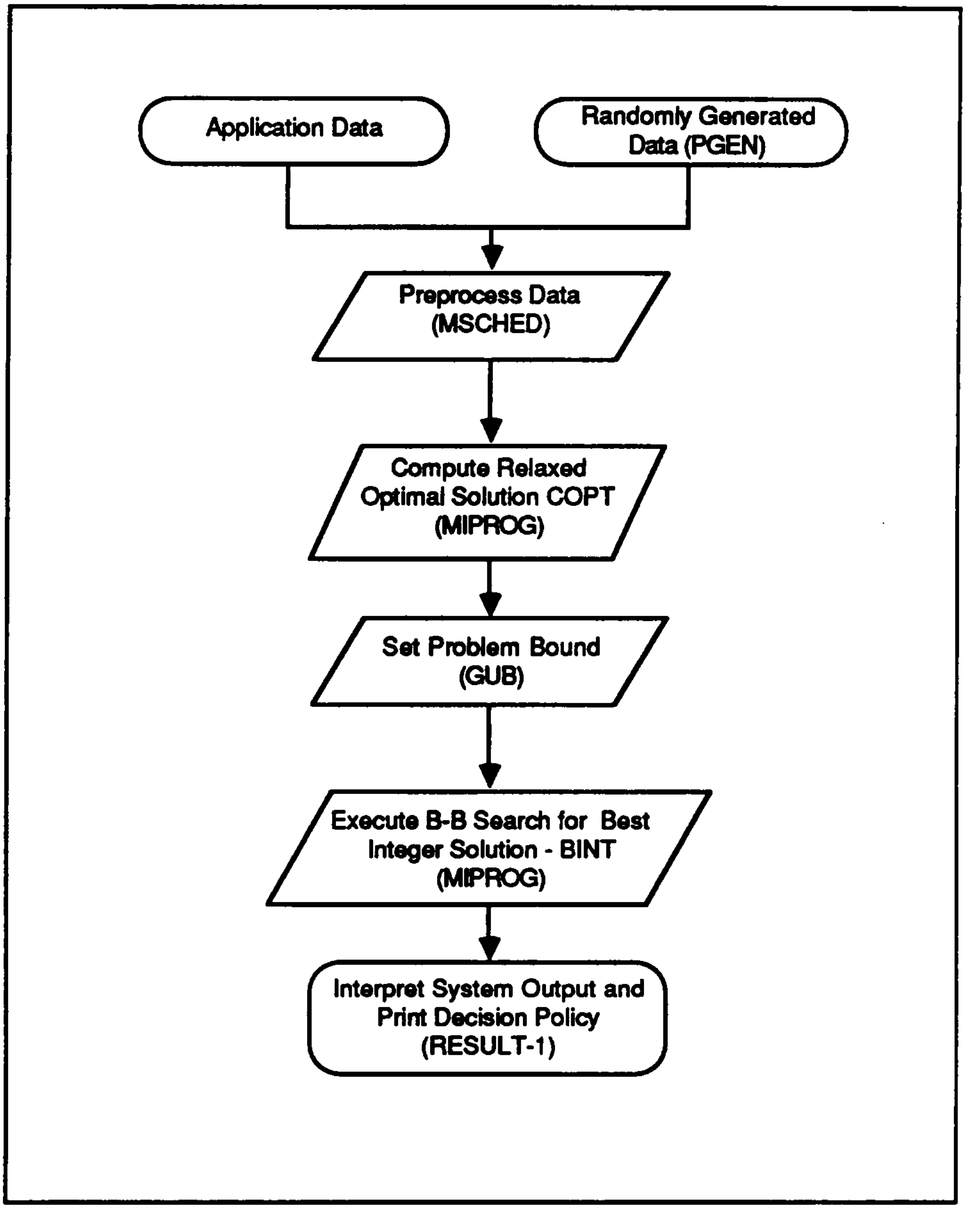

Figure 6.3. Flowchart of the MA-Schedule Solution Procedure

BINT solution is transferred to RESULT -1. Output from an MPS-III program is typically very lengthy and not easily deciphered. The RESULT-1 program is designed to interpret this output and reformat into a more user friendly style. RESULT-1 also computes the breakdown of the objective function. The MA-Schedule decision policy along with schedule performance are then printed out. Example output from RESULT-1 is shown in Appendix B. RESULT-1 also prints out the input data for transfer to CSCHED. This is the data linking the MA-Schedule and CP1-Schedule. The MA-Schedule solution procedure is flowcharted in Figure 6.3.

6.4. SOLUTION PROCEDURE FOR THE CP1-SCHEDULE

Solution of the CP1-Schedule is relatively simpler than the MA-Schedule. Though it also involves a B-B search, no preprocessing algorithms were developed for it. The only integer variable in the CP1-Schedule formulation is $\rho_{\tau,i,t}$. Therefore, for each period run there are 4N integer variables. The variable $\rho_{\tau,i,t}$ appears in the objective function with a negative coefficient, and is constrained by EPQ and BAT. Thus in any bucket in which $YG_{\tau,i,t} + \sum\sum Y_{q,\tau,i,t} \geq EPQ_i$, the variable $\rho_{\tau,i,t}$ takes the value '1'. Further, due to constraint BAT, $\rho_{\tau,i,t} = 0$, whenever $YG_{\tau,i,t} + \sum\sum Y_{q,\tau,i,t} = 0$. As a result, several $\rho_{\tau,i,t}$ have integer values in the relaxed solution. Sample runs indicated that typically 40-60% of $\rho_{\tau,i,t}$ are integer. Consequently, the search tree is relatively small. Additional reductions may be realized by preprocessing and should be explored in the future.

The CP1 solution system consists of four programs. Three of the programs, CSCHED, LPROG, and RESULT-2, are executed for each period, while the program DECS is executed only once. Production in any period of the schedule has two purposes: 1) to meet current period demand, and 2) to meet demand in successive periods. The MA-Schedule prescribes to each period the production quantity for

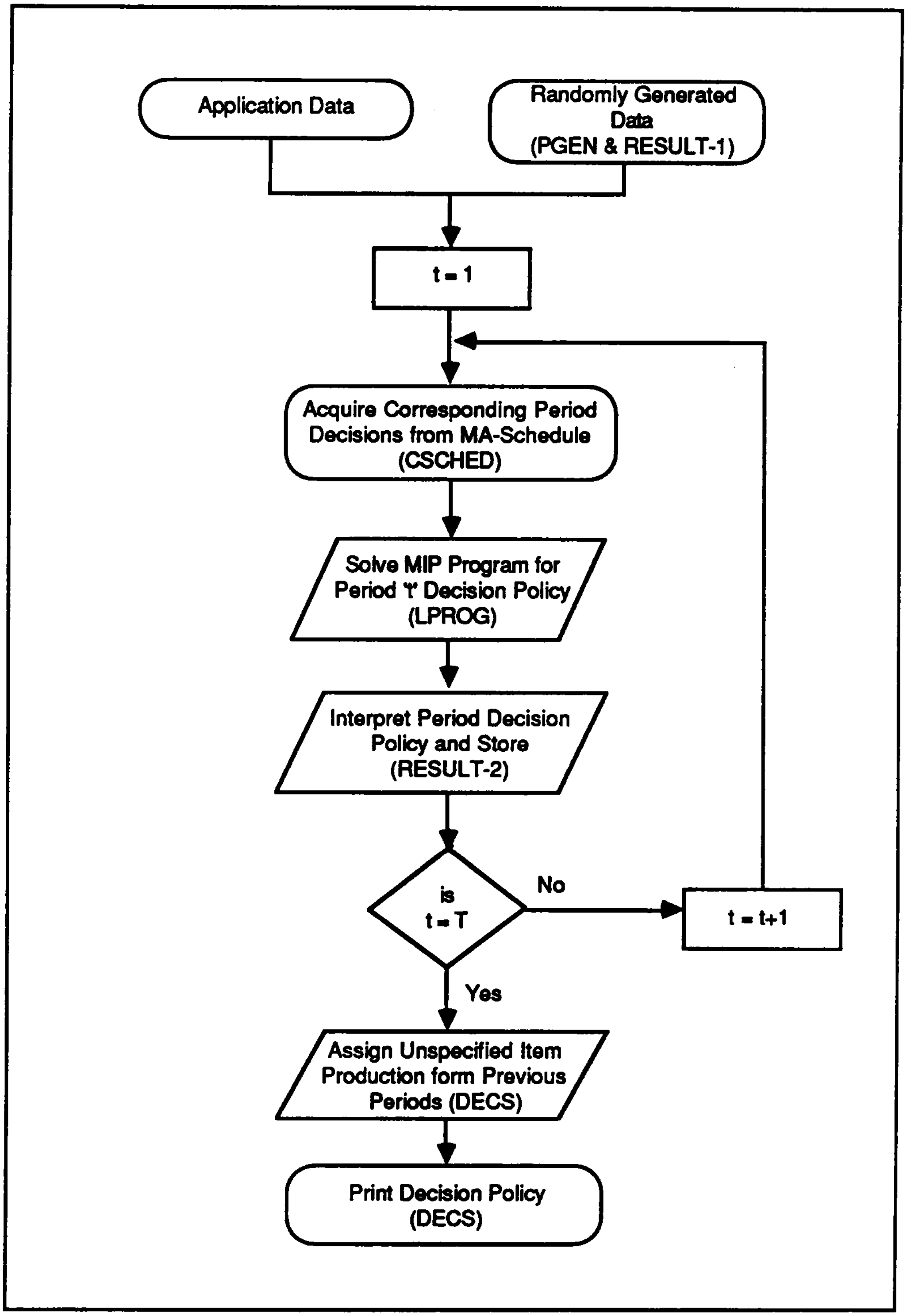

Figure 6.4. Flowchart of the CP1-Schedule Solution Procedure

successive period consumption, but this prescription does not contain an itemized breakdown of the group production. Hence, in each bucket there are two types of production: item assigned production labelled as $Y_{q,\tau,i,t}$, and unassigned production labelled as $YG_{\tau,i,t}$. Both of these variables were introduced in the Chapter five formulations. The variable $YG_{\tau,i,t}$ is transferred to $Y_{q,\tau,i,t}$ only when the CP1-Schedule for its period of consumption is determined. This transfer is flagged by the variable $YP_{q,\tau,i,t}$. That is, $YP_{q,\tau,i,t}$ indicates the quantity of previously produced $YG_{\tau,i,t}$ which is assigned item number 'q' for consumption in bucket τ,t. The transfer process is done by the DECS program.

For each period, three types of data are input to the CSCHED program. These are:

1. General problem parameters, and demand schedule for period 't'. The source is the user or program PGEN.
2. Prescribed production quantities, cell operation times, and processing routes for period 't'. The source is program RESULT-1.
3. Starting inventory levels. The source is RESULT-2 output at end of period 't-1'.

CSCHED then generates the formulation matrix for input to MPS-III via LPROG. The decisions are then interpreted by RESULT-2 and stored in DECS. At the end of all period runs, DECS executes the assignment process. The steps in the process are:

1. Identify the earliest non-zero $YP_{q,\tau,i,t}$
2. Identify the earliest non-zero $YG_{\tau,i,t}$
3. If $YG_{\tau,i,t} \geq YP_{q,\tau,i,t}$ then set:
   - $Y_{q,\tau,i,t} = Y_{q,\tau,i,t} + YP_{q,\tau,i,t}$
   - $YG_{\tau,i,t} = YG_{\tau,i,t} - YP_{q,\tau,i,t}$
   - $YP_{q,\tau,i,t} = 0$

Else if, $YP_{q,\tau,i,t} > YG_{\tau,i,t}$ then set:

- $Y_{q,\tau,i,t} = Y_{q,\tau,i,t} + YG_{\tau,i,t}$
- $YP_{q,\tau,i,t} = YP_{q,\tau,i,t} - YG_{\tau,i,t}$
- $YG_{\tau,i,t} = 0$

4. Repeat steps 1 to 3 , for each 'i', until there are no non-zero $YP_{q,\tau,i,t}$

Note that it is possible at the end to have some residual non-zero $YG_{\tau,i,t}$. This is due to the EPQ constraint. DECS also prints out the CP1-Schedule decision policy. The solution procedure is flowcharted in Figure 6.4. This completes the development of the solution procedures for the two schedules. In the next chapter, experiments with these procedures are reported.

6.5. ANALYTICAL SUMMARY

In this chapter MIP solution methods for the MA and CP1-Schedules were developed. It is difficult to comparatively analyze the solution methods with other methods, since the efficiency of solution methods is dependent on the formulation. The size of the formulations here, distinguish them from previous formulations. For instance, in Hax and Golovin's (1978) formulation there were 3 constraint sets, in Stecke (1983) and Berrada and Stecke (1985) there were 4-6 constraint sets after linearization, whereas here there are 15 constraint sets. Typically, large scale problems are more amenable to solution via descriptive methods such as queueing theory, petri nets, and simulation. Examples of such solution are reported by Buzacott and Yao (1986), and Stecke and Suri (1986). The approach used here, is one of the first to solve LS-MIPs in the FMS and CIMS environments.

The relatively smaller earlier models, were able to exploit ~~special~~ special structures and decomposition procedures in their solution. This is difficult to achieve in LS-MIP solution, as shown by Crowder, et al (1983). In contrast, LS-MIPs demand greater focus on preprocessing, search strategies, and the structure of the solution program. Most scheduling methods are not concerned with these. For example, Stecke (1983) did not discuss the MIP routine used and did no preprocessing. The reason for this is, that in smaller MIPs the benefits are minimal. This research, though, has explored and implemented these methods. The current state-of-the-art developments in LS-MIP solution by Crowder, et al (1983), Johnson, et al (1985), and Van Roy and Wolsey (1987) are incorporated in the preprocessing rules and search strategies, used in the solution of the MA and CP1-Schedules. Later experimentation confirmed the accelerated solution, as result of these rules and strategies. Considerable effort was also spent in understanding the mechanics of the MPS-III solver. Constraints and variables were rearranged to maximize solver performance. A critical performance measure for any algorithm is solution time. The work in this chapter emphasized this objective, and was able to achieve desired objectives.

Two drawbacks of the solution method are: 1) a mainframe computer is required, and 2) it is dependent on a commercial code. Currently, most small and mid-size companies have access to personal computers (PCs), and it would be advantageous to have a PC based procedure. The required memory and processing requirements limit this application. The methods developed here, are intended for application 4-8 years from now, in a CIMS environment. At that time, it can be anticipated, the required computing power will be widely available. The second weakness will be difficult to avoid, if the benefits of industrial research in LS-MIP solution is to be exploited. Another weakness in the solution method is the absence of special structure identification. This is planned in the future, and could significantly reduce solution time, if successful. In the next chapter, the solution method is tested, and the impact on solution time of the different refinements observed.

CHAPTER SEVEN

TESTING OF THE SCHEDULERS AND ANALYSIS OF RESULTS

In the last chapter an operating solution system for the MA-Schedule and CP1-Schedule was developed. In this chapter this solution system is tested with two objectives in mind; First, an analysis of the solution procedure, and second, an analysis of the improvements in manufacturing performance obtained as result of these schedules.

7.1. GENERATION OF TEST PROBLEMS

The testing of the solution system could be done with either actual factory data or hypothetical problems. Since factory data was not available all testing was done with randomly generated problem data. Both the MA-Schedule and CP1-Schedule require considerable amounts of system data. An experiment with $N=10$, $M=10$, $T=10$, and $R=2$ involves the generation of approximately 650 parameters for just the MA-Schedule. Further, there are significant interrelationships between parameters. For instance, plant capacity and demand are interrelated and cannot be generated from independent random streams. A plant with capacity to produce 100 units does not have demand for 1000 units, but rather, something in the range of 100. In some cases these interrelationships involve more than two parameters. In generating the experiment problems as many as possible of these interrelationships were captured. Table 7.1 shows the dependencies between the various parameters. For example, in dependent set-3 A_k, α_k, and $H_{i,r}$ are related to each other, and their derivation also uses predetermined values of $P_{i,r,k}$ and C_k. But, the derivation of $P_{i,r,k}$ or C_k does not include any of the parameters in set-3. The independent variables originate from a free random stream.

Table 7.1. Interrelationships and Dependencies of Generated Parameters

SET	Parameters	Set Dependent Variable
Independent	N, M, R, T, C_k, L	
Dependent #1	θ_k	C_k
Dependent #2	$P_{l,r,k}$	C_k
Dependent #3	$A_k, \alpha_k, H_{l,r}$	$P_{l,r,k}, C_k$
Dependent #4	NB, B	M
Dependent #5	$F_{i,t}, E_{l,t}$	$P_{l,r,k}, C_k$
Dependent #6	$QB_j, QC_j, QD_j, Q_j, \phi_l$	

One of the most common complaints against computer generated problems, is that they describe systems which are far from realistic. In order to duplicate, as closely as possible, real-life manufacturing scenarios a study of previous scheduling experiments, and descriptions of actual manufacturing installations was done. Two recent works in the master aggregate scheduling area are by Gonzalez and Reeves (1985) and Chung and Krajweski (1987). In their test experiments, Gonzalez and Reeves modeled 5 groups over a 6 period horizon, while the processing times varied from 75 to 85 secs. Chung and Krajweski tested their method on a 12-18 month horizon, but other data was not reported. Other references on group/cell technology typically recommend or describe 0-60 groups (Groover, 1980); 3 groups, 12 month horizon, demand of 15000-30000/period (Silver and Peterson, 1985); and 3-15 machines/cell (Greene and Sadowski, 1984). Some example industrial configurations are: IBM card production with 4 machines/cell, 6 groups and processing times of 20-100 secs (Akella et al, 1984); LTV Vought Aero Products FMS with 8 machines/cell and 500 item-groups (Knill, 1985); Hitachi Seikes plant with 3 cells and 4 machines/center (Chobineh and Suri, 1986); and Caterpillar plant with 10 machines/cell and 3 groups (Stecke, 1983).

Clearly, the domain of problems is very wide and at times inconsistent. The ranges selected for generating the primary parameters in the experimental problems are:

Number of cells = 4 - 13
Number of product groups = 4 - 18
Number of items/group = 4 - 10
Number of routes = 2 - 3
Length of horizon = 6 - 16 periods

Number of buckets/period = 4

Cell capacity = 220 - 3300 hours/period

Regular time capacity = 50% - 75% of C_k

Processing times = 0.1 - 3.5 hours

Product demand = 0.4 - 1.25 regular loading index

The problems generated with these ranges covered a wide spectrum of scenarios. Most of the above referenced examples fall within it. A survey of the generated problems indicate they are satisfactory for the purposes of testing the schedulers. The PGEN program was coded to generate the experiment problems.

7.1.1. Classification of Test Problems

In all 15 test problems were generated. Descriptions of some of the test problems are included in Appendix A. For each problem a complexity index was derived as:

$$\text{Complexity Index} = N + M + T + R$$

This index is an indication of problem size and the relative difficulty of solving that problem. For the test problems the indices ranged from 25 to 38. Future analysis of each problem will require an insight into the nature of that problem. In studying the problems four distinguishing features were identified and the problems were classified on the basis of these features. The classifications are:

TYPE I: Capacity is constrained - Expts - 1,10,11,12,13,15

TYPE II: Transporter availability is constrained - Expts - 1,6,9,10,12

TYPE III: Operating costs are relatively lower - Expts - 3,6,11,14

TYPE IV: Demand is imbalanced - Expts - 2,4,5,6

Problems with regular loading index[1] greater than 0.8 were classified as type-I. Those problems in which the central transportation resource is more than 90% dispatched in half the periods, are classified as type-II. Type-III and type-IV problems were selected by scanning the problems data. A problem which does not appear in any of the types is called 'general' and does not have any of the special features identified.

7.2. TESTING PROCEDURE

Fifteen experiments were conducted on the MA-scheduler, and one composite experiment was done with the CP1-Scheduler. The numbers were selected primarily due to the restrictions on available CPU time. Fifteen problems were considered adequate since the problems covered a wide spectrum. Also, the single experiment on the CP1-Schedule is equivalent to doing 10 experiments, since the procedure is repeated for each period. A review of the literature indicates that similar research involving large amounts of CPU time typically execute a total of 3-20 experiments.

Each problem generated by PGEN was inputted to MSCHED and CSCHED. The solution procedures outlined in Figures 6.4 and 6.5 were then executed.

7.3. RESULTS OF THE MA-SCHEDULE TESTING

The models solved in this research are not only large scale problems, but also problems with large number of decisions. These decisions provide the opportunity of analyzing several interesting facets of manufacturing systems, and the solution

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[1] Regular Loading Index $= \sum_k \left[\frac{\sum_t \sum_i P_{i,r,k} X_{i,t}}{MC_k T} \right]$

methodology itself. The detailed results of some of the experiments are included in Appendix B. While the summarized output of all experiments are given in Tables 7.2 to 7.7.

The solution of LS-MIPs, as noted earlier, is a difficult process. An indication of the complexity of the problems solved is summarized in Table 7.2. None of the methods related to master scheduling have reported solution of problems in this size range. The largest LP problem was expt-13 which had 4630 variables and 3830 constraints. The number of integer variables determines the size of the B-B tree. Thus, expt-4 with 520 integer variables had the largest search tree. During the testing process no major problems were encountered with the system of programs. The MPS-III system performed extremely well and did not crash even once.

Usually one of the prime objectives of testing a methodology is to compare it against other equivalent methods. But, this could not be accomplished since any comparison would be biased against one of the methods. Thus instead, this testing focussed more on the benefits and performance impacts attributable directly to the scheduler. Some comparison can be done with regard to problem size. For example consider the solution of expt #3:

	Problem Size	*Solution Time (mins)*
MA-Schedule	1050 x 1729	15.6
CP1-Schedule	10(780 x 1301)	20.0
Non-Aggregated	19224 x 24904	250.0 (projected)

The projected solution time is based on reported data (MPS Manual, 1984). The combined solution time for the developed models is 35.6 minutes. This represents over 85% reduction in solution time simply due to aggregation.

Table 7.2. Complexity of the Experiment MIPs

EXPT #	PROBLEM PARAMETERS	COMPLEX INDEX	NUMBER OF VARIABLES	NUMBER OF CNSTRNTS	NUMBER OF INTEGER VARIABLES	NUMBER OF NODES	SOLUTION TIME (Minutes)
1	N=6 M=4 T=13 R=2	25	1729	1056	208	500	9.20
2	N=14 M=5 T=10 R=3	32	2618	1950	470	500	12.61
3	N=12 M=7 T=10 R=2	31	1870	1570	310	500	15.60
4	N=15 M=7 T=10 R=3	35	2980	2170	520	500	21.15
5	N=16 M=7 T=7 R=2	32	1645	1155	273	500	7.8
6	N=6 M=9 T=12 R=2	29	1524	1284	252	500	25.10
7	N=9 M=5 T=15 R=2	31	1995	1755	345	500	12.41
8	N=17 M=9 T=10 R=2	38	2590	2170	430	500	23.50
9	N=15 M=10 T=10 R=2	37	2860	2020	400	500	19.90
10	N=12 M=5 T=9 R=2	28	1566	1323	261	500	14.05
11	N=13 M=8 T=7 R=3	31	1708	1626	329	500	16.60
12	N=13 M=8 T=13 R=2	36	2665	2601	442	500	26.00
13	N=17 M=9 T=10 R=2	38	4630	3830	430	500	28.25
14	N=11 M=11 T=6 R=3	31	1392	1002	264	500	12.80
15	N=11 M=5 T=13 R=2	31	1386	1781	351	500	27.10

Table 7.3. Solution Performance of the MA-Scheduler

EXPT #	PROBLEM PARAMETERS	COMPLEX INDEX	DECISION COST	LOWER BOUND COST	MAXIMUM POSSIBLE ERROR	EXPECTED ERROR
1	N=6 M=4 T=13 R=2	25	120618.37	106131.37	13.6%	2.9%
2	N=14 M=5 T=10 R=3	32	252745.37	237829.75	6.3%	0%
3	N=12 M=7 T=10 R=2	31	141576.30	138315.06	2.3%	0%
4	N=15 M=7 T=10 R=3	35	41367.05	37346.07	10.1%	0%
5	N=16 M=7 T=7 R=2	32	98217.81	86925.18	12.9%	2.3%
6	N=6 M=9 T=12 R=2	29	129920.70	127926.75	1.6%	0.6%
7	N=9 M=5 T=15 R=2	31	88961.87	73990.75	20.2%	0.7%
8	N=17 M=9 T=10 R=2	38	52805.45	46269.63	14.1%	8.7%
9	N=15 M=10 T=10 R=2	37	377981.43	331005.62	14.2%	1.4%
10	N=12 M=5 T=9 R=2	28	64712.60	61964.93	4.4%	0.8%
11	N=13 M=8 T=7 R=3	31	65112.02	53105.10	22.6%	2.1%
12	N=13 M=8 T=13 R=2	36	49682.52	44003.57	12.8%	0%
13	N=17 M=9 T=10 R=2	38	88173.38	79851.81	10.4%	0.6%
14	N=11 M=11 T=6 R=3	31	52563.73	38465.80	36.0%	5.9%
15	N=11 M=5 T=13 R=2	31	38170.20	35166.05	8.5%	0.2%

7.3.1. Suboptimality Due to Program Abortion

B-B procedures require large amounts of CPU time. Given the number of experiments to be conducted, and the restrictions on available CPU time, it was necessary to limit the search process. This was done by aborting the search process after the generation of 500 nodes. The 500 limit was an outcome of tests aimed at balancing the pros and cons of program abortion. With this limitation the longest solution time was 28.25 minutes for expt-13, and the shortest 7.8 minutes for expt-5. Abortion of the search process implies a portion of the tree has not been searched, and possibly a better solution exists in that portion. This would imply the prescribed decision policy is possibly suboptimal.

From the search summary printed at the end of run, the lowest NCOST and the best projected cost were noted. These two costs are an indication of the suboptimality in the decision policy. The lowest NCOST is actually a lower bound on the total system cost and is used to derive the:

$$\text{Maximum Possible Error} = \frac{DecisionCost - LowerBoundCost}{LowerBoundCost}$$

The best projected cost is used to derive the:

$$\text{Expected Error} = \frac{DecisionCost - BestProjection}{BestProjection}$$

The decision cost, lower bound cost, and the two error percentages, for the experiments, are given in Table 7.3. The maximum error varied from 1.6% to 36.0% and the expected error from 0% to 8.7%. A 0% expected error indicates that at time of abortion no node had a projected cost better than the decision cost.

The maximum error for most of the problems is considerably high, indicating the possibility of significant suboptimality in the decision policies. But, the maximum error percentage is an unreliable indicator of suboptimality. Since, typically the node with lowest NCOST is very high in the tree and has a large integer infeasibility. In about half the problems it had a node generation number of less than 10. It is actually possible to change the search strategy such that, the BINT solution is worse but a lower maximum error is attained. Studies of system output revealed no interrelationships between maximum error and LP problem size, B-B tree size, or complexity index. Instead a positive relationship between the average integer infeasibility in the COPT solution and maximum error was observed. For instance, expts-11 and 13, with the greatest maximum error, had 0.032 and 0.051 infeasibility/integer variable, while expt-10 with a low maximum error had a 0.013 infeasibility/integer variable. Future search strategies may consider introducing the COPT infeasibility/integer variable in the PROJFAC computation. This will reduce the maximum error.

A more reliable indicator of suboptimality is the expected error, since it combines both cost and infeasibility. 80% of the experiments had a projected error of less than 2.5%, and two-thirds had an error less than 1.5%. The acceptability of this error percentage is debatable. Note that the error percentages do not detract from the effectiveness of the solution methods. The restriction on nodes was imposed due to local constraints, and it is not intended this restriction be present in an actual application. Based on analyses of the fathoming and infeasibility patterns observed in the experiments, the projected solution time, for an exhaustive search, will be approximately three times that for 500 nodes. Further, it is projected that a solution search with 1000 nodes would give projected errors of less that 0.25%.

Solution time is a major criterion in determining the practicality of a method. It is estimated 60 minutes of CPU time would provide a "satisficing" if not optimal solution for all problems in the test range. Considering, the envisioned systems described in Chapters 2 and 3, this is a very reasonable demand for a periodic (annual-monthly) run. It is reasonable both in terms of cost[2] and resource availability. It is thus concluded the MA-Scheduler is a viable solution method with regard to its computational demands.

7.3.2. MA-schedule Cost Performance

The MA-Schedule objective function shown in Table 5.2 had seven components. the component cost for each experiment is listed in Table 7.4. In Figure 7.1 the percentage composition is plotted. In most experiments the cell activity cost and operating cost dominate. Cost comparisons and trend analyses between experiments are not relevant since the cost parameters in each experiment are independent. Figure 7.1 is an indication of the wide spectrum of problems solved. Expts-6 and 14 are cases with almost no operating cost, expt-12 is a case with very low cell activity cost, while expt-14 is a case with high lost quality cost.

In almost all the type-I experiments the under utilization cost was low, as would be expected. Conversely, lost quality costs were higher for type-I problems since quality is a function of loading. An increase in the start/stop cost was accompanied by a decrease in the cell activity cost (see expts-5,6, and 14). Overall inventory costs were much lower than would be expected. This is because the MA-Scheduler attempts to achieve just-in-time production as closely as possible.

Portions of the operating and start/stop cost are fixed costs and cannot be further reduced. One indicator of the power of a scheduler is its ability to minimize the variable (non-fixed) costs. The fixed cost of a schedule is computed as:

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[2] Commercial cost of 60 minutes of CPU time at Virginia Tech is $75.00 at idle priority.

Table 7.4. System Cost Performance of the MA-Scheduler

EXPT #	PROBLEM PARAMETERS	INV COST	INV VAR COST	START/ STOP COST	CELL ACTIVITY COST	OPER COST	LOST QLTY COST	LOW UTIL COST	TOTAL COST	FIXED COST
1	N=6 M=4 T=13 R=2	8667	1085	5967	73649	25793	4864	593	120618	27531
2	N=14 M=5 T=10 R=3	21661	884	6147	55071	157406	1859	9717	252745	162126
3	N=12 M=7 T=10 R=2	12936	866	6734	93168	24374	3498	0	141576	30930
4	N=15 M=7 T=10 R=3	3881	390	491	8360	26895	498	852	41367	27049
5	N=16 M=7 T=7 R=2	13143	1683	6252	33964	41786	1360	29	98217	43899
6	N=6 M=9 T=12 R=2	10119	1965	7536	101498	476	5246	3080	129920	2628
7	N=9 M=5 T=15 R=2	8703	1323	1440	24950	50324	1455	767	88962	45190
8	N=17 M=9 T=10 R=2	3960	606	504	26315	18825	1346	1249	52805	18985
9	N=15 M=10 T=10 R=2	34041	8128	5405	100738	219244	5150	5275	377981	211023
10	N=12 M=5 T=9 R=2	4104	487	468	21871	35603	1190	989	64712	33832
11	N=13 M=8 T=7 R=3	4694	860	1479	35021	21697	1199	162	65112	22289
12	N=13 M=8 T=13 R=2	6640	917	469	6364	34119	1041	476	49682	30566
13	N=17 M=9 T=10 R=2	6933	643	1604	39426	39342	2267	115	88173	37483
14	N=11 M=11 T=6 R=3	1609	229	4215	42298	2591	2709	0	52563	4253
15	N=11 M=5 T=13 R=2	3233	211	166	6806	27028	726	0	38170	26634

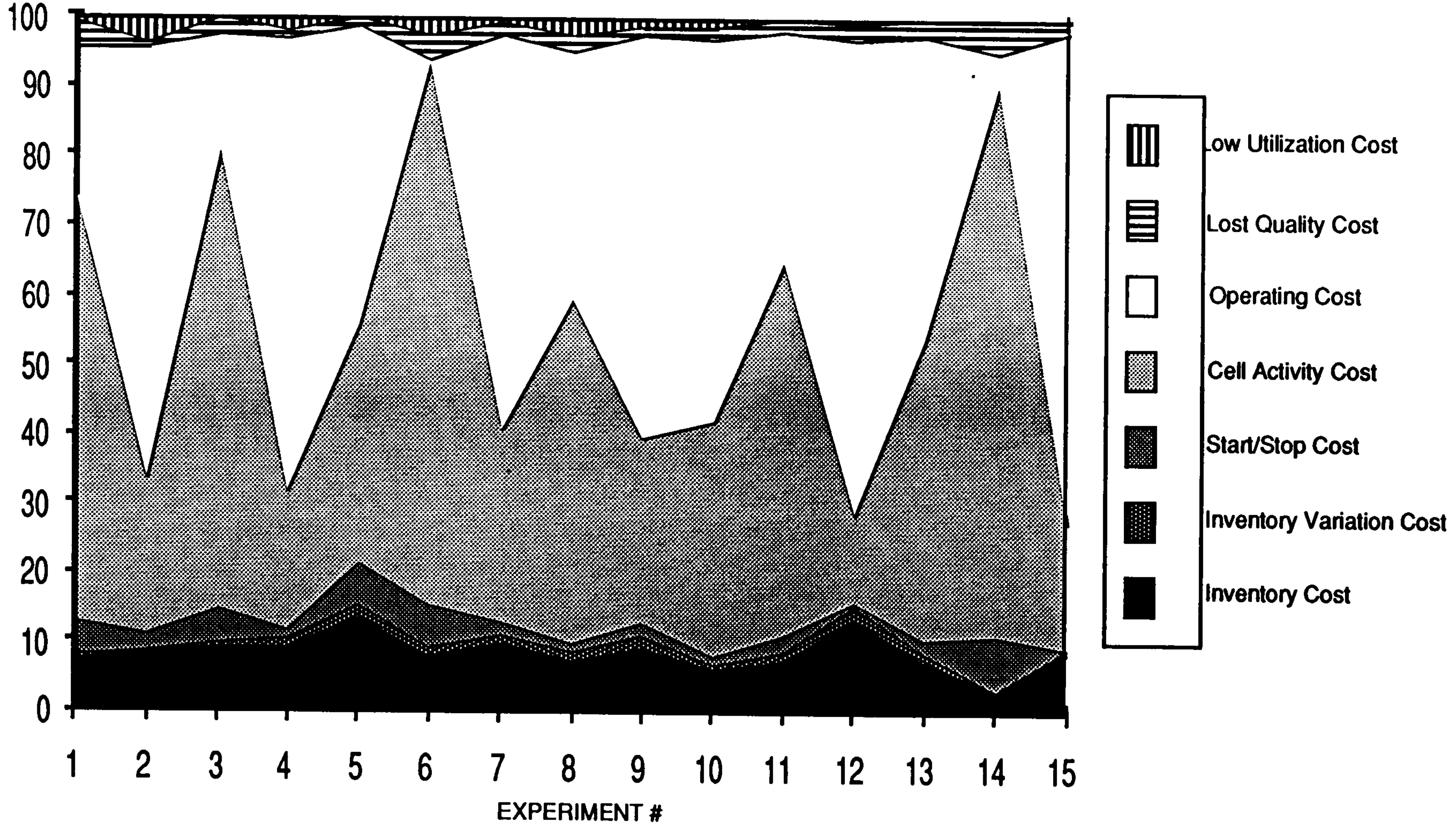

Figure 7.1. Percentage Composition of Total System Cost for the Experiments

$$\text{Fixed Cost} = \sum_k \theta_{r,k} \sum_t (W_{k,t} + O_{k,t}) + \sum_k S_k \tag{7.1}$$

This consists of, a cost for processing for the shortest route, and a cost for one start-up for each cell. The fixed costs for the experiments are listed in Table 7.4. In later analysis this cost will be used to estimate losses. Studying the cost structure of a schedule is an important step in model analysis. Future experimentation with a wider variety of problems could reveal interesting results. These studies will help better design CIM systems.

7.3.3. The Issue and Impact of Flexibility

Flexibility is a much touted benefit and characteristic of CIMS. Exhibition of this flexibility is a primary objective of new scheduling methods. But, as of now only few methods actually do so. Studies by Jaikumar (1986) and Adler (1988) indicate the majority of FMS's in the U.S. are still used simply as automated production lines. FMS scheduling methods only assume machining flexibility. The integration of routing and capacity flexibility into the scheduler is a significant development of this research. Measuring the flexibility of the resultant schedules will help determine how effective this development has been. Measures for the flexibility of a schedule are not reported in the literature, so two new measures were developed:

$$\text{Capacity Flexibility Shown} = \frac{\sum_k \sum_t (ZS_{k,t} + ZD_{k,t}) - M}{M(T-1)} \tag{7.2}$$

$$\text{Routing Flexibility Shown} = \frac{\sum_i \sum_t \sum_r ZY_{i,r,t}}{N(T-1) - \sum_i \sum_t ZX_{i,t}} \tag{7.3}$$

where, $ZY_{i,r,t} = 0.5$ [3], when $y_{i,r,t} - y_{i,r,t1} \neq 0$, and t1 is the first period of production for group 'i' following period 't', further $ZX_{i,t} = 1$ when $X_{i,t} = 0$.

The first measure is a ratio of the start/stops exhibited and the maximum number possible. It is adjusted for the mandatory start of a cell at the beginning of each horizon. The second measure is a ratio of the number of route changes between successive production periods, and the maximum number possible. It too is adjusted for an initial route selection. Using these two ratios the flexibilities shown by the experiments is listed in Table 7.5. The capacity flexibility varied from 0/62 for expt-3 to 25/55 for expt-14. While routing flexibility varied from 2/121 for expt-2 to 9/16 for expt-14. Figure 7.2A plots the flexibilities for all experiments. The graph displays the flexibility scheduling capability of the MA-Scheduler and validates the objective of exhibiting system flexibility.

In discussing the benefits of flexibilities most reports only describe their capabilities. The actual impact of flexibility on performance is seldom presented. In an attempt to better understand the impact of routing and capacity flexibility on manufacturing performance, the variable loss percent with no flexibility for each experiment was computed. This required additional experimental runs. The RFLEX program replaced MSCHED and formulated the MA-Schedule matrix with no flexibility. This was done by setting all cells on at all times, and fixing the route to the shortest route, the problem is then run through MIPROG. The resulting total cost minus flexibilities is listed in Table 7.5. The corresponding percentage loss in total cost, and the non-fixed (variable) cost are also listed. The variable loss ranged from 1.9% to 29.1%. It is evident from these results that flexibility can significantly improve

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[3] $ZY_{i,r,t} = 0.5$ because for every $y_{i,r,t} - y_{i,r,t1} = 1$ there is a corresponding $y_{i,r,t} - y_{i,r,t1} = -1$, hence over a set of routes $\sum_{r} ZY_{i,r,t} = 1$.

Table 7.5. The Impact of Flexibilities on Manufacturing Performance

EXPT #	PROBLEM PARAMETERS	MA-SCHED COST	REGULAR LOADING INDEX	ROUTING FLEXBLTY SHOWN	CAPACITY FLEXBLTY SHOWN	MINUS FLEXIBILITIES		
						TOTAL COST	TOTAL LOSS%	VARIABLE LOSS%
1	N=6 M=4 T=13 R=2	120618.37	0.90	8/64	3/48	122975.01	2.0%	2.6%
2	N=14 M=5 T=10 R=3	252745.37	0.79	2/121	1/45	256139.20	1.3%	3.7%
3	N=12 M=7 T=10 R=2	141576.30	0.66	2/103	0/63	144517.52	2.1%	2.7%
4	N=15 M=7 T=10 R=3	41367.05	0.70	33/117	8/63	43245.66	4.5%	13.1%
5	N=16 M=7 T=7 R=2	98217.81	0.75	20/47	11/42	99965.24	1.8%	3.2%
6	N=6 M=9 T=12 R=2	129920.70	0.68	10/37	28/99	143132.25	10.2%	10.5%
7	N=9 M=5 T=15 R=2	88961.87	0.72	18/80	19/70	89889.68	1.0%	2.1%
8	N=17 M=9 T=10 R=2	52805.45	0.80	9/145	0/81	53360.23	1.0%	1.9%
9	N=15 M=10 T=10 R=2	377981.43	0.62	8/80	20/90	387587.99	2.6%	5.8%
10	N=12 M=5 T=9 R=2	64712.60	0.81	8/75	3/40	66061.17	2.1%	4.3%
11	N=13 M=8 T=7 R=3	65112.02	0.92	11/66	1/48	68936.12	5.8%	8.9%
12	N=13 M=8 T=13 R=2	49682.52	0.95	14/76	22/96	50791.25	2.3%	5.8%
13	N=17 M=9 T=10 R=2	88173.38	0.85	16/109	10/81	89386.87	1.4%	2.4%
14	N=11 M=11 T=6 R=3	52563.73	0.71	9/16	25/55	66593.90	26.7%	29.1%
15	N=11 M=5 T=13 R=2	38170.20	0.93	16/124	3/60	39642.67	3.8%	12.8%

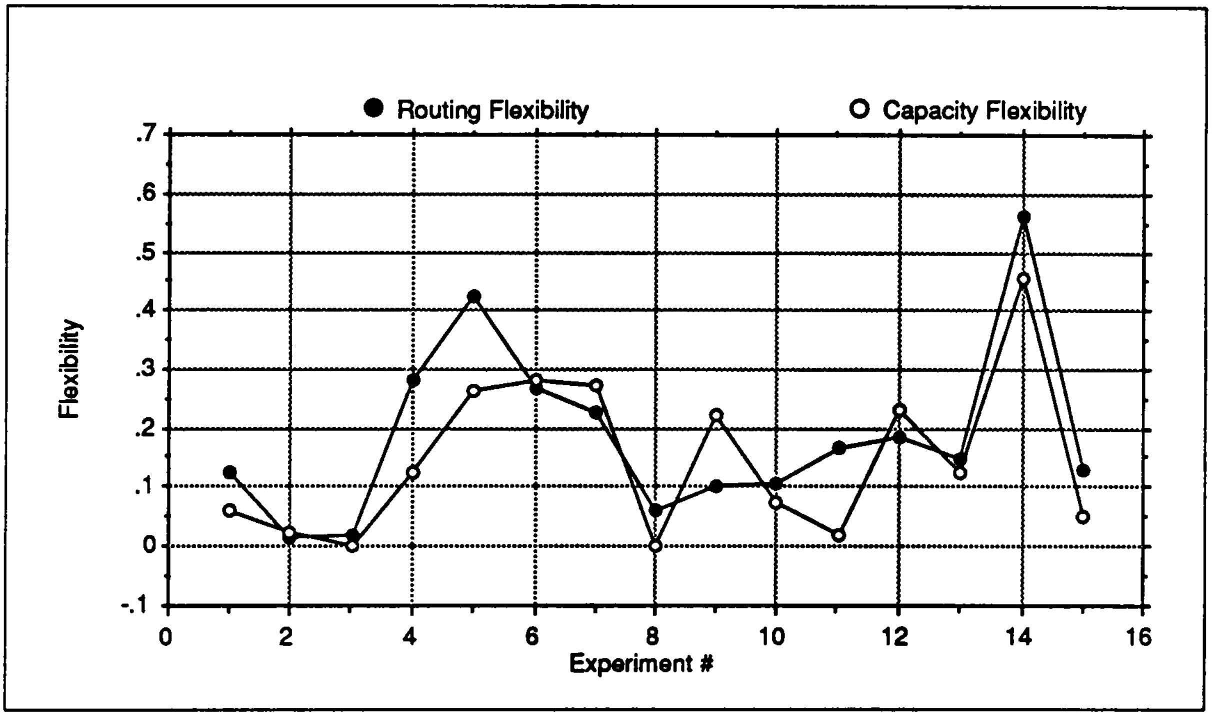

Figure 7.2A. Routing and Capacity Flexibility Exhibited by Experiments

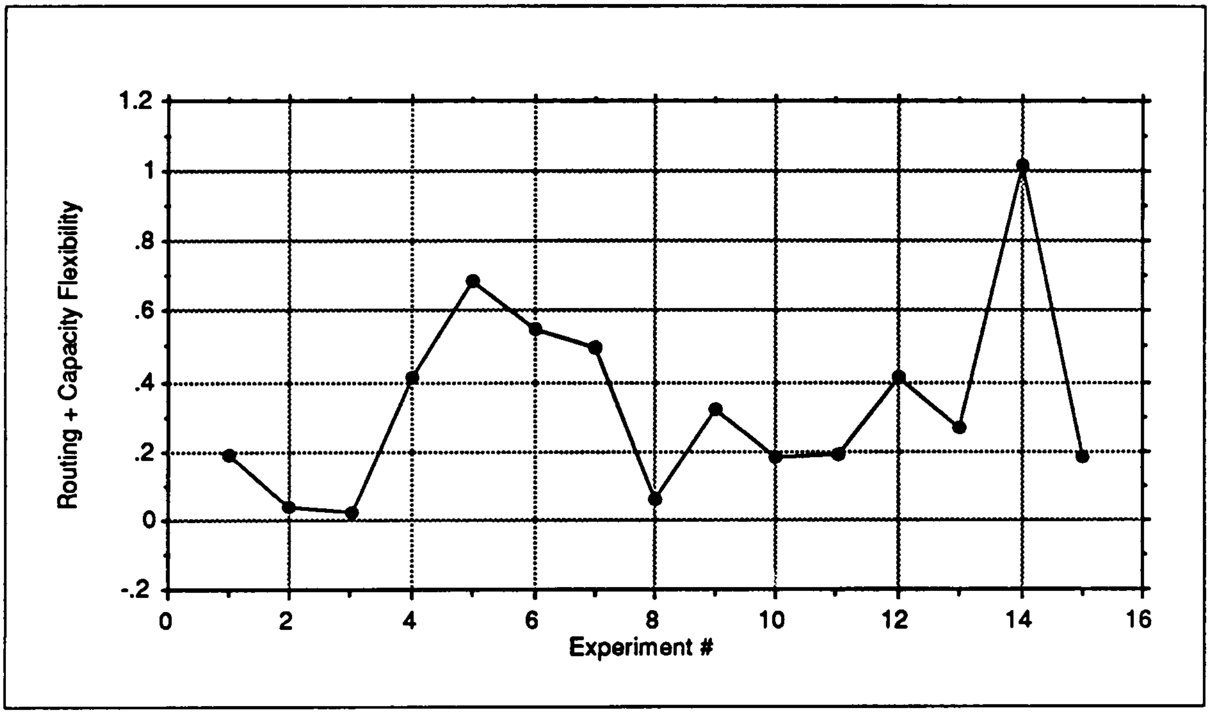

Figure 7.2B. Routing Plus Capacity Flexibility Exhibited by Experiments

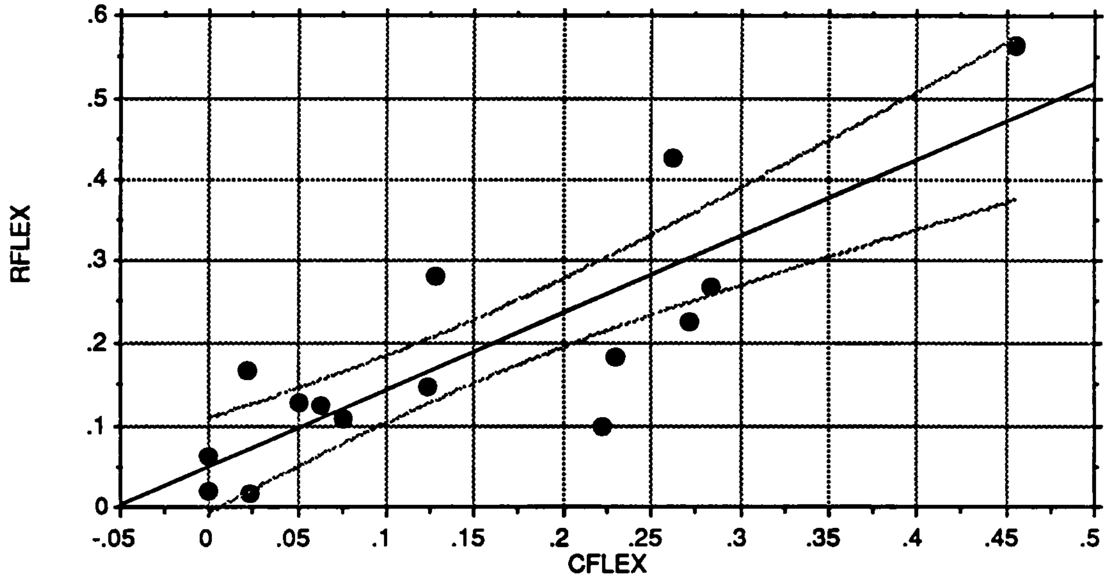

Figure 7.3. Relationship of Routing and Capacity Flexibility

performance. For instance, consider expt-3, the inability to make two routing changes resulted in a 2.7% loss in the variable cost. Experiments with high capacity flexibility were seen to typically have a higher variable loss. These results do not indicate any strict relationships, but they validate assumptions about the benefits of routing and capacity flexibility.

Figure 7.2B plots the combined routing and capacity flexibility exhibited. In expts-2,4, and 8 the flexibility exhibited was very minimal, while expt-4 exhibited flexibility in excess of '1'. The question to ask is 'in what situation does a schedule exhibit flexibility?' Answers to this question will help design better CIM systems. Two answers, in this vein, derived from this study concern the relationship between routing and capacity flexibilities, and that between the two flexibilities and the loading index. Figure 7.2A reveals a very interesting pattern in the flexibilities. The levels of routing and capacity flexibility are very close at all times, and follow the same path through the experiments. In Figure 7.3 a scattergram of the routing-capacity flexibility behavior is plotted. Superimposed on Figure 7.3 is a linear regression line (95%) along with 95% confidence limits. The sum of the residuals for the linear regression was 0.704. The primary hypothesis resulting from Figure 7.2A and Figure 7.3 is the following: there is a strong positive correlation between routing and capacity flexibility. Linearity of the relationship is not proposed. Since, it is doubtful whether it will be valid over a global set of problems. This correlation between the flexibilities has significant implications for CIMS design. Designers need to study and consider the synergism between all the inherent system flexibilities.

A detailed survey of the routing behavior over the experiments provided some insights into the route selection process. Process planning methods can generate multiple routes. The best route is then selected on the basis of some prespecified criteria. When more than one route (or process plan) is to be selected, the selection process is not well defined. For instance, should the top 'n' routes be selected, or a 'mixed bag' of routes chosen. Consider the following three processing routes for a product:

	Cell-1	Cell-2	Cell-3	Cell-4
Route-1	1.5	0.0	1.0	0.8
Route-2	1.7	0.0	0.3	1.2
Route-3	0.0	1.5	1.0	0.8

Generally, it could be said that routes-1 and 2 are similar while route-3 is different. Now, there are no measures for differentiating routes, but such measures can easily be developed. Survey of the experimental results indicate, that it is more likely a schedule will exhibit routing flexibility if its routing alternatives are more differentiable. Given the above three routes, the schedule will more likely switch between 1 and 3 than between 1 and 2. Such insights can be imbedded in generative CAPP to guide route selection.

In this section various facets of flexibility have been analyzed. The MA-Scheduler was found to be an effective tool for exhibiting and studying system flexibility. The scheduler can be used, as was done here, to further gain knowledge and understanding of manufacturing flexibility, and consequently result in the design of better CIM systems.

7.3.4. The Effects of Production Loading

When evaluating the application of tools to a manufacturing system, the question often asked is 'what are the effects of loading on the tool?' For the MA-Schedule experimentation the Regular Loading Index (RLI) varied from 0.62 to 0.95 (see Table

7.5). From the results, it can be concluded that, there are no adverse effects of loading on the MA-Scheduler performance. Though, at the lower RLI, some decisions may not be "to the liking" of management. When RLI is low the schedule is optimized by shutting down cells for several periods. In reality, strategic considerations may override these long periods of down time. Other than that, the scheduler is able to operate in any loading case.

Two facets of the production loading question were studied in the experiments. First, the effect of loading on system cost and second, the relationship of flexibility to loading. To study the first facet two additional experiments were done. Expt-10 was repeated with a higher loading and a lower loading. The results of these experiments are given in Table 7.6. As the loading decreased the scheduler exhibited greater flexibility resulting in higher cost savings. The MA-scheduler was able to reduce the variable cost by 0.2% in going from high to medium, and by 6.0% in going from high to low. Note that all seven elements of the cost did not decrease with loading. Five of the elements went up and only two came down. Significant increases are seen in inventory related cost, which are negated by savings in cell activity and operating costs. A scheduler such as HPP attempting to optimize only on the basis on inventory would give a weaker overall schedule than the MA-Scheduler, even though inventory costs may decrease. Clearly in environments with varying loading or low loading the MA-Scheduler is an effective tool.

Studies on the flexibility loading relationship revealed very interesting patterns. In Figures 7.4A and 7.4B the capacity and routing flexibilities are plotted against loading. Superimposed on the graphs is a second degree polynomial regression line, to indicate trend. Both graphs indicate a decrease in flexibility with loading. The regression lines provide an insight to the relationship, but the number of tests precludes any rigorous testing. While the CFLEX loading relationship appears to be

Table 7.6. The Impact of Job Loading on the MA-Schedule

Loading tests done for Expt #10

LOADING LEVEL	REGULAR LOADING INDEX	TOTAL LOADING INDEX	MA-SCHED COST	ROUTING FLEXIBLTY	CAPACITY FLEXIBLTY
HIGH	0.85	0.53	66040.69	5/87	1/40
MEDIUM	0.80	0.50	64712.60	8/75	3/40
LOW	0.71	0.45	59308.69	12/70	7/40

LOADING LEVEL	INV COST	INV VAR COST	STRT STOP COST	CELL-ON COST	OPRTNG COST	LOST QLTY COST	LOW UTIL COST	FIXED COST	RELATIVE COSTS	
									TOTAL LESS	VARYNG LESS
HIGH	3840	419	357	22611	36975	1242	596	35100	--	--
MEDIUM	4104	487	468	21871	35603	1190	989	33832	2.1%	0.2%
LOW	4901	728	654	19846	31454	1056	624	30230	11.4%	6.0%

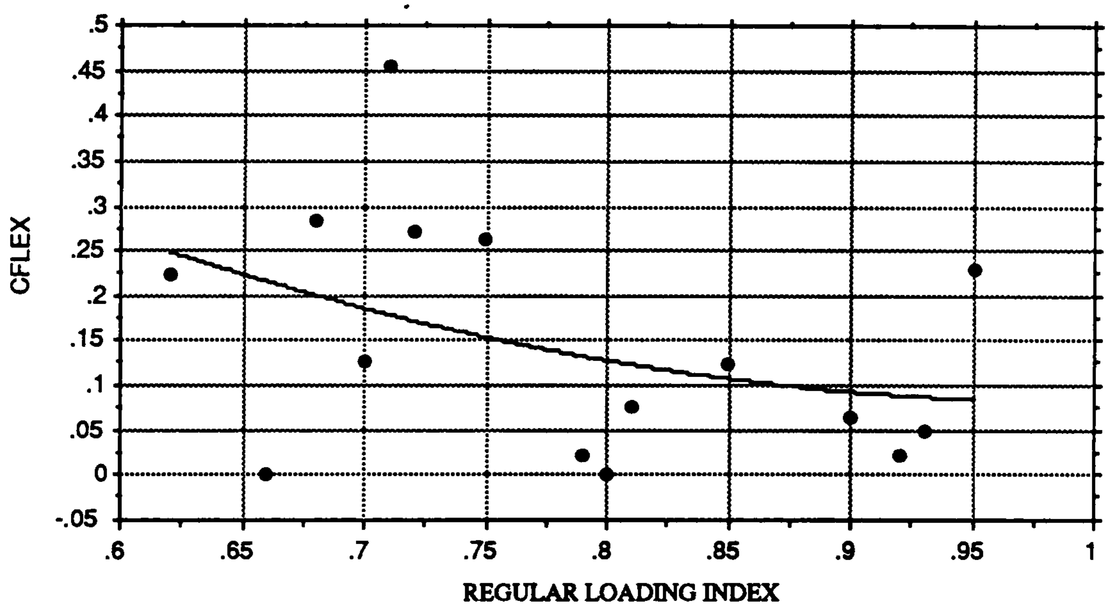

Figure 7.4A. Relationship of Capacity Flexibility to Loading

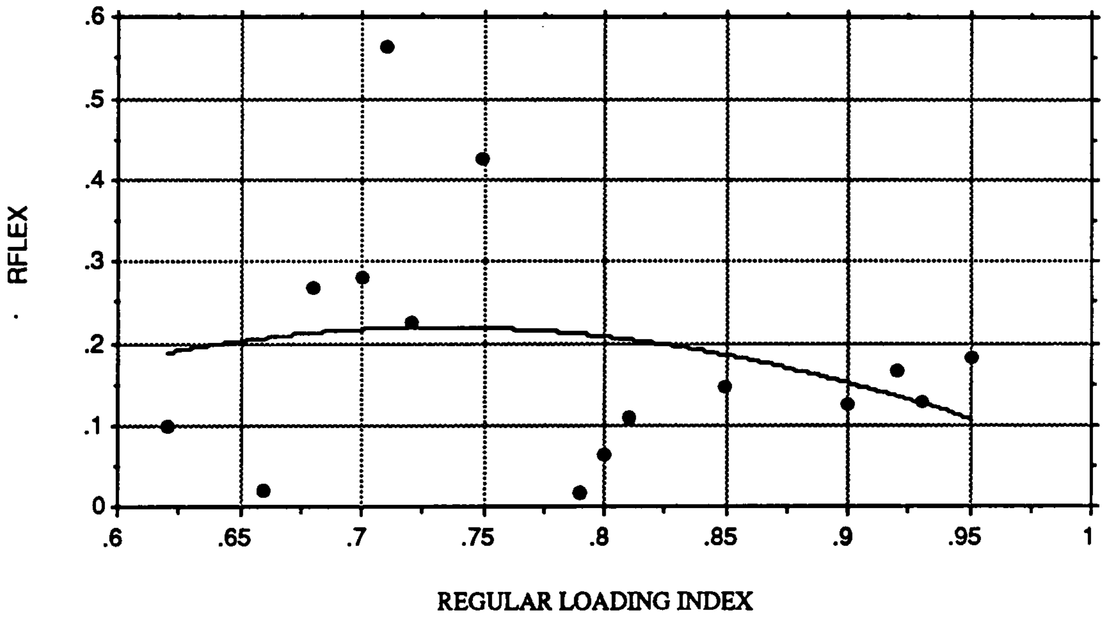

Figure 7.4B. Relationship of Routing Flexibility to Loading

Table 7.7. Number of Periods in Which Transportation is Constrained

EXPT #	PROBLEM PARAMETERS	# of Constrained Periods
1	N=6 M=4 T=13 R=2	8
2	N=14 M=5 T=10 R=3	0
3	N=12 M=7 T=10 R=2	1
4	N=15 M=7 T=10 R=3	0
5	N=16 M=7 T=7 R=2	1
6	N=6 M=9 T=12 R=2	7
7	N=9 M=5 T=15 R=2	1
8	N=17 M=9 T=10 R=2	0

EXPT #	PROBLEM PARAMETERS	# of Constrained Periods
9	N=15 M=10 T=10 R=2	3
10	N=12 M=5 T=9 R=2	7
11	N=13 M=8 T=7 R=3	0
12	N=13 M=8 T=13 R=2	8
13	N=17 M=9 T=10 R=2	9
14	N=11 M=11 T=6 R=3	0
15	N=11 M=5 T=13 R=2	0

monotonic, the RFLEX loading relationship seems to be concaved. This behavior may be explained as follows. Initially RFLEX and CFLEX both increased with decreased loading. But, increased CFLEX implies some cells are shut down. In such a scenario the effective loading (on active cells) has actually increased. From a routing perspective this is equivalent to the higher loading situation. Consequently RFLEX is relatively lower with low RLI.

7.3.5 The Impact of Transporter Availability

One of the novelties of the MA-Scheduler is its ability to consider the availability of transportation resource (material handler). A common cause of schedule variance is not having a vehicle on hand. The MA-Scheduler overcomes this problem, and in addition assigns transporters to cells on a period by period basis. To assess the impact of this attribute on system performance, we could rerun the experiments with no transporter constraints. But this was beyond the scope of this work. Instead, the effect of these constraints on the generated schedules was tracked.

Table 7.7 shows the number of periods in which the transportation constraints (TRC and TRAP) became active. This considers only resource accessed from the central transporter pool. In six experiments there was ample resource in all periods. But, in the remaining nine experiments the constraints were active in at least one of the periods. The most highly constrained scenario was expt-13, in which 9 of 10 periods has restrictions. In all experiments with active transporter constraints, the benefits of the MA-Scheduler include the cost of bringing in outside resource to handle the overload.

7.4. RESULTS OF CP1-SCHEDULE TESTING

The primary objective of testing the CP1-Scheduler is to evaluate the efficiency of the disaggregating mechanism, and the variation about the MA-Schedule decision policy. Only one composite experiment was done on the CP1-Scheduler, with expt-3. This involves 10 sub-experiments, since it is repeated for each period. Execution of this experiment was a lengthy process since it involves the execution of 37 programs, which are manually linked. Future exec programs will eliminate this inconvenience.

The search tree for the CP1-Schedule is relatively much smaller than that for the MA-Schedule. Therefore, in each period the tree was searched to optimality. The average search time was 3-4 minutes. The total CP1 solution time for expt-3 was 28.0 minutes. Given that 3160 primary decisions are made, this is a reasonable solution time. The scheduler performed well and no problems were encountered. The decision policy prescribed by DECS is included in Appendix C. Survey of the policy indicates the disaggregating procedure is efficient and accurate.

7.4.1. Variation From the CP1-Schedule

The CP1 objective function consists of three terms. Of these two are designed to minimize variation about the MA-Schedule. High penalties were assigned, in expt-3, for unit variation.

A major indicator of disaggregation efficiency is the variation in production quantities. Table 7.8 shows the period/group MA-CP1 schedule quantity variation. The variation rarely is more than the EPQ size, which indicates high efficiency. Further, it attempts to compensate positive variation with negative variation as quickly as possible. In 49 of 120 group/periods there was no variation. Scheduler also attempts to balance production time between buckets in a period. Depending on the cost structure it may or may not be successful in doing so.

Table 7.9. MA-CP1 Production Quantity Variation by Period

Group #	EPQ Size	(MA - CP1) Quantity by Period									
		1	2	3	4	5	6	7	8	9	10
1	20	-6	3	3	-11	0	5	4	-12	3	10
2	18	0	-54	0	20	0	-3	-7	18	10	0
3	8	0	-2	0	2	0	0	0	0	-7	7
4	17	-10	10	0	-4	4	0	0	-6	6	0
5	30	-2	-28	-18	24	20	-6	-31	33	7	2
6	25	0	0	0	0	-8	6	2	-18	15	3
7	25	-8	8	0	-2	2	0	0	0	0	0
8	50	0	0	0	-30	30	0	0	-8	8	0
9	10	0	0	0	-4	-1	3	0	0	-1	8
10	20	0	0	0	-16	-14	15	3	0	-9	9
11	15	0	0	-8	0	9	0	0	0	0	0
12	22	0	0	0	-2	-13	-12	20	4	0	0

7.5. ANALYTICAL SUMMARY

The primary purpose of this chapter was to test the developed methodologies. As a result of this testing, the major conclusions arrived at were:

1. Both the MA-Scheduler and CP1-Scheduler are feasible approaches to scheduling in a CIMS environment.
2. Routing and capacity flexibility are exploitable characteristics of a manufacturing system, and can result in significant improvements in system performance.
3. There is a possible positive correlation between routing and capacity flexibility.
4. Routing and capacity become less important with increasing loading.
5. The MA-Schedule cost benefits increase with decreased loading.
6. Modeling of transporter resource is a must in CIMS control, and the MA-Scheduler was able to handle this.
7. The aggregate modeling approach is applicable to CIMS control. The benefits derived from reductions in problem size and solution time, are critical to the success of CIPP&C. The collective action of the MA/CP1-Schedulers was able to reduce solution time by about 85%, from a disaggregate solver.

At the macro level, there are two additional outcomes from this research: 1) the further applicability of HPP based methods, and 2) the realistic solution of LS-MIPs in production control. The HPP method was introduced by Hax and Meal (1975), since then the method has gained only minimal acceptance in research, and almost none in industry. This has been primarily due to the popularity of MRP based methods, and other arithmetic schedulers. The bulk of the HPP literature has been contributed by the MIT group (Hax, Meal, Golovin, Candea, etc.), others have not investigated the approach much. Hierarchy and disaggregation will be the key characteristics of future production control systems, and this research has demonstrated the application of these to CIMS. The next generation of production controllers will need integrated decision making, and combinatorial schedulers. The CIPP&C plan, the MA-Scheduler, and the CP-Scheduler provide these attributes.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

The primary objectives of this research were to develop the first level "city plan" for a CIPP&C system, and to build specific modules within that plan. Both these objectives were accomplished. The "city plan" could not be validated by testing, but was rationalized on the basis of documented research and previous experience. Two models within the plan were built, these were the MA-Schedule and the CP1-Schedule. Both the models were tested on randomly generated problems. The results of the tests are reported in chapter seven. The results indicate the modules are viable and are able to control the facility, in order to minimize the appropriate costs.

In chapter one, three critical elements for CIPP&C development identified were: systems modeling, aggregate planning, and integration. With integration as an objective, the first two elements characterized the model building efforts.

8.1. CONCLUSIONS: SYSTEMS OF PRODUCTION CONTROL

A major contribution of this research is the introduction of the CIPP&C "city plan". While several other systems have been proposed in the past, most are not based on a well thought through plan. The "city plan" provides not only the base for a system, but ensures it is an integrated system. In the future, any implementable control methodology will have to be part of, or compatible with, a production control system. CIPP&C provides the opportunity to include a good portion of the existing methods in the discipline, into the plan. This was demonstrated in the research by the inclusion of the Ham-Hitomi group flowshop scheduling method. No other system has this capability.

Only two of the "city plan" modules were built here. Further structural analysis of the remaining modules will expand the domain of CIPP&C. We have demonstrated in this research the analytical and model building efforts to be followed in these further efforts. It is also evident the majority of these models will involve large scale mathematical and computer solutions. The feasibility of such modeling and solution was shown in the MA and CP-Schedules. Several of the existing, and more popular, commercial systems are based primarily on arithmetic algorithms[1]. A common paradigm is that operations research methods are too cumbersome for large-scale modeling. But effective control of CIM systems demands controllers which are more powerful than the simple arithmetic solvers. We believe that with aggregation and appropriate decision distribution it is possible to build large scale systems incorporating state-of-the-art operations research methods. The "city plan" is designed to be such a system. It is envisioned as a system consisting of various mathematical methods, which are able to communicate with each other.

A primary concern of CIPP&C is integration and the consequent communication between modules. Mathematically, this communication can be done via objective function terms and constraints. This was the mode employed in the MA and CP-Schedule formulations. As a result both models consisted of a large number of constraints. An important characteristic of system modeling is often missed by researchers and practitioners. A system rarely prescribes a better solution (than a fragmented methodology), it only prescribes a more feasible solution. For instance, if the MA-Schedule was not constrained by the transportation resource it would generate a better solution. But, as the results have shown, it would most likely be an in-

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[1] An 'arithmetic' algorithm uses only '+', '-', 'x', and '/' operators to make decisions. In contrast, a combinatorial algorithm consists of finding, from among a finite set of alternatives, one that optimizes the value of an objective function.

feasible solution. Thus, in a theoretical comparison, HPP may appear to be superior to the MA-schedule, but the reality is that in a CIM environment HPP is a scheduler of low intelligence. To ensure system integrability it is imperative that both feasibility and optimality be considered. And this has been followed in the model building efforts here. Future researchers must be interested not only in the solution of a 'straight forward' problem, but more importantly in the 'constrained' problem.

A baseline plan and method for a system of production control to be used in CIM environments has been developed. It is a plan which is potentially superior to all other plans, and can guide future efforts.

8.2. CONCLUSIONS: AGGREGATE SCHEDULING IN CIMS

Most production control systems are hierarchical in structure, with an upper level decision serving as guideline for a lower level sub-system. One method for achieving this hierarchical linkage is to aggregate decisions/parameters upwards. Hax and Meal (1975) were one of the first to formulate such a system in two layers. One of the feature of CIMS is the use of group technology/cellular manufacturing. These technologies are amenable to aggregate modeling since they themselves are aggregations. This aggregation was incorporated in the CIPP&C plan, and used to formulate the MA and CP-Schedules. From the results, it is apparent that aggregation enables a much faster and viable method of solution to the problems. In the absence of aggregation it is doubtful whether realistic solutions to the experiment problems would have been possible.

When there is aggregation there is a corresponding disaggregation. Prior to solving an aggregated problem the disaggregating process must be thought through, since an aggregated decision in itself has no value. Several of the scheduling modules in the CIPP&C plan will function both as aggregators and disaggregators. This will help reduce the inherent complexity of CIMS. The models formulated here aggregated time, machines, and products.

8.2. RECOMMENDATIONS: FUTURE RESEARCH

The CIPP&C plan and its associated modules provides several opportunities for further research. The efforts of this dissertation were not intended to have a start and finish, but rather to be a part of an evolution in production control systems. We do not envision these systems being implemented widely 'till the mid 90's, and concur with the OTA Report's (1984) projections for their availability. The following efforts are recommended, to further establish the CIPP&C system:

1. The CIPP&C "city plan" was developed primarily from previous research and ICAM documentation. Only the first three layers of the ICAM functional model were studied in the process. Studies of the remaining layers, along with analyses of existing CIM systems, and new technologies should be done. Based on these studies the "city plan" should be improved and further extended.
2. Structural analysis of the remaining portions of the CIPP&C plan. Only two of the CIPP&C modules were analyzed here. Each of the remaining coordinating schedules and departmental schedules needs to be similarly analyzed. Guidelines for this analysis have been presented in Chapters 1-4. The modular analysis should begin at the coordinating level and progress downwards. Layer-6 of the plan focuses on feedback and adjustments, also needs to be analyzed.
3. Development of solution procedures for each module. In Chapters 5 and 6 solution procedures for the MA and CP1-schedules were developed. Similarly, procedures for the other modules, after structural analysis, need to be developed. These procedures must incorporate the best available mathematical methods and be able to communicate with existing schedules.

4. It is doubtful whether significant improvements in solution time can be obtained from reformulation of the MA and CP1-Schedules. Rather, it is recommended future efforts be focussed on the preprocessing methods. Almost all previous research indicates that preprocessing is critical to the rapid solution of MIPs. The preprocessing rules in Chapter 6 need to be augmented. Other procedures described by Brearly et al (1975) and Crowder et al (1983) should be studied and incorporated. The goal should be to reduce solution time by as much as 70%.
5. The search strategy is a critical factor in the solution of MIPs. The strategy used here was relatively simple. A more effective strategy, incorporating cluster search algorithms (Johnson et al, 1985) needs to be developed.
6. The MA-Scheduler is an effective tool for studying the behavior of manufacturing systems. In Chapter 7, several such studies are reported. Based on the MA-Schedule outputs, further analyses of the effects of system flexibility, loading, transportation resource, objective function parameters, regular/overtime balance, etc. should be done.
7. System Performance with different configurations can be estimated by the MA-Scheduler. As such the scheduler can be used to develop design guidelines for machine cell and product group formation, process routing alternatives, system capacity, available flexibilities, and material handling devices/systems.

The above research will increase the applicability of the CIPP&C plan. Further, they will contribute in the quest for the envisioned 'factory of the future'.

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APPENDIX A

This appendix describes some of the experiment problems, namely, expts #3, #4, #6, and #12. The descriptions report the majority of input data for the MA-Schedule experiments. Cost parameters and other minor data have been omitted. Since only one CP1-Schedule was conducted, the relevant information is reported only for expt #3.

Each description is divided into five parts. Each part is briefly described below.

1. This part defines macro system parameters. These are N, T, M, and R (see section 5.1.3. for definitions). The number of key cells is the number of bottleneck stations, their utilization is to be maximized.
2. CELL PARAMETERS - Defines the regular and overtime production capacity, in hours, for each cell in the system. Further, the available transportation resource for intra-cell movement is specified.
3. GROUP DEMAND SCHEDULE - The number of firm orders (F), and expected orders (E) to be delivered at the end of each period is stated, by groups.
4. PROCESSING MATRIX - Defines all the possible process routes for each product group. The matrix gives the time spent by a product on each cell in the route. A zero processing time implies the cell is not visited.

```
DESCRIPTION OF PROBLEM NUMBER -   3
==========================================================================================
NUMBER OF CELLS              =   7        NUMBER OF PERIODS        =  10
NUMBER OF GROUPS             =  12        NUMBER OF ROUTES         =   2
NUMBER OF BUCKETS/PERIOD     =   4        NUMBER OF KEY CELLS      =   2
TOTAL LOAD INDEX             = 0.4138     REGULAR LOAD INDEX       = 0.6563

CELL PARAMETERS:
----------------

CELL #                   1      2      3      4      5      6      7
CELL CAPACITY(HRS)   523.6  803.0  835.0  576.2  719.1  851.1  860.6
MAX REG CAP (HRS)    281.9  425.3  538.1  406.2  388.3  628.5  590.3
TRANS RESOURCE         0.0   94.7    0.0   76.1   67.1   84.0   93.6

GROUP PARAMETERS:
-----------------

GROUP #                 1     2     3     4     5     6     7     8     9    10    11    12
DESIRED INV LEVEL    10.0  11.0   5.0   7.0   6.0  14.0   9.0  31.0   5.0   7.0  13.0  16.0
NO. OF ITEMS IN GROUP   4     9     5     8     6     9     9     6     5     9     5     4

GROUP DEMAND SCHEDULE:
----------------------

PERIOD #                1     2     3     4     5     6     7     8     9    10
GROUP #  1     (F)     80    65    53    71    82    63    62    61    68    49
               (E)      7     8     0     2     8     9     2     6     1     1
GROUP #  2     (F)     74    70    49    35    48    59    44    53    95    74
               (E)     10    13     0     4     3     4     8     4    14     4
GROUP #  3     (F)     26    22    22    20    28    46    33    40    27    22
               (E)      3     2     2     2     0     5     5     2     0     1
GROUP #  4     (F)     38    40    33    27    44    38    33    45    34    44
               (E)      3     4     2     3     4     3     6     0     6     0
GROUP #  5     (F)     27    21    48    31    47    27    35    37    26    20
               (E)      5     2     6     3     7     2     5     5     0     0
GROUP #  6     (F)     52   122    57   109    49    55    73    61    80    51
               (E)      4    22     3     3     3     1     2     1    10     4
GROUP #  7     (F)     61    42    69    44    56    53    35    52    29    67
               (E)      6     1     8     4    10     7     0     4     1     1
GROUP #  8     (F)    137   185   233   119   127   105   209   164   146   172
               (E)      0     6     0     1    22    19    12     0    17     6
GROUP #  9     (F)     36    31    23    19    19    40    22    35    39    42
               (E)      2     5     1     2     2     5     2     3     0     6
GROUP # 10     (F)     40    64    55    50    56    42    25    53    44    47
               (E)      1     0     3     1     3     3     2     5     0     7
GROUP # 11     (F)     53    49    91    52   107   103    90    75    51   104
               (E)      8     2     5     5     3    14     8    10     0     2
GROUP # 12     (F)     54    75    68    56    77    67   111    89   135    59
               (E)      2    14     1     7     0     9    15    16    18     6
```

```
 PROCESSING MATRIX
 ------------------

 CELL #                  1      2      3      4      5      6      7

 GROUP#  1  RT-1        0.0    0.8    0.0    0.5    0.7    0.8    0.7
            RT-2        0.0    0.8    0.0    0.0    1.2    0.8    0.7

 GROUP#  2  RT-1        0.5    0.0    0.7    0.7    0.6    0.5    0.8
            RT-2        0.5    0.0    0.7    0.7    1.0    0.0    1.2

 GROUP#  3  RT-1        0.4    0.5    0.9    0.5    0.0    0.7    0.0
            RT-2        0.0    0.8    0.9    0.5    0.0    0.7    0.0

 GROUP#  4  RT-1        0.6    0.0    0.7    0.5    0.7    0.9    0.5
            RT-2        0.6    0.0    1.1    0.0    1.0    0.9    0.5

 GROUP#  5  RT-1        0.0    0.7    0.7    0.3    0.5    0.6    0.5
            RT-2        0.0    0.7    1.0    0.0    0.8    0.6    0.5

 GROUP#  6  RT-1        0.4    0.8    0.9    0.6    0.8    0.0    0.5
            RT-2        0.0    1.1    0.9    0.6    0.8    0.0    0.5

 GROUP#  7  RT-1        0.5    0.4    0.7    0.5    0.7    0.8    0.0
            RT-2        0.7    0.0    0.9    0.5    0.7    0.8    0.0

 GROUP#  8  RT-1        0.0    0.0    0.5    0.0    0.6    0.0    0.7
            RT-2        0.0    0.0    0.0    0.0    0.6    0.0    0.7

 GROUP#  9  RT-1        0.6    0.8    0.5    0.4    0.0    0.8    0.9
            RT-2        0.6    0.8    0.9    0.0    0.0    0.8    0.9

 GROUP# 10  RT-1        0.6    0.6    0.8    0.5    0.0    0.5    0.0
            RT-2        0.6    0.6    0.8    0.5    0.0    0.0    0.0

 GROUP# 11  RT-1        0.0    0.0    0.6    0.5    0.4    0.9    0.0
            RT-2        0.0    0.0    0.6    0.7    0.0    1.2    0.0

 GROUP# 12  RT-1        0.4    0.0    0.7    0.6    0.5    0.6    1.0
            RT-2        0.0    0.0    0.7    0.6    0.5    0.6    1.0

DEMAND SCHEDULE:
-----------------

ERIOD #    1  ---------------------   2  ---------------------   3  ---------------------   4  ---------------------
UCKET #    1     2     3     4        1     2     3     4        1     2     3     4        1     2     3     4
ITEM#

 1   (F)   7    11     8     8        5     9     7     6        4     7     6     5        6    10     8     7
     (E)   1     1     0     0        1     1     1     0        0     0     0     0        0     0     0     0

 2   (F)   5     5     5     4        4     4     4     3        3     3     3     2        4     4     5     3
     (E)   1     1     0     0        1     1     0     0        0     0     0     0        0     0     0     0

 3   (F)   2     1     1     2        2     1     1     2        2     1     1     1        2     1     1     2
     (E)   0     0     0     0        0     0     0     0        0     0     0     0        0     0     0     0

 4   (F)   9    11     0     1        7     9     0     1        6     7     0     2        8     9     0     1
     (E)   1     1     0     1        1     1     0     1        0     0     0     0        0     0     0     2

 1   (F)   3     2     1     1        3     2     1     1        2     1     0     1        1     1     0     0
     (E)   1     0     0     0        1     1     0     0        0     0     0     0        0     0     0     0

 2   (F)   2     1     2     2        2     1     2     2        1     0     2     1        1     0     1     1
     (E)   0     0     1     0        1     0     1     0        0     0     0     0        0     0     0     0

 3   (F)   1     0     1     1        1     0     1     1        1     0     0     1        0     0     0     1
     (E)   0     0     0     0        0     0     0     0        0     0     0     0        0     0     0     0

 4   (F)   4     3     4     4        3     3     3     4        2     2     2     3        2     1     2     2
     (E)   1     1     1     0        1     1     1     0        0     0     0     0        0     0     0     0

 5   (F)   4     1     1     4        4     1     1     3        3     1     1     2        2     1     0     2
     (E)   1     0     0     0        1     0     0     0        0     0     0     0        0     0     0     0

 6   (F)   2     1     3     0        2     1     3     0        1     1     2     0        1     0     1     0
     (E)   0     0     0     0        1     0     0     0        0     0     0     0        0     0     0     0

 7   (F)   1     0     4     3        1     0     4     2        0     0     3     2        0     0     2     1
     (E)   0     0     0     0        0     0     0     0        0     0     0     0        0     0     0     0

 8   (F)   4     3     3     2        4     3     3     2        3     2     2     1        2     2     1     1
     (E)   1     1     0     0        1     1     0     0        0     0     0     0        0     0     0     0

 9   (F)   3     0     2     1        3     0     1     2        2     0     1     3        2     0     1     3
     (E)   1     0     0     1        1     0     0     1        0     0     0     0        0     0     0     4
```

1	(F)	2	1	0	0	2	1	0	0	2	1	0	0	1	1	0	0
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	(F)	1	0	0	2	1	0	0	2	1	0	0	2	1	0	0	2
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	(F)	1	3	2	0	1	2	2	0	1	2	2	0	0	2	2	0
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	(F)	2	2	1	0	2	2	1	0	2	2	1	0	2	2	1	0
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	(F)	3	1	1	4	3	1	0	2	3	1	0	2	2	1	0	3
	(E)	1	0	0	2	0	0	0	2	0	0	0	2	0	0	0	2
1	(F)	2	2	2	2	2	2	2	3	1	2	2	2	1	1	1	2
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	(F)	1	1	0	2	1	1	0	2	1	1	0	1	1	1	0	1
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	(F)	1	0	0	1	1	0	0	1	0	0	0	1	0	0	0	1
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	(F)	2	0	1	1	2	0	1	1	2	0	1	0	1	0	1	0
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	(F)	3	2	0	1	3	2	0	1	2	2	0	1	2	1	0	1
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	(F)	1	1	2	1	1	1	2	1	1	1	2	1	1	1	1	1
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	(F)	0	0	1	2	0	0	1	2	0	0	0	2	0	0	0	2
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	(F)	2	0	2	2	3	0	2	2	2	0	1	4	2	0	1	3
	(E)	0	0	0	3	0	0	0	4	0	0	0	2	0	0	0	3
1	(F)	2	0	2	0	1	0	1	0	3	1	3	1	2	0	2	0
	(E)	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
2	(F)	1	2	1	1	1	2	1	1	2	4	1	3	1	3	1	2
	(E)	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
3	(F)	1	2	0	0	0	2	0	0	1	3	1	1	1	2	1	0
	(E)	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
4	(F)	2	1	0	2	2	1	0	2	4	2	0	4	2	1	0	2
	(E)	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
5	(F)	3	0	2	1	2	0	2	0	5	1	4	1	3	0	2	1
	(E)	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
6	(F)	1	0	0	3	1	0	0	2	2	0	0	1	1	0	0	4
	(E)	0	0	0	1	0	0	0	2	0	0	0	1	0	0	0	3
1	(F)	2	1	0	1	4	3	1	1	2	2	1	1	4	3	1	1
	(E)	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
2	(F)	1	0	2	1	3	1	4	3	1	0	2	1	3	1	4	2
	(E)	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0
3	(F)	1	0	0	1	2	0	1	2	1	0	1	1	1	0	1	2
	(E)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
4	(F)	2	2	3	3	6	5	6	7	3	2	3	3	5	5	5	6
	(E)	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0
5	(F)	3	1	1	3	7	2	2	6	3	1	1	3	7	2	1	5
	(E)	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
6	(F)	1	1	2	0	3	1	4	1	1	1	2	0	3	1	4	0
	(E)	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
7	(F)	0	0	3	2	1	0	7	4	0	0	3	2	1	0	6	4
	(E)	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
8	(F)	3	2	2	1	7	6	5	3	3	3	2	1	6	5	4	3
	(E)	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
9	(F)	2	0	1	4	6	0	3	5	3	0	1	3	5	0	2	6
	(E)	0	0	0	4	1	0	1	1	0	0	0	3	0	0	0	3
1	(F)	2	2	1	1	2	1	0	0	2	2	1	1	2	1	0	1
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	(F)	2	0	2	1	1	0	1	1	2	1	2	2	1	0	1	1
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	(F)	1	0	1	1	1	0	0	1	1	0	1	1	1	0	0	1
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

4	(F)	3	3	3	3	2	2	2	2	3	3	3	4	2	2	2	2
	(E)	0	0	0	1	0	0	0	0	1	1	1	0	0	0	0	0
5	(F)	4	1	1	3	3	1	1	2	4	1	1	3	3	1	1	2
	(E)	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
6	(F)	2	1	2	0	1	0	2	0	2	1	2	0	1	0	2	0
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	(F)	0	0	4	2	0	0	2	1	1	0	4	2	0	0	3	2
	(E)	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
8	(F)	3	3	2	2	2	2	2	1	4	3	3	2	2	2	2	1
	(E)	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
9	(F)	3	0	1	1	2	0	1	3	3	0	1	3	2	0	1	2
	(E)	0	0	0	2	0	0	0	1	1	0	0	1	0	0	0	4
1	(F)	8	2	9	2	11	2	13	3	13	3	16	3	7	1	8	2
	(E)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2	(F)	5	12	4	7	7	17	6	10	9	21	7	12	5	11	4	6
	(E)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
3	(F)	3	10	2	2	4	13	3	3	5	17	4	4	2	9	2	2
	(E)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
4	(F)	10	6	0	11	14	8	0	14	18	10	1	18	9	5	0	9
	(E)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
5	(F)	13	2	10	3	18	2	14	4	22	3	17	5	11	1	9	3
	(E)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
6	(F)	6	1	1	8	8	1	1	9	10	1	1	13	5	1	1	6
	(E)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
1	(F)	2	2	1	0	2	2	0	0	2	1	0	0	1	1	0	0
	(E)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2	(F)	2	1	0	3	1	0	0	3	1	0	0	2	1	0	0	2
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	(F)	1	4	3	0	1	3	3	0	1	2	2	0	0	2	2	0
	(E)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	(F)	3	3	1	1	3	3	1	1	2	2	1	0	2	2	1	0
	(E)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	(F)	4	2	1	2	4	2	1	1	3	1	0	3	2	1	0	2
	(E)	0	0	0	2	1	0	0	1	0	0	0	1	0	0	0	2
	(F)	1	1	0	0	2	2	1	1	2	2	1	1	2	1	0	1
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	(F)	1	0	1	1	2	1	2	1	1	0	2	1	1	0	2	1
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	(F)	0	0	0	1	1	0	1	1	1	0	1	1	1	0	0	1
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	(F)	2	2	2	2	3	3	3	4	3	2	3	3	2	2	2	3
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	(F)	2	1	1	2	4	1	1	3	3	1	1	3	3	1	1	2
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	(F)	1	0	1	0	2	1	2	0	1	1	2	0	1	1	2	0
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	(F)	0	0	2	1	1	0	4	2	0	0	3	2	0	0	3	2
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	(F)	2	2	1	1	4	3	2	0	3	3	2	1	3	2	2	1
	(E)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	(F)	2	0	1	6	3	0	1	2	2	0	1	2	2	0	1	4
	(E)	0	0	0	1	0	0	0	0	0	0	0	3	0	0	0	1
	(F)	4	3	1	0	3	2	1	0	6	5	1	0	4	3	1	0
	(E)	1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0
	(F)	3	1	0	5	2	1	0	4	4	1	0	8	2	1	0	5
	(E)	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	(F)	1	6	4	0	1	5	4	0	2	10	7	1	1	6	4	0
	(E)	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0
	(F)	5	5	2	1	4	4	2	1	8	8	3	2	5	5	2	1
	(E)	1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0
	(F)	6	3	1	2	6	3	1	5	10	5	2	8	6	3	1	2
	(E)	1	0	0	1	0	0	0	2	1	0	0	1	1	0	0	1

```
 1   (F)  5    8    6    5     6   10    8    7     6    9    7    7     5    8    6    6
     (E)  0    0    0    0     1    2    2    0     0    0    0    0     1    1    0    0

 2   (F)  3    3    4    2     4    5    5    3     4    4    4    3     3    3    4    3
     (E)  0    0    0    0     1    1    1    0     0    0    0    0     1    1    0    0

 3   (F)  2    1    1    0     2    1    1    2     2    1    1    2     2    1    1    0
     (E)  0    0    0    0     1    0    0    0     0    0    0    0     0    0    0    0

 4   (F)  6    7    0    1     8   10    0    3     8    9    0    1     6    7    0    1
     (E)  0    0    0    2     2    2    0    1     0    0    0    1     1    1    0    1

ERIOD #   5  ----------------  6  ----------------  7  ----------------  8  ----------------
CKET  #   1    2    3    4     1    2    3    4     1    2    3    4     1    2    3    4
TEM#

 1   (F)  7   11    9    8     5    9    7    6     5    9    7    6     5    8    6    6
     (E)  1    1    1    0     1    1    1    0     0    0    0    0     1    1    0    0

 2   (F)  5    5    5    4     4    4    4    3     4    4    4    3     4    4    4    3
     (E)  1    1    0    0     1    1    1    0     0    0    0    0     1    1    0    0

 3   (F)  2    2    1    0     2    1    1    0     2    1    1    0     2    1    1    1
     (E)  0    0    0    0     0    0    0    0     0    0    0    0     0    0    0    0

 4   (F)  9   11    1    2     7    8    0    2     7    8    0    1     7    8    0    1
     (E)  1    1    0    1     1    1    0    1     0    0    0    2     1    0    0    1

 1   (F)  2    1    0    1     2    2    1    1     2    1    0    1     2    1    0    1
     (E)  0    0    0    0     0    0    0    0     0    0    0    0     0    0    0    0

 2   (F)  1    0    2    1     1    0    2    1     1    0    1    1     1    0    2    1
     (E)  0    0    0    0     0    0    0    0     0    0    0    0     0    0    0    0

 3   (F)  1    0    0    1     1    0    1    1     1    0    0    1     1    0    1    1
     (E)  0    0    0    0     0    0    0    0     0    0    0    0     0    0    0    0

 4   (F)  2    2    2    3     3    3    3    3     2    2    2    2     3    2    3    3
     (E)  0    0    0    0     0    0    0    0     1    1    1    0     0    0    0    0

 5   (F)  3    1    1    2     4    1    1    3     3    1    1    2     3    1    1    3
     (E)  0    0    0    0     0    0    0    0     1    0    0    0     0    0    0    0

 6   (F)  1    0    2    0     2    1    2    0     1    0    2    0     1    1    2    0
     (E)  0    0    0    0     0    0    0    0     0    0    0    0     0    0    0    0

 7   (F)  0    0    3    2     0    0    3    2     0    0    3    2     0    0    3    2
     (E)  0    0    0    0     0    0    0    0     0    0    0    0     0    0    0    0

     (F)  3    2    2    1     3    3    2    2     2    2    2    1     3    2    2    1
     (E)  0    0    0    0     0    0    0    0     1    1    0    0     0    0    0    0

     (F)  2    0    1    3     3    0    1    1     2    0    1    2     2    0    1    3
     (E)  0    0    0    3     0    0    0    4     1    0    0    1     0    0    0    4

     (F)  2    1    0    0     3    2    1    0     2    2    0    0     3    2    1    0
     (E)  0    0    0    0     1    0    0    0     1    0    0    0     0    0    0    0

     (F)  1    0    0    2     2    1    0    4     2    0    0    3     2    1    0    4
     (E)  0    0    0    0     0    0    0    0     0    0    0    0     0    0    0    0

     (F)  1    3    2    0     1    5    4    0     1    4    3    0     1    4    3    0
     (E)  0    0    0    0     0    1    0    0     0    1    0    0     0    0    0    0

     (F)  3    2    1    1     4    4    2    1     3    3    1    1     4    3    1    1
     (E)  0    0    0    0     1    0    0    0     1    0    0    0     0    0    0    0

     (F)  3    2    1    3     5    2    1    4     4    2    1    1     5    2    1    2
     (E)  0    0    0    0     1    0    0    1     1    0    0    1     0    0    0    2

     (F)  2    2    2    3     2    2    2    2     1    2    2    2     2    2    2    3
     (E)  0    0    0    0     0    0    0    0     0    0    1    0     0    0    0    0

     (F)  1    1    0    2     1    1    0    2     1    1    0    1     1    1    0    2
     (E)  0    0    0    0     0    0    0    0     0    0    0    0     0    0    0    0

     (F)  1    0    0    1     1    0    0    1     0    0    0    1     1    0    0    1
     (E)  0    0    0    0     0    0    0    0     0    0    0    0     0    0    0    0

     (F)  2    0    2    1     2    0    1    1     2    0    1    0     2    0    2    1
     (E)  0    0    0    0     0    0    0    0     1    0    0    0     0    0    0    0

     (F)  3    2    0    1     3    2    0    1     2    2    0    1     3    2    0    1
     (E)  0    0    0    0     0    0    0    0     1    0    0    0     0    0    0    0

     (F)  1    1    2    1     1    1    2    1     1    1    2    1     1    1    2    1
     (E)  0    0    0    0     0    0    0    0     0    0    1    0     0    0    0    0

     (F)  0    1    1    3     0    0    1    2     0    0    0    2     0    1    1    3
     (E)  0    0    0    0     0    0    0    0     0    0    0    0     0    0    0    0

     (F)  3    0    2    3     2    0    2    2     2    0    1    4     3    0    2    4
     (E)  0    0    0    4     0    0    0    3     1    0    0    1     0    0    0    0
```

```
DESCRIPTION OF PROBLEM NUMBER -   4
=================================================================================================
NUMBER OF CELLS              =   7        NUMBER OF PERIODS        =  10
NUMBER OF GROUPS             =  15        NUMBER OF ROUTES         =   3
NUMBER OF BUCKETS/PERIOD     =   4        NUMBER OF KEY CELLS      =   5
TOTAL LOAD INDEX             = 0.4327     REGULAR LOAD INDEX       = 0.6978

CELL PARAMETERS:
----------------

CELL #                   1      2      3      4      5      6      7
CELL CAPACITY(HRS)  2414.7 2313.2 1463.6 2012.3 1872.5 1886.8 2335.9
MAX REG CAP (HRS)   1727.8 1639.1  777.1 1038.5 1037.5 1116.3 1531.3
TRANS RESOURCE       331.3  295.7    0.0    0.0  140.5  254.1  208.5

GROUP PARAMETERS:
-----------------

GROUP #                  1     2     3     4     5     6     7     8     9    10    11    12    13    14    15
DESIRED INV LEVEL     38.0  15.0  38.0  52.0  13.0  32.0  28.0  38.0  37.0  37.0  16.0   7.0  35.0  27.0  22.
NO. OF ITEMS IN GROUP    5     8     9     6     5     8     5     4     7     8     5     5     7     4     5

GROUP DEMAND SCHEDULE:
----------------------

PERIOD #                 1     2     3     4     5     6     7     8     9    10
GROUP #  1    (F)      213   196   323   284   131   171   262   136   298   134
              (E)       20     8    35     3     8    22    14    15    41     4

GROUP #  2    (F)      124    73    62    48    63    68   118   124    96   119
              (E)       18    12    10     1     9     8    11    24     3    10

GROUP #  3    (F)      262   226   188   231   158   193   206   182   152   208
              (E)       41    28    16    46    16     9    25    24    12    18

GROUP #  4    (F)      209   175   393   295   226   165   167   390   185   398
              (E)        0     8    72    28    21     4     4    55    10     1

GROUP #  5    (F)       73    49    79    75    69    46   114    91    45    78
              (E)        9     0     8     8    13     0    14    14     1    12

GROUP #  6    (F)      131   166   119   226   248   121   172   208   201   242
              (E)        3    17     9    34    41    14    12    17    20    12

GROUP #  7    (F)      106   181   166   239   227   207   173    97   206   138
              (E)       17     6    13    36    22     0    16     3    28    15

GROUP #  8    (F)      217   247   217   283   319   144   302   132   283   135
              (E)       18    38     6    30    13    10    48    19    45     7

GROUP #  9    (F)      161   265   245   131   123   153   216   133   141   121
              (E)        0    52     8     2     3    16    36     9     2    12

GROUP # 10    (F)      202   152   285   167   158   126   124   205   158   180
              (E)        2     4    37    21    12    11    11    24    12    32

GROUP # 11    (F)       87    79    52   128   101    51   109   105    59   123
              (E)        0    11     9    10    19     2    21    11    10     1

GROUP # 12    (F)       34    23    36    50    27    36    57    31    40    47
              (E)        0     2     1     8     3     0     3     3     5     2

GROUP # 13    (F)      145   131   123   181   197   140   242   281   223   151
              (E)        6    23    18     4    38    27    36    56    28    26

GROUP # 14    (F)      139   133    95   156   135   119    97   142   164   142
              (E)       10    11    18    28     6    22    16    25    16    14

GROUP # 15    (F)       73   174   153   142    70    70   182   141   114   110
              (E)        4     0    15    11     0     0     4    20    13    13
```

PROCESSING MATRIX

CELL #		1	2	3	4	5	6	7
GROUP# 1	RT-1	0.7	0.5	0.0	0.4	0.3	0.3	0.4
	RT-2	0.7	0.5	0.0	0.4	0.6	0.0	0.6
	RT-3	0.7	0.5	0.0	0.8	0.0	0.0	0.6
GROUP# 2	RT-1	0.1	0.7	0.4	0.5	0.0	0.0	0.0
	RT-2	0.1	0.7	0.4	0.5	0.0	0.0	0.0
	RT-3	0.1	1.0	0.0	0.8	0.0	0.0	0.0
GROUP# 3	RT-1	0.0	0.4	0.0	0.6	0.5	0.3	0.8
	RT-2	0.0	0.4	0.0	0.6	0.7	0.0	1.0
	RT-3	0.4	0.0	0.0	0.5	0.8	0.0	1.0
GROUP# 4	RT-1	0.0	0.6	0.4	0.4	0.5	0.5	0.6
	RT-2	0.0	0.6	0.7	0.0	0.7	0.5	0.6
	RT-3	0.7	0.0	0.0	0.0	0.7	0.5	0.6
GROUP# 5	RT-1	0.0	0.4	0.0	0.0	0.0	0.3	0.3
	RT-2	0.0	0.4	0.0	0.0	0.0	0.0	0.5
	RT-3	0.0	0.4	0.0	0.0	0.0	0.0	0.0
GROUP# 6	RT-1	0.7	0.0	0.0	0.5	0.3	0.6	0.7
	RT-2	0.7	0.0	0.0	0.8	0.0	0.9	0.7
	RT-3	0.7	0.0	0.0	0.8	0.0	0.9	0.7
GROUP# 7	RT-1	0.8	0.4	0.0	0.6	0.4	0.0	0.7
	RT-2	1.1	0.0	0.0	0.6	0.4	0.0	0.7
	RT-3	1.1	0.0	0.0	0.9	0.0	0.0	0.7
GROUP# 8	RT-1	0.6	0.6	0.4	0.0	0.5	0.5	0.8
	RT-2	0.6	0.9	0.0	0.0	0.5	0.5	0.8
	RT-3	0.6	0.9	0.0	0.0	0.0	0.8	0.8
GROUP# 9	RT-1	0.7	0.4	0.0	0.0	0.5	0.0	0.7
	RT-2	0.7	0.4	0.0	0.0	0.5	0.0	0.7
	RT-3	0.9	0.0	0.0	0.0	0.5	0.0	0.7
GROUP# 10	RT-1	0.6	0.8	0.0	0.6	0.5	0.6	0.7
	RT-2	0.6	0.8	0.0	1.1	0.0	1.0	0.7
	RT-3	1.1	0.0	0.0	1.1	0.0	1.0	0.7
GROUP# 11	RT-1	0.4	0.6	0.4	0.0	0.0	0.6	0.0
	RT-2	0.4	0.6	0.4	0.0	0.0	0.6	0.0
	RT-3	0.0	0.9	0.4	0.0	0.0	0.6	0.0
GROUP# 12	RT-1	0.8	0.7	0.0	0.4	0.0	0.4	0.7
	RT-2	0.8	0.7	0.0	0.4	0.0	0.4	0.7
	RT-3	0.8	0.7	0.0	0.4	0.0	0.4	0.7
GROUP# 13	RT-1	0.5	0.7	0.0	0.6	0.0	0.3	0.8
	RT-2	0.5	0.7	0.0	0.6	0.0	0.0	1.0
	RT-3	0.0	1.0	0.0	0.6	0.0	0.0	1.0
GROUP# 14	RT-1	0.5	0.5	0.5	0.5	0.6	0.3	0.6
	RT-2	0.5	0.5	0.5	0.5	0.9	0.0	0.9
	RT-3	0.5	0.5	0.5	0.5	0.9	0.0	0.9
GROUP# 15	RT-1	0.5	0.0	0.3	0.3	0.5	0.6	0.7
	RT-2	0.5	0.0	0.5	0.0	0.7	0.6	0.7
	RT-3	0.4	0.0	0.6	0.0	0.7	0.6	0.7

```
DESCRIPTION OF PROBLEM NUMBER -   6
==============================================================================================
NUMBER OF CELLS               =   9         NUMBER OF PERIODS      =  12
NUMBER OF GROUPS              =   6         NUMBER OF ROUTES       =   2
NUMBER OF BUCKETS/PERIOD      =   4         NUMBER OF KEY CELLS    =   1
TOTAL LOAD INDEX              = 0.4292      REGULAR LOAD INDEX     = 0.6801

CELL PARAMETERS:
----------------

CELL #                  1      2      3      4      5      6      7      8      9
CELL CAPACITY(HRS)    363.1  230.5  401.9  247.5  375.3  233.0  275.3  360.5  320.4
MAX REG CAP (HRS)     185.6  168.1  239.8  184.5  251.5  146.4  155.4  222.4  218.3
TRANS RESOURCE         41.3    0.0   42.1    0.0   51.2   29.5    0.0    0.0   27.5

GROUP PARAMETERS:
-----------------

GROUP #                 1      2      3      4      5      6
DESIRED INV LEVEL      6.0   12.0   19.0    4.0    3.0    4.0
NO. OF ITEMS IN GROUP   8      4      8      8      9      7

GROUP DEMAND SCHEDULE:
----------------------

PERIOD #                1     2     3     4     5     6     7     8     9    10    11    12
GROUP #  1   (F)       48    31    30    26    42    24    29    25    23    20    27    41
             (E)        9     0     5     1     4     2     4     1     3     1     3     7
GROUP #  2   (F)       89    81    82    91    89    88    61    45    74    99    86    83
             (E)       10    12     4    15    11     1     0     3    10    15     5    16
GROUP #  3   (F)      109   101    97   155   158   126   118    91   162    98   125   100
             (E)       12     9     3    25     4    14    16    12     9     8    15     1
GROUP #  4   (F)       29    39    24    23    17    36    25    27    29    29    19    29
             (E)        2     3     3     4     3     0     3     1     1     4     1     4
GROUP #  5   (F)       25    21    12    10    16    17    14    20    12    21    20    15
             (E)        0     1     1     1     1     1     0     2     0     1     1     2
GROUP #  6   (F)       28    33    17    35    25    16    33    34    14    20    33    20
             (E)        2     2     0     6     2     2     1     2     0     2     5     1

PROCESSING MATRIX
-----------------

CELL #                  1      2      3      4      5      6      7      8      9
GROUP#  1  RT-1        0.9    0.0    1.0    0.6    0.5    0.0    0.0    0.5    0.5
           RT-2        0.9    0.0    1.0    0.6    0.5    0.0    0.0    0.0    0.9
GROUP#  2  RT-1        0.8    0.4    1.0    0.0    0.5    0.7    0.6    0.5    0.9
           RT-2        1.2    0.0    1.4    0.0    0.5    0.7    0.6    0.5    0.9
GROUP#  3  RT-1        0.8 ·  0.0    0.0    0.0    0.6    0.4    0.8    0.8    0.0
           RT-2        0.8    0.0    0.0    0.0    0.9    0.0    1.0    0.8    0.0
GROUP#  4  RT-1        0.8    0.0    0.0    0.0    0.0    0.0    0.6    0.6    0.6
           RT-2        0.8    0.0    0.0    0.0    0.0    0.0    0.0    1.0    0.6
GROUP#  5  RT-1        0.9    0.4    0.5    0.0    0.8    0.7    0.5    0.6    0.9
           RT-2        1.2    0.0    0.8    0.8    0.0    0.7    0.6    0.5    0.9
GROUP#  6  RT-1        0.8    0.0    0.5    0.7    0.0    0.0    0.0    0.7    0.9
           RT-2        0.8    0.0    0.0    1.2    0.0    0.0    0.0    0.7    0.9
```

```
DESCRIPTION OF PROBLEM NUMBER -  12
==========================================================================================

NUMBER OF CELLS              =   8       NUMBER OF PERIODS        =  13

NUMBER OF GROUPS             =  13       NUMBER OF ROUTES         =   2

NUMBER OF BUCKETS/PERIOD     =   4       NUMBER OF KEY CELLS      =   5

TOTAL LOAD INDEX             = 0.5552    REGULAR LOAD INDEX       = 0.9472

CELL PARAMETERS:
----------------

CELL #                     1      2      3      4      5      6      7      8

CELL CAPACITY(HRS)    1753.9 1903.7 1408.9 2279.1 1451.6 2266.8 1323.9 1664.7

MAX REG CAP (HRS)      960.9 1073.5  974.2 1175.6  893.2 1252.6  962.9  944.3

TRANS RESOURCE         199.3  190.8  178.3  232.0  184.6  280.4  120.7  159.2

GROUP PARAMETERS:
-----------------

GROUP #                    1      2      3      4      5      6      7      8      9     10     11     12     13

DESIRED INV LEVEL       38.0   32.0   20.0   29.0   36.0   22.0   28.0   20.0    2.0   23.0   12.0   11.0   28.0

NO. OF ITEMS IN GROUP      6      8      6      7      9      5      4      7      4      5      6      5      9

GROUP DEMAND SCHEDULE:
----------------------

PERIOD #                   1      2      3      4      5      6      7      8      9     10     11     12     13

GROUP #  1    (F)        299    285    324    273    217    310    186    215    315    226    330    190    200
              (E)         35     30     44     42     27     19      6     28     10     25     37     31     29

GROUP #  2    (F)        261    216    257    144    155    272    175    101    171    244    192    240    270
              (E)         31     37     23     27     14     32      2      8      4     20     20     19     44

GROUP #  3    (F)         95    138    143    120    111    136    133    118     96    158    135    118     72
              (E)          5     17     11      1     12      5     14     10     16      2     11     12      8

GROUP #  4    (F)        111    203    183    247    202    239    211    214    113    154    191    128    172
              (E)         15      2      7     31     40     14     27     39     17     30     37     14      1

GROUP #  5    (F)        154    267    244    170    206    154    235    284    310    222    304    174    193
              (E)         23      4     28      0     16      2     33      5     35      3     51      3      0

GROUP #  6    (F)        146     80    153    132    117    156    105    118    100    107     93    160    135
              (E)         21      1     13     17     11     23      0     15      5      9     15     27      9

GROUP #  7    (F)        225    112    162     96    194     93    186    115     92    141    168    104    219
              (E)         13     12     20     18     28     17      0      2      9     10     23     12      1

GROUP #  8    (F)        105     98    154    103     79    141     83     90     89     99     77    121    120
              (E)         11      0     12      7      0     24      4      8      4      7      0     20      7

GROUP #  9    (F)         14     18     14     13     16     24     15     20     16     14     22     13     17
              (E)          2      1      1      1      2      0      1      0      2      0      0      1      0

GROUP # 10    (F)        132    178    145    106    194    115    159    115     82     80     85    122    146
              (E)         11     17     24      1     26     16     14     10     12     12      9      3     10

GROUP # 11    (F)         60     69     55     66     39     50     67     53    104     95     58     62     82
              (E)          1      2     10      4      3      0      6      6     19      6      7      9      2

GROUP # 12    (F)         47     62     44     85     66     68     88     52     62     48     36     94     48
              (E)          2      7      0      8     11      1      6      4      8      3      1     16      3

GROUP # 13    (F)         98     95    124    213    192    156    154    232    188     96    219    162    209
              (E)          1     15     13     27     37      4      6     35     27      9      8     15     11
```

```
PROCESSING MATRIX
------------------

CELL #                   1      2      3      4      5      6      7      8

GROUP#  1  RT-1         0.7    0.0    0.7    0.0    0.0    1.4    0.0    0.9
           RT-2         0.0    0.7    0.7    0.0    0.0    1.4    0.0    0.9

GROUP#  2  RT-1         0.8    0.0    0.0    0.0    0.6    0.8    0.6    0.8
           RT-2         0.8    0.0    0.0    0.0    0.6    1.3    0.0    1.2

GROUP#  3  RT-1         1.1    0.7    0.0    0.0    0.8    0.7    0.0    0.7
           RT-2         1.1    0.7    0.0    0.0    1.3    0.0    0.0    0.7

GROUP#  4  RT-1         1.2    0.0    0.0    0.7    0.0    0.7    0.7    0.7
           RT-2         1.2    0.0    0.0    0.7    0.0    1.4    0.0    1.2

GROUP#  5  RT-1         0.0    0.9    1.0    0.0    0.0    1.6    0.0    0.8
           RT-2         0.0    0.9    1.0    0.0    0.0    1.6    0.9    0.0

GROUP#  6  RT-1         1.1    1.0    0.0    0.0    0.9    1.3    0.6    0.8
           RT-2         0.9    1.2    0.0    0.0    0.9    1.8    0.0    1.3

GROUP#  7  RT-1         0.7    0.7    0.7    0.0    0.0    1.0    0.8    0.8
           RT-2         0.7    1.3    0.0    0.0    0.0    1.0    0.7    0.9

GROUP#  8  RT-1         1.3    0.8    0.0    1.5    0.0    1.3    0.8    0.0
           RT-2         1.9    0.0    0.0    1.6    0.0    1.3    0.8    0.0

GROUP#  9  RT-1         0.7    1.0    0.0    1.3    0.0    1.2    0.0    0.0
           RT-2         0.0    1.5    0.0    1.3    0.0    1.2    0.0    0.0

GROUP# 10  RT-1         1.2    1.4    0.0    1.0    0.0    1.1    1.0    0.2
           RT-2         1.2    1.4    0.0    1.0    0.0    1.8    0.0    0.2

GROUP# 11  RT-1         0.0    1.3    1.1    1.2    0.7    0.9    0.8    1.1
           RT-2         0.0    1.3    1.1    1.8    0.0    1.3    0.8    1.1

GROUP# 12  RT-1         0.0    0.9    1.0    0.0    0.0    0.9    0.7    0.0
           RT-2         0.0    0.9    1.0    0.0    0.0    1.4    0.0    0.0

GROUP# 13  RT-1         0.9    1.0    1.0    0.0    0.0    0.9    0.0    0.0
           RT-2         0.0    1.6    0.9    0.0    0.0    1.0    0.0    0.0
```

APPENDIX B

This appendix describes the MA-Schedule decision policies for some of the experiments. This is the output from program RESULT-1. A description of each section in the policy follows.

1. CELL OPERATING STATUS - Since the system has capacity flexibility capability, it may shutdown cells for a period. This section defines when a cell is started and when it is shut down.
2. ACTIVE PROCESSING ROUTE - Since the system has routing flexibility capability, it may choose one from a set of possible routes. This matrix defines the route number followed in each period, by the different groups. Route changing within a period is not permitted.
3. PRODUCT INVENTORY - This tables defines the product inventory remaining at the end of period.
4. REGULAR/OVERTIME PROCESSING - Defines the required amounts of regular and overtime processing required to meet the schedule.
5. PRODUCTION QUANTITIES - The production quantity for each period.
6. TRANSPORTER ASSIGNMENT - Defines the assignment of transporters from the central pool to cells, on a period by period basis. Also, the transporter resources assigned to inter cell movement.
7. CELL UTILIZATION - A performance measure of the schedule, gives the utilization rate for the cells.
8. OBJECTIVE FUNCTION - Performance measure of the schedule. Gives a breakup of the objective function, by period.

```
MA-SCHEDULE DECISIONS FOR PROBLEM -  3
=================================================================================================

 CELL OPERATING STATUS
 ---------------------

 CELL # / PERIOD #      1     2    3    4    5    6    7    8    9    10
      1               START ON   ON   ON   ON   ON   ON   ON   ON   ON
      2               START ON   ON   ON   ON   ON   ON   ON   ON   ON
      3               START ON   ON   ON   ON   ON   ON   ON   ON   ON
      4               START ON   ON   ON   ON   ON   ON   ON   ON   ON
      5               START ON   ON   ON   ON   ON   ON   ON   ON   ON
      6               START ON   ON   ON   ON   ON   ON   ON   ON   ON
      7               START ON   ON   ON   ON   ON   ON   ON   ON   ON

ACTIVE PROCESSING ROUTES
------------------------

 GROUP # / PERIOD #     1    2    3    4    5    6    7    8    9    10
      1                 2.   2.   2.   2.   2.   2.   2.   2.   2.   2.
      2                 1.   UUU  UUU  1.   1.   1.   1.   1.   1.   1.
      3                 2.   2.   2.   2.   2.   2.   2.   2.   2.   2.
      4                 2.   2.   2.   2.   2.   2.   2.   2.   2.   2.
      5                 2.   UUU  2.   2.   2.   2.   2.   2.   2.   2.
      6                UUU   2.   2.   2.   2.   2.   UUU  2.   2.   2.
      7                 1.   2.   1.   1.   1.   1.   1.   1.   1.   1.
      8                 2.   2.   2.   2.   2.   2.   2.   2.   2.   2.
      9                 2.   2.   2.   2.   2.   2.   2.   2.   2.   2.
     10                 2.   2.   2.   2.   2.   2.   2.   2.   2.   2.
     11                 1.   1.   1.   1.   1.   1.   1.   1.   1.   1.
     12                 2.   2.   2.   2.   2.   2.   2.   2.   2.   2.
```

```
PRODUCT INVENTORY
-----------------

GRP#/PERD#     1      2      3      4      5      6      7      8      9     10
    1        97.0   63.0   53.0   73.0   90.0   72.0   64.0   67.0   69.0   50.0
    2       216.0    0.0    0.0   58.7   31.5   55.8   59.0   68.0  109.0   67.0
    3        29.0   24.0   24.0   22.0   28.0   51.0   38.0   42.0   27.0   23.0
    4        41.0   44.0   35.0   30.0   48.0   41.0   39.0   45.0   40.0   44.0
    5        61.0    0.0   54.0   34.0   47.6   35.4   40.0   42.0   20.0   20.0
    6        56.0  144.0   60.0  112.0   52.0   56.0   75.0   62.0   90.0   55.0
    7        67.0   43.0   77.0   48.0   66.0   60.0   35.0   56.0   30.0   68.0
    8       168.0  160.0  233.0  120.0  149.0  124.0  221.0  195.0  132.0  178.0
    9        43.0   31.0   24.0   21.0   19.0   40.0   36.0   33.0   39.0   48.0
   10        48.0   57.0   65.0   44.0   66.0   35.0   37.0   51.0   51.0   47.0
   11        61.0   64.0   96.0   57.0  110.0  117.0   98.0   85.0   51.0   93.0
   12        61.1   83.9   68.0   64.0   77.0   76.0  111.0  120.0  153.0   65.0

REGULAR/OVERTIME PROCESSING
---------------------------

CELL#/PER#     1      2      3      4      5      6      7      8      9     10
  1 (R)     240.3  110.4  110.4  110.4  126.9  126.9  126.9  139.3  149.6  150.5
    (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
  2 (R)     286.1  288.3  257.3  287.2  268.9  262.9  249.6  266.2  264.9  227.3
    (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
  3 (R)     523.7  414.1  399.5  392.9  428.4  441.5  447.1  474.9  478.1  410.1
    (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
  4 (R)     325.8  231.8  206.6  233.6  233.3  250.3  257.7  274.2  303.0  234.3
    (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
  5 (R)     388.3  388.3  388.3  388.3  388.3  388.3  388.3  388.3  388.3  388.3
    (O)     191.8   26.7   51.1   32.7   71.8   37.1   92.3  100.0   79.0   30.5
  6 (R)     456.0  275.9  333.6  295.2  393.8  412.7  379.6  403.7  369.5  359.2
    (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
  7 (R)     533.1  357.6  357.6  350.1  355.1  355.1  459.4  454.5  484.1  375.4
    (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
```

```
PRODUCTION QUANTITIES
---------------------

GROUP # / PERIOD #      1      2      3      4      5      6      7      8      9     10
      1(+)           10.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
       (-)            0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

      2(+)          132.0   49.0    0.0   19.7    3.2    0.0    0.0   11.0   11.0    0.0
       (-)            0.0    0.0    0.0    0.0    3.0    7.0    0.0    0.0    0.0    0.0

      3(+)            0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
       (-)            0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

      4(+)            0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
       (-)            0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

      5(+)           29.0    6.0    6.0    6.0    0.0    6.0    6.0    6.0    0.0    0.0
       (-)            0.0    0.0    0.0    0.0    0.4    0.0    0.0    0.0    0.0    0.0

      6(+)            0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
       (-)            0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

      7(+)            0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
       (-)            0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

      8(+)           31.0    0.0    0.0    0.0    0.0    0.0    0.0   31.0    0.0    0.0
       (-)            0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

      9(+)            5.0    0.0    0.0    0.0    0.0    0.0    5.0    0.0    0.0    0.0
       (-)            0.0    0.0    0.0    0.0    2.0    7.0    0.0    0.0    0.0    0.0

     10(+)            7.0    0.0    7.0    0.0    7.0    0.0    7.0    0.0    7.0    0.0
       (-)            0.0    0.0    0.0    0.0    0.0    3.0    0.0    0.0    0.0    0.0

     11(+)            0.0   13.0   13.0   13.0   13.0   13.0   13.0   13.0   13.0    0.0
       (-)            0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

     12(+)            5.1    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
       (-)            0.0    0.0    1.0    0.0    0.0    0.0   15.0    0.0    0.0    0.0

TRANSPORTER ASSIGNMENT  (CENTRAL CAP =  1374.1)
----------------------

     PERIOD #     1       2       3       4       5       6       7       8       9      10
CELL  1         57.7    26.5    26.5    26.5    30.5    30.5    30.5    33.4    35.9    36.1
CELL  2          0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
CELL  3         68.1    53.8    51.9    51.1    55.7    57.4    58.1    61.7    62.2    53.3
CELL  4          0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
CELL  5         14.1     0.0     0.0     0.0     0.0     0.0     0.2     1.2     0.0     0.0
CELL  6          0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
CELL  7          0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
INTER-CELL    1234.2   507.0   576.8   663.8   726.3   779.2   798.2   839.5   905.0   732.9
```

```
CELL UTILIZATION
----------------

CELL # / PERIOD #       1     2     3     4     5     6     7     8     9    10
       1               0.9   0.4   0.4   0.4   0.5   0.5   0.5   0.5   0.5   0.5
       2               0.7   0.7   0.6   0.7   0.6   0.6   0.6   0.6   0.6   0.5
       3               1.0   0.8   0.7   0.7   0.8   0.8   0.8   0.9   0.9   0.8
       4               0.8   0.6   0.5   0.6   0.6   0.6   0.6   0.7   0.7   0.6
       5               1.5   1.1   1.1   1.1   1.2   1.1   1.2   1.3   1.2   1.1
       6               0.7   0.4   0.5   0.5   0.6   0.7   0.6   0.6   0.6   0.6
       7               0.9   0.6   0.6   0.6   0.6   0.6   0.8   0.8   0.8   0.6

OBJECTIVE FUNCTION PERFORMANCE
------------------------------

      PERIOD #      1       2       3       4       5       6       7       8       9      10
INVENTORY COST   1574.9  1181.1  1381.1  1027.2  1280.6  1196.9  1370.4  1437.6  1212.0  1274.5
INV VAR COST      112.7   100.3    80.4    87.3    82.5    88.3    74.7    55.1    79.0   106.0
STRT-STOP COST   6734.1     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
CELL ON COST     9316.8  9316.8  9316.8  9316.8  9316.8  9316.8  9316.8  9316.8  9316.8  9316.8
OPERTNG COST     3061.5  2181.7  2164.1  2169.8  2336.6  2366.4  2528.4  2633.8  2684.1  2248.3
LOST QLTY COST    443.4   315.4   314.4   312.6   341.0   343.8   353.3   371.8   373.6   328.5
IDLE TIME COST      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0


TOTAL DECISION COST =   141576.30
```

```
MA-SCHEDULE DECISIONS FOR PROBLEM -  4
==========================================================================================

 CELL OPERATING STATUS
 ---------------------

 CELL # / PERIOD #      1     2     3     4     5     6     7     8     9     10
       1                START ON    ON    ON    ON    ON    ON    ON    ON    ON
       2                START ON    ON    ON    ON    ON    ON    ON    ON    ON
       3                START DOWN  OFF   START ON    DOWN  OFF   START DOWN  START
       4                START ON    ON    ON    ON    ON    ON    ON    ON    ON
       5                START ON    ON    ON    ON    ON    DOWN  START ON    ON
       6                START ON    ON    ON    ON    ON    ON    ON    ON    ON
       7                START ON    ON    ON    ON    ON    ON    ON    ON    ON

ACTIVE PROCESSING ROUTES
------------------------

 GROUP # / PERIOD #     1     2     3     4     5     6     7     8     9     10
        1               1.    1.    1.    1.    1.    1.    3.    1.    1.    1.
        2               2.    3.    3.    2.    1.    3.    3.    2.    3.    2.
        3               1.    1.    1.    1.    1.    1.    UUU   1.    1.    1.
        4               1.    3.    3.    1.    1.    3.    UUU   1.    3.    2.
        5               3.    3.    3.    3.    3.    3.    3.    3.    3.    3.
        6               2.    2.    2.    3.    2.    2.    2.    2.    2.    2.
        7               3.    1.    1.    1.    1.    1.    3.    1.    1.    1.
        8               3.    3.    3.    3.    3.    3.    3.    3.    3.    3.
        9               1.    1.    1.    2.    1.    1.    UUU   1.    2.    2.
       10               1.    2.    2.    1.    1.    2.    2.    1.    2.    2.
       11               3.    UUU   UUU   3.    3.    UUU   UUU   3.    UUU   3.
       12               2.    1.    1.    1.    3.    1.    1.    1.    1.    3.
       13               3.    3.    3.    3.    3.    3.    3.    3.    3.    3.
       14               1.    UUU   UUU   1.    1.    UUU   UUU   1.    UUU   1.
       15               3.    UUU   UUU   3.    3.    UUU   UUU   3.    UUU   1.
```

```
PRODUCTION QUANTITIES
---------------------

GRP#/PERD#    1      2      3      4      5      6      7      8      9     10

     1      233.0  204.0  358.0  287.0  139.0  199.8  269.2  151.0  339.0  138.0
     2      136.7   90.3   62.0   48.0   63.0   96.0  118.0  124.0   96.0  167.0
     3      303.0  254.0  204.0  277.0  174.0  433.0    0.0  206.0  164.0  226.0
     4      209.0  183.0  412.1  375.9  299.0  284.0    0.0  449.0  185.0  409.0
     5       82.0   49.0   87.0   83.0   82.0   46.0  128.0  105.0   46.0   90.0
     6      131.0  186.0  128.0  226.0  248.0  210.0  184.0  208.0  212.9  279.1
     7      106.0  204.0  179.0  275.0  249.0  207.0  189.0   97.0  237.0  153.0
     8      217.0  303.0  219.9  283.0  319.0  144.0  406.1  132.0  334.3  154.7
     9      161.0  317.0  253.0  133.0  126.0  385.0    0.0  178.0  143.0  133.0
    10      202.0  195.0  422.2   53.6  134.2  207.0  188.0  115.0  231.0  175.0
    11      218.0    0.0    0.0  174.0  264.0    0.0    0.0  198.0    0.0  134.0
    12       34.0   25.0   37.0   58.0   30.0   36.0   60.0   34.0   45.0   49.0
    13      151.0  189.0  106.0  185.0  235.0  167.0  313.0  257.6  295.4  177.0
    14      377.0    0.0    0.0  213.0  357.0    0.0    0.0  369.0    0.0  172.0
    15      402.7    0.0    0.0  178.2  300.0    0.0    0.0  255.0    0.0  173.1

REGULAR/OVERTIME PROCESSING
---------------------------

CELL#/PER#     1      2      3      4      5      6      7      8      9     10

   1 (R)    1091.7 1093.2 1346.8 1095.6 1132.1 1152.3  933.0  905.7 1180.8  921.7
     (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

   2 (R)    1480.0 1137.0 1161.8 1489.1 1623.8 1090.9 1155.8 1540.4 1287.6 1367.2
     (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

   3 (R)     674.0    0.0    0.0  475.6  634.0    0.0    0.0  673.5    0.0  538.9
     (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

   4 (R)    1038.5  891.7 1038.5 1038.5 1038.5 1032.2 1038.5 1038.5 1038.5 1021.2
     (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

   5 (R)    1037.5  572.7  717.6  886.1  946.1  773.1    0.0  956.3  505.0  779.2
     (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

   6 (R)    1116.3  847.0 1116.3 1116.3 1116.3  865.5  696.6 1088.0  955.6 1116.3
     (O)      61.9    0.0    0.0    0.0  134.4    0.0    0.0    0.0    0.0    0.0

   7 (R)    1531.3 1449.5 1531.3 1531.3 1531.3 1531.3 1241.3 1531.3 1531.3 1528.7
     (O)     157.2    0.0    6.1  178.0  270.4   47.0    0.0  129.0    0.0    0.0
```

```
GROUP # / PERIOD #      1     2     3     4     5     6     7     8     9    10
      1(+)            0.0   0.0   0.0   0.0   0.0   6.8   0.0   0.0   0.0   0.0
       (-)            0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
      2(+)            0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
       (-)            5.3   0.0  10.0  11.0  20.0   0.0  11.0  35.0  38.0   0.0
      3(+)            0.0   0.0   0.0   0.0   0.0 231.0   0.0   0.0   0.0   0.0
       (-)            0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
      4(+)            0.0   0.0   0.0   0.0  52.0 167.0   0.0   0.0   0.0   0.0
       (-)            0.0   0.0  52.9   0.0   0.0   0.0   4.0   0.0  10.0   0.0
      5(+)            0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
       (-)            0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
      6(+)            0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
       (-)            3.0   0.0   0.0  34.0  75.0   0.0   0.0  17.0  25.1   0.0
      7(+)            0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
       (-)           17.0   0.0   0.0   0.0   0.0   0.0   0.0   3.0   0.0   0.0
      8(+)            0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
       (-)           18.0   0.0   3.1  33.1  46.1  56.1   0.0  19.0  12.7   0.0
      9(+)            0.0   0.0   0.0   0.0   0.0 216.0   0.0   0.0   0.0   0.0
       (-)            0.0   0.0   0.0   0.0   0.0   0.0  36.0   0.0   0.0   0.0
     10(+)            0.0  37.0 137.2  23.8   0.0  37.0  90.0   0.0  37.0   0.0
       (-)            2.0   0.0   0.0  21.0  33.0   0.0   0.0  24.0   0.0   0.0
     11(+)          131.0  52.0   0.0  16.0 160.0 109.0   0.0  59.0   0.0   0.0
       (-)            0.0  11.0  20.0   0.0   0.0   2.0  23.0   0.0  10.0   0.0
     12(+)            0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
       (-)            0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
     13(+)            0.0  35.0   0.0   0.0   0.0   0.0  35.0   0.0   0.0   0.0
       (-)            0.0   0.0   0.0   0.0   0.0   0.0   0.0  44.4   0.0   0.0
     14(+)          228.0  95.0   0.0   0.0 216.0  97.0   0.0 164.0   0.0   0.0
       (-)            0.0  11.0  29.0   0.0   0.0  22.0  38.0   0.0  16.0   0.0
     15(+)          327.0 153.0   0.0  22.0 252.0 182.0   0.0 114.0   0.0   0.0
       (-)            1.3   1.3  16.3  13.1  13.1  13.1  17.1  37.1  50.1   0.0

TRANSPORTER ASSIGNMENT  (CENTRAL CAP =  8911.2)

    PERIOD #      1      2      3      4      5      6      7      8      9     10
 CELL  1        0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 CELL  2        0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 CELL  3      121.3    0.0    0.0   85.6  114.1    0.0    0.0  121.2    0.0   97.0
 CELL  4      155.8  133.8  155.8  155.8  155.8  154.8  155.8  155.8  155.8  153.2
 CELL  5       56.6    0.0    0.0   27.9   39.3    6.4    0.0   41.2    0.0    7.6
 CELL  6        0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 CELL  7      129.2   81.4   99.0  133.4  151.9  107.2   39.8  123.6   97.8   97.3
 INTER-CELL  4732.7 4364.8 4604.4 5301.9 5774.9 5030.4 2125.7 5451.8 4199.4 4648.7
```

```
CELL UTILIZATION
----------------

CELL # / PERIOD #      1    2    3    4    5    6    7    8    9    10
       1              0.6  0.6  0.8  0.6  0.7  0.7  0.5  0.5  0.7  0.5
       2              0.9  0.7  0.7  0.9  1.0  0.7  0.7  0.9  0.8  0.8
       3              0.9  UUU  UUU  0.6  0.8  UUU  UUU  0.9  UUU  0.7
       4              1.0  0.9  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0
       5              1.0  0.6  0.7  0.9  0.9  0.7  UUU  0.9  0.5  0.8
       6              1.1  0.8  1.0  1.0  1.1  0.8  0.6  1.0  0.9  1.0
       7              1.1  0.9  1.0  1.1  1.2  1.0  0.8  1.1  1.0  1.0

OBJECTIVE FUNCTION PERFORMANCE
------------------------------

      PERIOD #     1       2       3       4       5       6       7       8       9       10
INVENTORY COST   484.6   328.0   288.6   403.7   508.3   505.9   273.2   440.3   323.1   325.6
INV VAR COST      76.4    34.5    30.5    16.0    66.6    60.2    23.6    40.9    18.2    22.8
STRT-STOP COST   239.2     9.2     0.0    51.0     0.0     9.2    11.3   111.4     9.2    51.0
CELL ON COST     910.7   807.0   807.0   910.7   910.7   807.0   579.1   910.7   807.0   910.7
OPERTNG COST    3125.1  2291.9  2647.2  2969.1  3176.3  2555.8  1950.2  2978.4  2473.9  2727.4
LOST QLTY COST    59.8    41.5    47.8    56.0    60.2    47.1    32.0    57.6    44.0    52.2
IDLE TIME COST     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0


TOTAL DECISION COST =    41367.05
```

```
MA-SCHEDULE DECISIONS FOR PROBLEM -  6
==================================================================================

 CELL OPERATING STATUS
 ---------------------

 CELL # / PERIOD #        1     2     3     4     5     6     7     8     9     10    11    12
      1                  START ON    ON    ON    ON    ON    ON    ON    ON    ON    ON    ON
      2                  START ON    ON    DOWN  OFF   OFF   OFF   OFF   START DOWN  OFF   OFF
      3                  START ON    ON    DOWN  START ON    DOWN  START ON    DOWN  START ON
      4                  START DOWN  START DOWN  START ON    ON    ON    DOWN  OFF   DOWN  START
      5                  START ON    ON    ON    ON    ON    ON    DOWN  START DOWN  START ON
      6                  START ON    ON    ON    ON    DOWN  START ON    ON    DOWN  START ON
      7                  START ON    ON    ON    ON    ON    ON    DOWN  START DOWN  START ON
      8                  START ON    ON    ON    ON    ON    ON    ON    ON    ON    ON    ON
      9                  START ON    ON    ON    ON    ON    ON    ON    ON    ON    ON    ON
ACTIVE PROCESSING ROUTES
------------------------

 GROUP # / PERIOD #       1     2     3     4     5     6     7     8     9     10    11    12
       1                 2.    UUU   2.    UUU   2.    2.    UUU   UUU   UUU   UUU   2.    2.
       2                 1.    2.    2.    UUU   2.    UUU   UUU   UUU   2.    UUU   2.    2.
       3                 2.    2.    2.    1.    UUU   2.    UUU   UUU   UUU   UUU   2.    2.
       4                 2.    2.    2.    2.    UUU   2.    2.    2.    UUU   2.    UUU   2.
       5                 2.    1.    2.    UUU   UUU   UUU   UUU   UUU   1.    UUU   2.    2.
       6                 2.    UUU   2.    UUU   2.    1.    2.    1.    UUU   UUU   1.    1.
PRODUCTION QUANTITIES
---------------------

GRP#/PERD#     1       2       3       4       5       6       7       8       9      10      11      12
     1        79.0     0.0    59.0     0.0    39.0   146.0     0.0     0.0     0.0     0.0    27.0    56.0
     2       104.7   165.2   110.8     0.0   256.9     0.0     0.0     0.0   173.0     0.0   157.6   101.8
     3       109.0   120.0    78.0   313.0     0.0   212.0   293.7     0.0   163.4     0.0   125.0   153.9
     4        29.0    43.0    20.0    52.0     0.0    39.0    28.0    57.0     0.0    53.0     0.0    34.0
     5        28.0    43.5    63.5     0.0     0.0     0.0     0.0     0.0    33.0     0.0    20.0    26.0
     6        63.0     0.0    52.0     0.0    25.0    28.0    34.0    70.0     0.0     0.0    40.0    21.0
```

```
REGULAR/OVERTIME PROCESSING
---------------------------

CELL#/PER#      1      2      3      4      5      6      7      8      9     10     11     12

  1 (R)     185.6  185.6  185.6  185.6  185.6  185.6  185.6   95.9  185.6   39.8  185.6  185.6
    (O)     177.5  177.5  177.5   91.3  177.5  160.4   84.5    0.0  177.5    0.0  177.5  177.5

  2 (R)      25.0   17.8   16.2    0.0    0.0    0.0    0.0    0.0   13.5    0.0    0.0    0.0
    (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

  3 (R)     226.5  239.8  239.8    0.0  239.8  158.5    0.0   38.5  239.8    0.0  239.8  230.8
    (O)       0.0   12.9   13.0    0.0  158.0    0.0    0.0    0.0   18.6    0.0   46.0    0.0

  4 (R)     143.4    0.0  147.0    0.0   52.5  106.0   40.1   49.7    0.0    0.0   60.3   68.8
    (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

  5 (R)     186.3  222.1  151.7  236.7  142.0  260.9  249.1    0.0  252.7    0.0  201.1  214.3
    (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

  6 (R)      91.5  144.1  120.3   66.6  146.4    0.0   22.6    0.0  146.4    0.0  122.5   88.2
    (O)       0.0    0.0    0.0    0.0   30.8    0.0    0.0    0.0    1.3    0.0    0.0    0.0

  7 (R)     155.4  155.4  155.4  155.4  151.6  155.4  155.4    0.0  155.4    0.0  155.4  155.4
    (O)      29.5   81.2   25.0  119.9    0.0   50.3  119.9    0.0  119.9    0.0   71.2   70.1

  8 (R)     222.4  222.4  211.2  222.4  159.5  222.4  222.4  108.7  222.4   53.5  222.4  222.4
    (O)      10.0   31.9    0.0   77.4    0.0    4.9   62.7    0.0   20.9    0.0    1.8   17.3

  9 (R)     218.3  204.5  218.3   30.7  218.3  176.1   46.4   95.2  176.8   31.3  211.5  197.5
    (O)      37.6    0.0   40.5    0.0   59.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

PRODUCT INVENTORY
-----------------

GROUP # / PERIOD #     1     2     3     4     5     6     7     8     9    10    11    12

        1(+)        31.0   0.0  29.0   3.0   0.0 101.0  68.0  43.0  20.0   0.0   0.0   0.0
         (-)         9.0   9.0  14.0  15.0  19.0   0.0   0.0   1.0   4.0   5.0   8.0   0.0

        2(+)         5.7  88.3 117.1  26.1 194.0 106.0  45.0   0.0  99.0   0.0   0.0   0.0
         (-)         0.0  10.4  14.4  29.4  40.4  41.4  41.4  44.4  54.4  69.4   2.8   0.0

        3(+)         0.0  19.0   0.0 158.0   0.0  19.0 187.6  96.6  98.0   0.0   0.0   0.0
         (-)        12.0  21.0  24.0  49.0  53.0   0.0   8.9  20.9  29.9  37.9  52.9   0.0

        4(+)         0.0   4.0   0.0  17.0   0.0   0.0   0.0  29.0   0.0  19.0   0.0   0.0
         (-)         2.0   5.0   8.0   0.0   3.0   0.0   0.0   0.0   1.0   0.0   1.0   0.0

        5(+)         3.0  25.5  77.0  67.0  51.0  34.0  20.0   0.0  21.0   0.0   0.0   0.0
         (-)         0.0   1.0   2.0   3.0   4.0   5.0   5.0   7.0   7.0   8.0   9.0   0.0

        6(+)        33.0   0.0  35.0   0.0   0.0   0.0   0.0  34.0  20.0   0.0   0.0   0.0
         (-)         0.0   2.0   2.0   8.0  10.0   0.0   0.0   0.0   0.0   2.0   0.0   0.0
```

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-----------------------
     PERIOD #    1      2      3      4      5      6      7      8      9     10     11     12
 CELL  1       34.9   34.9   34.9   16.8   34.9   31.3   15.4    0.0   34.9    0.0   34.9   34.9
 CELL  2        2.5    1.8    1.6    0.0    0.0    0.0    0.0    0.0    1.4    0.0    0.0    0.0
 CELL  3        0.0    0.0    0.0    0.0   17.6    0.0    0.0    0.0    0.0    0.0    0.8    0.0
 CELL  4       18.6    0.0   19.1    0.0    6.8   13.8    5.2    6.5    0.0    0.0    7.8    8.9
 CELL  5        0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 CELL  6        C.0    0.7    0.0    0.0    7.7    0.0    0.0    0.0    1.5    0.0    0.0    0.0
 CELL  7       38.8   49.7   37.9   57.8   31.8   43.2   57.8    0.0   57.8    0.0   47.6   47.4
 CELL  8       51.1   56.0   46.5   66.0   35.1   50.0   62.7   23.9   53.5   11.8   49.3   52.7
 CELL  9        3.2    0.0    3.5    0.0    5.8    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 INTER-CELL   441.2  447.4  446.9   99.0  450.7  176.2  105.6  196.9  407.9   30.7  404.0  316.9

 CELL UTILIZATION
 ----------------
CELL # / PERIOD #     1    2    3    4    5    6    7    8    9   10   11   12
      1              2.0  2.0  2.0  1.5  2.0  1.9  1.5  0.5  2.0  0.2  2.0  2.0
      2              0.1  0.1  0.1  UUU  UUU  UUU  UUU  UUU  0.1  UUU  UUU  UUU
      3              0.9  1.1  1.1  UUU  1.7  0.7  UUU  0.2  1.1  UUU  1.2  1.0
      4              0.8  UUU  0.8  UUU  0.3  0.6  0.2  0.3  UUU  UUU  0.3  0.4
      5              0.8  0.9  0.6  0.9  0.5  1.1  1.0  UUU  1.0  UUU  0.9  0.9
      6              0.6  1.0  0.8  0.5  1.2  UUU  0.2  UUU  1.0  UUU  0.8  0.6
      7              1.2  1.5  1.2  1.8  1.0  1.3  1.8  UUU  1.8  UUU  1.5  1.5
      8              1.0  1.1  0.9  1.3  0.7  1.0  1.3  0.5  1.1  0.2  1.0  1.1
      9              1.2  0.9  1.2  0.1  1.3  0.8  0.2  0.4  0.8  0.1  1.0  0.9
OBJECTIVE FUNCTION PERFORMANCE
------------------------------
       PERIOD #      1        2        3        4        5        6        7        8        9       10       11       12
INVENTORY COST     884.3    871.3   1167.3   1172.7   1136.0   1199.0   1296.3    743.9   1205.1    211.4    678.9    633.3
INV VAR COST        79.3    110.0    253.4    227.6    264.8    220.5    278.1    171.1    215.4     53.2     45.9     45.9
STRT-STOP COST    2199.6    164.9    238.3    379.4    384.8    154.2    431.0    444.0    779.9    666.3   1359.7    334.1
CELL ON COST     10637.1   9332.0  10637.1   6820.6   9349.1   8487.1   8125.7   6735.1   9332.0   3344.5   9349.1   9349.1
OPERTNG COST        48.4     49.6     48.2     41.4     47.9     40.8     40.2     10.2     51.6      3.4     48.1     46.6
LOST QLTY COST     564.8    537.8    576.3    415.7    538.4    435.8    404.0    126.7    554.0     36.6    541.9    514.0
IDLE TIME COST       0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0      0.0

TOTAL DECISION COST =   129920.70
```

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MA-SCHEDULE DECISIONS FOR PROBLEM - 12
==================================================================================

 CELL OPERATING STATUS
 ---------------------

 CELL # / PERIOD #    1     2     3     4     5     6     7     8     9     10    11    12    13
      1               START ON    ON    ON    ON    ON    ON    ON    ON    DOWN  START ON    ON
      2               START ON    ON    ON    ON    ON    ON    ON    ON    ON    ON    ON    ON
      3               START ON    ON    ON    ON    ON    DOWN  START ON    ON    ON    ON    DOWN
      4               START ON    DOWN  START DOWN  START DOWN  START DOWN  OFF   START ON    ON
      5               START DOWN  START ON    ON    DOWN  OFF   START ON    DOWN  START DOWN  OFF
      6               START ON    ON    ON    ON    ON    ON    ON    ON    ON    ON    ON    ON
      7               START ON    ON    ON    ON    ON    ON    ON    ON    ON    ON    DOWN  START
      8               START ON    ON    ON    ON    ON    ON    ON    ON    ON    ON    ON    ON

ACTIVE PROCESSING ROUTES
------------------------

GROUP # / PERIOD #    1     2     3     4     5     6     7     8     9     10    11    12    13
      1               UUU   UUU   1.    UUU   1.    UUU   UUU   UUU   1.    2.    UUU   1.    UUU
      2               1.    UUU   1.    1.    1.    UUU   UUU   1.    1.    UUU   1.    UUU   UUU
      3               2.    UUU   2.    2.    2.    UUU   UUU   2.    2.    UUU   2.    UUU   UUU
      4               1.    1.    UUU   1.    UUU   1.    UUU   1.    UUU   UUU   1.    2.    1.
      5               1.    1.    2.    1.    UUU   1.    UUU   1.    UUU   UUU   UUU   1.    UUU
      6               1.    UUU   1.    UUU   1.    UUU   UUU   UUU   1.    UUU   1.    UUU   UUU
      7               2.    1.    UUU   2.    UUU   UUU   2.    UUU   UUU   UUU   UUU   UUU   2.
      8               2.    2.    UUU   2.    UUU   2.    UUU   2.    UUU   UUU   2.    UUU   1.
      9               2.    2.    UUU   2.    UUU   2.    UUU   2.    UUU   UUU   2.    2.    2.
     10               1.    1.    UUU   1.    UUU   1.    UUU   1.    UUU   UUU   1.    2.    UUU
     11               1.    UUU   UUU   1.    UUU   UUU   UUU   1.    UUU   UUU   1.    UUU   UUU
     12               1.    1.    1.    1.    1.    1.    UUU   1.    1.    1.    1.    UUU   UUU
     13               UUU   1.    1.    UUU   1.    1.    UUU   2.    1.    2.    2.    1.    UUU
```

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PRODUCTION QUANTITIES
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GRP#/PERD#     1      2      3      4      5      6      7      8      9     10     11     12     13
     1      303.4  304.2  324.0  273.0  255.0  458.0    0.0  215.0  315.0  602.4  196.0  487.0    0.0
     2      477.0    0.0  348.0  150.9  602.0    0.0    0.0  101.0  443.3    0.0  856.8    0.0    0.0
     3      233.0    0.0  176.0  316.3  196.7    0.0    0.0  357.1  384.6    0.0   33.3    0.0    0.0
     4      111.0  410.0    0.0  480.0    0.0  563.1    0.0  408.7    0.0    0.0  191.0  128.0  350.2
     5      154.0  303.0  208.0  372.4  210.6  182.0    0.0  284.0  310.0  675.0    0.0  421.0    0.0
     6      226.0    0.0  493.0    0.0  288.0    0.0    0.0    0.0  549.4    0.0  211.6    0.0    0.0
     7      225.0  112.0  208.9   49.1  222.0   65.0  856.2    0.0    0.0    0.0    0.0    0.0  333.8
     8      105.0  285.5    0.0  148.5    0.0  244.0    0.0  258.0    0.0    0.0  198.0    0.0  224.0
     9       14.0   34.0    0.0   27.0    0.0   41.0    0.0   48.0    0.0    0.0   22.0   13.0   28.0
    10      132.0  323.0    0.0  300.0    0.0  297.0    0.0  254.0    0.0    0.0   85.0  122.0  311.0
    11      184.0    0.0    0.0  222.0    0.0    0.0    0.0  252.0    0.0    0.0  277.0    0.0    0.0
    12       47.0  101.9   47.3   41.8  154.3   78.7    0.0   41.0   62.0  222.2   73.8    0.0    0.0
    13       98.0  123.0  309.0    0.0  364.2  137.8    0.0  232.0  188.0  135.6  191.0  567.4    0.0

REGULAR/OVERTIME PROCESSING
---------------------------

CELL#/PER#      1      2      3      4      5      6      7      8      9     10     11     12     13
   1 (R)     960.9  960.9  960.9  960.9  960.9  960.9  642.1  960.9  960.9    0.0  960.9  960.9  960.9
     (O)     762.5  793.0  701.0  793.0  723.5  793.0    0.0  793.0  793.0    0.0  793.0  147.4  338.8
   2 (R)    1073.5 1073.5 1073.5 1073.5 1073.5 1073.5 1073.5 1073.5 1073.5 1073.5 1073.5 1073.5 1073.5
     (O)     434.1    0.0  294.8  423.1  278.9    0.0   13.9  689.8  299.0  334.7  111.4   46.8    0.0
   3 (R)     690.8  799.0  868.3  824.9  974.2  724.0    0.0  932.5  760.5  974.2  668.4  974.2    0.0
     (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0  434.7    0.0  315.8    0.0
   4 (R)     620.8 1099.2    0.0 1175.6    0.0 1121.4    0.0 1175.6    0.0    0.0  898.4  228.9  919.9
     (O)       0.0    0.0    0.0    0.0    0.0    0.0    0.0  140.7    0.0    0.0    0.0    0.0    0.0
   5 (R)     893.1    0.0  893.1  646.4  893.1    0.0    0.0  687.0  893.1    0.0  893.1    0.0    0.0
     (O)      32.7    0.0    0.0    0.0    0.0    0.0    0.0    0.0  378.4    0.0   64.7    0.0    0.0
   6 (R)    1252.6 1252.6 1252.6 1252.6 1252.6 1252.6  873.3 1252.6 1252.6 1252.6 1252.6 1252.6 1252.6
     (O)    1014.2 1014.2 1014.2 1014.2 1014.2 1014.2    0.0 1014.2 1014.2 1014.2 1014.2 1014.2    0.0
   7 (R)     962.9  962.9  896.1  962.9  962.9  962.9  556.5  962.9  876.8  305.0  962.9    0.0  918.7

     (O)     103.2   15.0    0.0  111.7    0.0    0.0    0.0   70.9    0.0    0.0  361.0    0.0    0.0

   8 (R)     944.3  944.3  944.3  944.3  944.3  944.3  762.0  944.3  944.3  944.3  944.3  944.3  604.4
     (O)     669.7   14.9  287.5  630.2  329.2  123.4    0.0  427.5  427.5    0.0  544.3   11.7    0.0
```

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PRODUCT INVENTORY
-----------------

GROUP # / PERIOD #   1     2     3     4     5     6     7     8     9    10    11    12    13
      1(+)          0.0   0.0   0.0   0.0  38.0 186.0   0.0   0.0   0.0 134.0   0.0 229.0   0.0
       (-)         30.6  41.4  85.4 127.4 154.4 173.4 179.4 207.4 217.4   0.0  37.0   0.0   0.0
      2(+)        216.0   0.0   0.0   0.0 447.0 175.0   0.0   0.0 244.0   0.0 573.0 314.0   0.0
       (-)         31.0  68.0   0.0  20.1  34.1  66.1  68.1  76.1  51.8  71.8   0.0   0.0   0.0
      3(+)        138.0   0.0   0.0 195.3 269.0 133.0   0.0 210.1 482.7 322.7 210.0  80.0   0.0
       (-)          5.0  22.0   0.0   0.0   0.0   5.0  19.0   0.0   0.0   0.0   0.0   0.0   0.0
      4(+)          0.0 190.0   0.0 202.0   0.0 283.3  72.3 267.0 154.0   0.0   0.0   0.0   0.0
       (-)         15.0   0.0   0.0   0.0  40.0  13.2  40.2  79.2  96.2 126.2 163.2 177.2   0.0
      5(+)          0.0  36.0   0.0 202.4 207.0 235.0   0.0   0.0   0.0 304.0   0.0 193.0   0.0
       (-)         23.0  27.0  55.0  55.0  71.0  73.0 106.0 111.0 146.0   0.0  51.0   0.0   0.0
      6(+)         80.0   0.0 340.0 208.0 379.0 223.0 118.0   0.0 343.4 227.4 331.0 144.0   0.0
       (-)         21.0  22.0  35.0  52.0  63.0  86.0  86.0 101.0   0.0   0.0   0.0   0.0   0.0
      7(+)          0.0   0.0  46.9   0.0  28.0   0.0 620.0 505.0 413.0 272.0 104.0   0.0   0.0
       (-)         13.0  25.0  45.0  63.0  91.0 108.0  57.8  59.8  68.8  78.8 101.8 113.8   0.0
      8(+)          0.0 187.5  33.5  79.0   0.0 103.0  20.0 188.0  99.0   0.0 121.0   0.0   0.0
       (-)         11.0  11.0  23.0  30.0  30.0  54.0  58.0  66.0  70.0  77.0  77.0  97.0   0.0
      9(+)          0.0  16.0   2.0  16.0   0.0  17.0   2.0  30.0  14.0   0.0   0.0   0.0   0.0
       (-)          2.0   3.0   4.0   5.0   7.0   7.0   8.0   8.0  10.0  10.0  10.0  11.0   0.0
     10(+)          0.0 145.0   0.0 194.0   0.0 182.0  23.0 162.0  80.0   0.0   0.0   0.0   0.0
       (-)         11.0  28.0  52.0  53.0  79.0  95.0 109.0 119.0 131.0 143.0 152.0 155.0   0.0
     11(+)        124.0  55.0   0.0 156.0 117.0  67.0   0.0 199.0  95.0   0.0 155.0  84.0   0.0
       (-)          1.0   3.0  13.0  17.0  20.0  20.0  26.0  32.0  51.0  57.0   0.0   0.0   0.0
     12(+)          0.0  39.9  43.2   0.0  88.3  99.0  11.0   0.0   0.0 124.2 161.0  51.0   0.0
       (-)          2.0   9.0   9.0  17.0  28.0  29.0  35.0  39.0  47.0   0.0   0.0   0.0   0.0
     13(+)          0.0  28.0 213.0   0.0 172.2 154.0   0.0   0.0   0.0  28.0   0.0 220.0   0.0
       (-)          1.0  16.0  29.0  56.0  93.0  97.0 103.0 138.0 165.0 162.4 170.4   0.0   0.0

TRANSPORTER ASSIGNMENT  (CENTRAL CAP =  2987.2)
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    PERIOD #    1      2      3      4      5      6      7      8      9     10     11     12     13
CELL  1       59.2   63.8   50.0   63.8   53.3   63.8    0.0   63.8   63.8    0.0   63.8    0.0    0.0
CELL  2       80.6    2.4   55.5   78.6   52.6    2.4    4.9  126.6   56.2   62.7   22.5   10.9    2.4
CELL  3        0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0   61.2    0.0   40.9    0.0
CELL  4        0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
CELL  5        9.8    0.0    3.0    0.0    3.0    0.0    0.0    0.0   82.4    0.0   16.5    0.0    0.0
CELL  6       36.9   36.9   36.9   36.9   36.9   36.9    0.0   36.9   36.9   36.9   36.9   36.9    0.0
CELL  7       71.2   55.3   40.6   72.7   52.6   52.6    0.0   65.4   37.1    0.0  117.6    0.0   44.6
CELL  8       99.1    0.0   37.9   92.8   44.6   11.7    0.0   60.3   60.3    0.0   79.0    0.0    0.0
INTER-CELL  2630.4 2711.0 2763.3 2642.4 2499.2 2782.4 1498.3 2634.2 2471.5  674.1 2650.9 1359.7 2435.7
```

```
CELL UTILIZATION
----------------

CELL # / PERIOD #     1    2    3    4    5    6    7    8    9   10   11   12   13
       1             1.8  1.8  1.7  1.8  1.8  1.8  0.7  1.8  1.8  UUU  1.8  1.2  1.4
       2             1.4  1.0  1.3  1.4  1.3  1.0  1.0  1.6  1.3  1.3  1.1  1.0  1.0
       3             0.7  0.8  0.9  0.8  1.0  0.7  UUU  1.0  0.8  1.4  0.7  1.3  UUU
       4             0.5  0.9  UUU  1.0  UUU  1.0  UUU  1.1  UUU  UUU  0.8  0.2  0.8
       5             1.0  UUU  1.0  0.7  1.0  UUU  UUU  0.8  1.4  UUU  1.1  UUU  UUU
       6             1.8  1.8  1.8  1.8  1.8  1.8  0.7  1.8  1.8  1.8  1.8  1.8  1.0
       7             1.1  1.0  0.9  1.1  1.0  1.0  0.6  1.1  0.9  0.3  1.4  UUU  1.0
       8             1.7  1.0  1.3  1.7  1.3  1.1  0.8  1.5  1.5  1.0  1.6  1.0  0.6

OBJECTIVE FUNCTION PERFORMANCE
------------------------------

        PERIOD #     1       2       3       4       5       6       7       8       9      10      11      12      13
INVENTORY COST     375.0   432.3   263.0   542.7   548.1   685.4   574.1   770.1   672.5   451.7   614.0   486.0   225.4
INV VAR COST        42.1    36.8    38.1    68.9    86.5    91.5    73.1   102.7   108.8    76.1    93.8    79.5    19.1
STRT-STOP COST     135.3     8.2    10.9    29.0     8.0    25.3    18.0    76.1     7.4    22.8    70.6    23.0    34.7
CELL ON COST       556.4   541.4   461.6   556.4   461.6   541.4   367.0   556.4   461.6   358.7   556.4   483.5   461.8
OPERTNG COST      3144.4  2554.7  2959.3  3160.9  3023.9  2533.1   986.3  3380.8  3173.4  2317.1  3010.4  2412.9  1461.7
LOST QLTY COST      99.8    83.0    85.3   104.5    88.4    83.3    34.4   107.1    91.6    46.2   104.1    55.2    58.5
IDLE TIME COST       0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0


TOTAL DECISION COST =    49682.52
```

APPENDIX C

This appendix describes the CP1-Schedule decision policy for expt #3.

```
CP1-SCHEDULE DECISIONS FOR PROBLEM -  3
==========================================================================================

PERIOD  1 PRODUCTION QUANTITIES
------------------------------

 GRP#-ITEM#  1-1   1-2   1-3   1-4   2-1   2-2   2-3   2-4   2-5   2-6   2-7   2-8   2-9

BUCKET - 1   7.0   5.0   2.0   9.0   3.0   2.0   1.0   4.0   4.0   2.0   1.0   4.0   3.0
BUCKET - 2  11.0   5.0   1.0  11.0   3.0   1.0   0.0   5.0   2.0   1.0   0.0   6.6   5.0
BUCKET - 3  10.0   7.0   1.0   2.0   7.0  10.0   4.0  19.2   6.0   7.0   8.0   7.4   4.0
BUCKET - 4  21.3   4.0   3.0   4.0   6.0  12.0   5.0  14.8  18.7   8.0   5.6  15.0  10.7

 GRP#-ITEM#  3-1   3-2   3-3   3-4   3-5   4-1   4-2   4-3   4-4   4-5   4-6   4-7   4-8

BUCKET - 1   2.0   1.0   1.0   2.0   3.0   2.0   1.0   1.0   4.0   6.0   1.0   0.0   2.0
BUCKET - 2   1.0   0.0   5.0   3.0   3.0   2.0   1.0   0.0   0.0   0.0   4.0   3.0   7.0
BUCKET - 3   0.0   0.0   0.0   0.0   0.0   7.0   4.0   2.0   0.0   0.0   1.0   0.0   3.0
BUCKET - 4   0.0   2.0   0.0   0.0   6.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

 GRP#-ITEM#  5-1   5-2   5-3   5-4   5-5   5-6   6-1   6-2   6-3   6-4   6-5   6-6   6-7   6-8   6-9

BUCKET - 1   2.0   3.0   3.0   3.0   3.0   1.0   3.0   4.0   1.0   4.0   4.0   2.0   0.0   5.0   2.0
BUCKET - 2   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 3   2.0   2.0   1.0   1.0   3.0   0.0   1.0   0.0   1.0   6.0   4.0   2.0   5.0   3.0   9.0
BUCKET - 4   6.0   8.0   3.0   8.2   5.0   9.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

 GRP#-ITEM#  7-1   7-2   7-3   7-4   7-5   7-6   7-7   7-8   7-9   8-1   8-2   8-3   8-4   8-5   8-6

BUCKET - 1   4.0   2.0   2.0   3.0   5.0   2.0   0.0   4.0   3.0  15.4   5.0   3.0  10.0  13.0   6.0
BUCKET - 2   1.0   2.0   0.0   6.0   2.0   3.0   5.0   5.0   1.0   5.6  23.0  11.5  17.0   2.0   1.0
BUCKET - 3   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0  19.5   0.0  19.0  17.0
BUCKET - 4   1.0   2.0   1.0   6.0   5.0   0.0   3.0   3.0   4.0   0.0   0.0   0.0   0.0   0.0   0.0

 GRP#-ITEM#  9-1   9-2   9-3   9-4   9-5  10-1  10-2  10-3  10-4  10-5  10-6  10-7  10-8  10-9

BUCKET - 1   2.0   2.0   1.0   3.0   4.0   1.0   1.0   0.0   8.0   2.0   1.0   0.0   2.0   5.0
BUCKET - 2   2.0   1.0   4.0   3.0   2.1   3.0   3.0   1.0   0.0   5.0   2.0   3.0   6.0   5.0
BUCKET - 3   1.0   4.0   5.0   2.0   6.9   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 4   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

 GRP#-ITEM# 11-1  11-2  11-3  11-4  11-5  12-1  12-2  12-3  12-4

BUCKET - 1   4.0   3.0   1.0   5.0   6.0   5.0   9.0   2.0   6.0
BUCKET - 2   3.0   1.0   6.0   5.0   3.0  24.1   3.0   2.0  10.0
BUCKET - 3   3.0   6.0   5.0   5.0   5.0   0.0   0.0   0.0   0.0
BUCKET - 4   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
PERIOD  2 PRODUCTION QUANTITIES
------------------------------

 GRP#-ITEM#  1-1   1-2   1-3   1-4   2-1   2-2   2-3   2-4   2-5   2-6   2-7   2-8   2-9

BUCKET - 1   6.0   5.0   1.0   8.0   4.0   0.0   0.0   4.0   5.0   0.0   0.0   5.0   0.0
BUCKET - 2   4.0   5.0   1.0  10.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 3   8.0   7.0   3.0   2.0   1.0   3.0   1.0   1.0   1.0   3.0   4.0   3.0   1.0
BUCKET - 4   0.0   0.0   0.0   0.0   1.0   2.0   1.0   1.0   3.0   0.0   4.4   2.0   3.0
```

```
 GRP#-ITEM#   3-1    3-2    3-3    3-4    3-5    4-1    4-2    4-3    4-4    4-5    4-6    4-7    4-8

BUCKET - 1    2.0    1.0    1.0    2.0    3.0    2.0    1.0    1.0    4.0    5.0    1.0    0.0    3.0
BUCKET - 2    1.0    0.0    4.0    3.0    1.0    4.0    1.0    0.0    0.0    1.0    3.0    3.0    5.0
BUCKET - 3    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 4    1.0    2.0    0.0    0.0    5.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

 GRP#-ITEM#   5-1    5-2    5-3    5-4    5-5    5-6    6-1    6-2    6-3    6-4    6-5    6-6    6-7    6-8    6-9

BUCKET - 1    0.0    0.0    0.0    0.0    0.0    0.0    4.0    3.0    2.0    6.0    7.0    3.0    1.0    7.0    6.0
BUCKET - 2    0.0    0.0    0.0    0.0    0.0    0.0    5.0    6.2    1.0    7.0    4.0    2.0    0.0    8.0    4.0
BUCKET - 3    0.0    0.0    0.0    0.0    0.0    0.0    1.0    0.8    0.0    6.0    2.0    4.2    7.0    5.0    0.0
BUCKET - 4    2.9    6.5    4.0    5.8    7.0    2.0    1.0    4.0    3.0    9.0    7.0    1.8    5.0    4.0    7.0

 GRP#-ITEM#   7-1    7-2    7-3    7-4    7-5    7-6    7-7    7-8    7-9    8-1    8-2    8-3    8-4    8-5    8-6

BUCKET - 1    3.0    2.0    2.0    6.0    5.0    3.0    2.0    6.0    6.0   14.0   25.0    4.0   23.0   19.0    8.0
BUCKET - 2    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 3    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0   16.0   16.0    3.0   14.0   14.0    4.0
BUCKET - 4    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

 GRP#-ITEM#   9-1    9-2    9-3    9-4    9-5   10-1   10-2   10-3   10-4   10-5   10-6   10-7   10-8   10-9

BUCKET - 1    3.0    0.0    0.0    4.0    3.0    2.0    2.0    1.0    6.0    4.0    2.0    1.0    5.0    3.0
BUCKET - 2    2.0    0.0    3.0    3.0    2.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 3    0.0    3.0    3.0    2.0    3.0    2.0    3.0    2.0    7.0    4.0    2.0    6.0    2.0    3.0
BUCKET - 4    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

 GRP#-ITEM#  11-1   11-2   11-3   11-4   11-5   12-1   12-2   12-3   12-4

BUCKET - 1    3.0    2.0    1.0    4.0    6.0    4.0    5.0    3.0   10.0
BUCKET - 2    3.0    1.0    5.1    7.0    3.0   12.0   14.9    1.0   12.0
BUCKET - 3    0.0    4.0    5.9    8.0   11.0   14.9    0.1    3.0    4.0
BUCKET - 4    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
PERIOD   3 PRODUCTION QUANTITIES
 --------------------------------


 GRP#-ITEM#   1-1    1-2    1-3    1-4    2-1    2-2    2-3    2-4    2-5    2-6    2-7    2-8    2-9

BUCKET - 1    6.0    3.0    5.0    6.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 2   14.7    8.0    0.0    7.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 3    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 4    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

 GRP#-ITEM#   3-1    3-2    3-3    3-4    3-5    4-1    4-2    4-3    4-4    4-5    4-6    4-7    4-8

BUCKET - 1    1.0    1.0    1.0    2.0    3.0    3.0    2.0    0.0    3.0    5.0    2.0    0.0    2.0
BUCKET - 2    1.0    1.0    2.0    3.0    1.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 3    0.0    1.0    2.0    0.0    5.0    4.0    1.0    1.0    0.0    0.0    3.0    2.0    7.0
BUCKET - 4    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

 GRP#-ITEM#   5-1    5-2    5-3    5-4    5-5    5-6    6-1    6-2    6-3    6-4    6-5    6-6    6-7    6-8    6-9

BUCKET - 1    0.0    0.0    0.0    0.0    0.0    0.0    4.0    1.0    1.0    5.0    4.0    2.0    0.0    6.0    3.0
BUCKET - 2    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 3    4.0    2.5    2.0    0.0    5.0    2.0    2.0    3.0    2.0    6.0    4.0    2.0    5.0    3.0    7.0
BUCKET - 4    4.2   12.0    4.0   17.0    9.0   10.3    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
```

```
GRP#-ITEM#   7-1   7-2   7-3   7-4   7-5   7-6   7-7   7-8   7-9   8-1   8-2   8-3   8-4   8-5   8-6

BUCKET - 1   3.0   2.0   2.0   3.0   4.0   2.0   1.0   4.0   4.0  13.0   9.0   5.0  18.0  22.0  10.0
BUCKET - 2   2.0   3.0   0.0   6.0   2.0   3.0   4.0   6.0   0.0   3.0  21.0  17.0  10.0   3.0   1.0
BUCKET - 3   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0  19.0   8.0   4.0   1.0  17.0   1.0
BUCKET - 4   1.0   2.0   1.0   7.0   4.0   0.0   2.0   4.0   5.0   0.0  11.0   4.0  18.0   5.0  13.0

GRP#-ITEM#   9-1   9-2   9-3   9-4   9-5  10-1  10-2  10-3  10-4  10-5  10-6  10-7  10-8  10-9

BUCKET - 1   2.0   1.0   1.0   2.0   4.0   2.0   1.0   1.0   7.0   3.0   1.0   0.0   3.0   2.0
BUCKET - 2   1.0   2.0   4.0   3.0   4.0   3.0   2.0   1.0   1.0   2.0   3.0   3.0   5.0   1.0
BUCKET - 3   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 4   0.0   0.0   0.0   0.0   0.0   3.0   2.0   2.0   5.0   4.0   0.0   2.0   1.0   5.0

GRP#-ITEM#  11-1  11-2  11-3  11-4  11-5  12-1  12-2  12-3  12-4

BUCKET - 1   6.0   4.0   0.0   0.0   7.0   6.0   6.0   2.0   8.0
BUCKET - 2   5.0   1.0  10.0   8.0   5.0   9.0   3.0   1.0   9.0
BUCKET - 3   2.0   5.7   9.0   6.0   3.0  14.0   6.0   3.0   1.0
BUCKET - 4   4.0   4.3   2.6   5.0  16.0   0.0   0.0   0.0   0.0
PERIOD  4 PRODUCTION QUANTITIES
-------------------------------


GRP#-ITEM#   1-1   1-2   1-3   1-4   2-1   2-2   2-3   2-4   2-5   2-6   2-7   2-8   2-9

BUCKET - 1   6.0   4.0   2.0   8.0   2.0   1.0   0.0   3.0   3.0   1.0   0.0   6.0   2.0
BUCKET - 2  10.0   4.0   1.0   9.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 3  12.0   5.0   3.0   0.0   0.0   2.0   1.0   4.0   2.0   1.0   3.0   0.0   8.0
BUCKET - 4  14.0   3.0   0.0   3.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

GRP#-ITEM#   3-1   3-2   3-3   3-4   3-5   4-1   4-2   4-3   4-4   4-5   4-6   4-7   4-8

BUCKET - 1   1.0   1.0   0.0   4.0   2.0   1.0   1.0   0.0   2.0   4.0   1.0   2.0   6.0
BUCKET - 2   1.0   2.0   4.0   1.0   4.0   6.0   2.0   1.0   0.0   0.0   5.0   0.0   3.0
BUCKET - 3   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 4   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

GRP#-ITEM#   5-1   5-2   5-3   5-4   5-5   5-6   6-1   6-2   6-3   6-4   6-5   6-6   6-7   6-8   6-9

BUCKET - 1   0.0   0.0   0.0   0.0   0.0   0.0   4.0   3.0   1.0   5.0   7.0   5.0   1.0   6.0   5.0
BUCKET - 2   0.0   0.0   0.0   0.0   0.0   0.0   3.0   1.0   0.0   5.0   2.0   1.0   0.0   5.0   8.0
BUCKET - 3   2.0   1.0   1.0   0.0   3.0   3.4   1.0   5.0   1.0   5.0   1.0   4.0   6.0   4.0   0.0
BUCKET - 4   0.0   0.0   0.0   0.0   0.0   0.0   1.0   1.0   2.0   6.0   5.0   0.0   4.0   3.0   3.0

GRP#-ITEM#   7-1   7-2   7-3   7-4   7-5   7-6   7-7   7-8   7-9   8-1   8-2   8-3   8-4   8-5   8-6

BUCKET - 1   3.0   1.0   2.0   4.0   4.0   1.0   0.0   4.0   6.0  18.0   5.0   2.0   9.0  11.0   5.0
BUCKET - 2   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0  21.0  11.0   6.0  10.0   2.0
BUCKET - 3   1.0   2.0   0.0   6.0   3.0   2.0   5.0   3.0   3.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 4   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0  15.0  11.6   9.0  14.4

GRP#-ITEM#   9-1   9-2   9-3   9-4   9-5  10-1  10-2  10-3  10-4  10-5  10-6  10-7  10-8  10-9

BUCKET - 1   2.0   1.0   4.0   5.0   3.0   2.0   1.0   1.0   3.0   3.0   1.0   0.0   7.0   2.0
BUCKET - 2   0.0   0.0   0.0   0.0   0.0   1.0   2.0   0.0   6.0   2.0   3.0   3.0   0.0   3.0
BUCKET - 3   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 4   2.0   3.0   1.0   0.0   4.0   2.0   1.0   1.0   1.0   4.0   1.0   2.0   3.0   5.0
```

```
 BUCKET - 1    0.0    0.0    0.0    0.0    0.0    6.0    6.0    2.0    8.0
 BUCKET - 2    4.0    1.0    8.4    7.0    3.0    9.0    4.0    1.0    8.0
 BUCKET - 3    0.0    0.0    0.0    0.0    0.0   14.0    5.0    1.0    2.0
 BUCKET - 4    8.0   10.0    1.0    2.0   13.5    0.0    0.0    0.0    0.0
PERIOD   5 PRODUCTION QUANTITIES
 -------------------------------


  GRP#-ITEM#   1-1    1-2    1-3    1-4    2-1    2-2    2-3    2-4    2-5    2-6    2-7    2-8    2-9

 BUCKET - 1    2.0    6.0    2.0   10.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 BUCKET - 2    8.8    6.0    2.0   12.0    1.0    1.0    0.0    4.0    2.0    2.0    3.0    4.0    1.0
 BUCKET - 3   13.0    5.0    1.0    1.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 BUCKET - 4   10.2    8.0    0.2    3.0    1.0    1.0    0.0    3.0    2.0    0.0    2.0    1.0    3.3

  GRP#-ITEM#   3-1    3-2    3-3    3-4    3-5    4-1    4-2    4-3    4-4    4-5    4-6    4-7    4-8

 BUCKET - 1    3.0    1.0    4.0    5.0    5.0    4.0    2.0    1.0    4.0    5.0    2.0    2.0    5.0
 BUCKET - 2    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 BUCKET - 3    0.0    2.0    2.0    2.0    4.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 BUCKET - 4    0.0    0.0    0.0    0.0    0.0    3.0    2.0    1.0    1.0    1.0    1.0    3.0    7.0

  GRP#-ITEM#   5-1    5-2    5-3    5-4    5-5    5-6    6-1    6-2    6-3    6-4    6-5    6-6    6-7    6-8    6-9

 BUCKET - 1    0.0    0.0    0.0    0.0    0.0    0.0    3.0    3.0    1.0    6.0    5.0    4.0    3.0    7.0    3.0
 BUCKET - 2    2.0    5.0    6.0    3.0    1.0    1.1    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 BUCKET - 3    4.0    1.0    0.0    0.0    3.0    1.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 BUCKET - 4    0.0    0.0    0.0    0.0    0.0    0.0    2.8    1.0    1.0    6.0    2.0    0.0    5.2    1.0    6.0

  GRP#-ITEM#   7-1    7-2    7-3    7-4    7-5    7-6    7-7    7-8    7-9    8-1    8-2    8-3    8-4    8-5    8-6

 BUCKET - 1    4.0    1.0    1.0    3.0    4.0    2.0    0.0    7.0    3.0   10.0   19.0    3.0   15.4   14.0    6.0
 BUCKET - 2    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 BUCKET - 3    3.0    4.0    2.0    9.0    5.0    2.0    5.0    4.0    5.0   13.0   13.0    3.0   10.0   11.0    1.6
 BUCKET - 4    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

  GRP#-ITEM#   9-1    9-2    9-3    9-4    9-5   10-1   10-2   10-3   10-4   10-5   10-6   10-7   10-8   10-9

 BUCKET - 1    1.0    1.0    0.0    2.0    6.0    2.0    1.0    1.0    3.0    3.0    1.0    0.0    3.0    6.0
 BUCKET - 2    1.0    1.0    4.0    3.0    1.0    2.0    0.0    0.0    8.0    1.0    1.0    0.0    6.0    2.0
 BUCKET - 3    0.0    0.0    0.0    0.0    0.0    2.0    3.0    2.0    1.0    4.0    2.0    5.0    0.0    1.0
 BUCKET - 4    0.0    0.0    0.0    0.0    0.0    0.0    2.0    0.0    3.0    4.0    2.0    3.0    5.0    1.0

  GRP#-ITEM#  11-1   11-2   11-3   11-4   11-5   12-1   12-2   12-3   12-4

 BUCKET - 1    0.0    0.0    3.0   10.0    2.5    6.0    5.0    2.0    9.0
 BUCKET - 2    5.9    2.0   12.0    9.0    6.6    9.0    4.0    1.0   10.0
 BUCKET - 3    1.1    1.0    9.0    4.0    2.0   10.0    9.0    3.0    0.0
 BUCKET - 4    0.0   10.0    3.0   11.0    9.4   11.0   10.0    0 0    1.0
PERIOD   6 PRODUCTION QUANTITIES
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  GRP#-ITEM#   1-1    1-2    1-3    1-4    2-1    2-2    2-3    2-4    2-5    2-6    2-7    2-8    2-9

 BUCKET - 1    5.2    4.0    3.8    7.0    2.0    1.0    1.0    3.0    3.0    2.0    0.0    3.0    3.0
 BUCKET - 2    8.8    4.0    0.0    8.0    3.0    0.0    0.0    6.0    1.3    3.0    3.0    5.0    1.0
 BUCKET - 3    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
 BUCKET - 4   14.9    6.0    0.0    5.0    1.0    1.0    1.0    3.0    3.0    0.0    2.0    2.0    5.0
```

```
GRP#-ITEM#   3-1   3-2   3-3   3-4   3-5   4-1   4-2   4-3   4-4   4-5   4-6   4-7   4-8

BUCKET - 1   3.0   2.0   1.0   4.0   5.0   2.0   1.0   1.0   4.0   6.0   1.0   0.0   2.0
BUCKET - 2   3.0   1.0   6.0   5.6   3.0   6.0   3.0   1.0   0.0   0.0   4.0   3.0   7.0
BUCKET - 3   1.0   0.0   4.0   2.4   2.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 4   0.0   4.0   0.0   0.0   4.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

GRP#-ITEM#   5-1   5-2   5-3   5-4   5-5   5-6   6-1   6-2   6-3   6-4   6-5   6-6   6-7   6-8   6-9

BUCKET - 1   2.0   0.0   1.0   2.0   3.0   1.0   4.0   1.0   1.0   5.0   4.0   2.0   0.0   6.0   2.0
BUCKET - 2   2.0   2.0   2.0   1.0   2.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 3   0.0   0.0   0.0   0.0   0.0   0.0   1.0   3.0   2.0   3.0   4.0   2.0   3.0   3.0   4.0
BUCKET - 4   2.8   3.0   2.0   6.0   5.0   4.2   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

GRP#-ITEM#   7-1   7-2   7-3   7-4   7-5   7-6   7-7   7-8   7-9   8-1   8-2   8-3   8-4   8-5   8-6

BUCKET - 1   3.0   1.0   1.0   6.0   4.0   2.0   0.0   6.0   2.0   8.0  16.0  12.0  15.0  13.0   5.0
BUCKET - 2   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 3   1.0   3.0   2.0   7.0   5.0   2.0   6.0   4.0   5.0  10.0  10.0   4.0   9.0  12.0  10.0
BUCKET - 4   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

GRP#-ITEM#   9-1   9-2   9-3   9-4   9-5  10-1  10-2  10-3  10-4  10-5  10-6  10-7  10-8  10-9

BUCKET - 1   1.0   2.0   0.0   4.0   5.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 2   2.0   1.0   4.0   3.0   2.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 3   1.0   4.0   3.0   2.0   3.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 4   0.0   0.0   0.0   0.0   0.0   4.0   1.0   1.0   3.0   1.0   1.0   0.0   2.0   7.0

GRP#-ITEM#  11-1  11-2  11-3  11-4  11-5  12-1  12-2  12-3  12-4

BUCKET - 1   7.0   5.0   0.0   0.0  10.0   7.0   5.0   2.0   8.0
BUCKET - 2   5.0   2.0  11.0   9.0   6.0  10.0   1.0   1.0  10.0
BUCKET - 3   4.0   2.0  11.0   5.0   2.0  13.0   8.0   1.0   0.0
BUCKET - 4   1.0  10.0   3.0   4.0  20.0   3.0   0.0   2.0  17.0
PERIOD   7 PRODUCTION QUANTITIES
-------------------------------

GRP#-ITEM#   1-1   1-2   1-3   1-4   2-1   2-2   2-3   2-4   2-5   2-6   2-7   2-8   2-9

BUCKET - 1   6.0   4.0   3.0   7.0   2.0   1.0   1.0   3.0   4.0   1.0   0.0   3.0   3.0
BUCKET - 2   8.0   4.0   0.0   8.0   1.0   1.0   0.0   4.0   2.0   2.0   3.0   4.0   1.0
BUCKET - 3   9.0   7.0   1.0   3.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 4   0.0   0.0   0.0   0.0   1.0   1.0   1.0   4.0   2.0   0.0   2.0   2.0   3.0

GRP#-ITEM#   3-1   3-2   3-3   3-4   3-5   4-1   4-2   4-3   4-4   4-5   4-6   4-7   4-8

BUCKET - 1   2.0   2.0   1.0   3.0   4.0   1.0   1.0   0.0   4.0   6.0   1.0   1.0   3.0
BUCKET - 2   3.0   0.0   7.0   5.0   3.0   7.0   2.0   1.0   0.0   0.0   5.0   1.0   6.0
BUCKET - 3   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 4   0.0   3.0   1.0   1.0   3.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

GRP#-ITEM#   5-1   5-2   5-3   5-4   5-5   5-6   6-1   6-2   6-3   6-4   6-5   6-6   6-7   6-8   6-9

BUCKET - 1   0.0   0.0   0.0   0.0   0.0   0.0   4.2   3.0   1.0   6.0   5.0   3.0   1.0   7.0   3.0
BUCKET - 2   0.0   3.0   4.0   2.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 3   2.0   1.0   1.0   0.0   3.0   2.0   2.0   4.0   2.0   8.0   5.0   3.0   5.8   5.0   5.0
BUCKET - 4   4.1  12.1   8.0  16.9   8.0   5.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
```

```
 GRP#-ITEM#   7-1   7-2   7-3   7-4   7-5   7-6   7-7   7-8   7-9   8-1   8-2   8-3   8-4   8-5   8-6

BUCKET - 1    2.0   3.0   1.0   7.0   5.0   2.0   3.0   6.0   6.0  12.0   8.0   4.0  16.0  20.0   9.0
BUCKET - 2    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   3.0  19.0  15.0   9.0   3.0   1.0
BUCKET - 3    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0  16.0   9.0   4.0   3.0  17.0   1.0
BUCKET - 4    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   3.0  11.0   3.0  16.0   4.0  15.0

 GRP#-ITEM#   9-1   9-2   9-3   9-4   9-5  10-1  10-2  10-3  10-4  10-5  10-6  10-7  10-8  10-9

BUCKET - 1    2.0   1.0   1.0   3.0   3.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 2    2.0   0.0   3.0   2.0   4.6   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 3    2.0   2.0   2.0   4.0   2.4   0.0   3.0   1.0   3.0   1.0   1.0   2.0   2.0   7.0
BUCKET - 4    0.0   0.0   0.0   0.0   0.0   1.0   1.0   1.0   2.0   6.0   1.0   2.0   4.0   2.0

 GRP#-ITEM#  11-1  11-2  11-3  11-4  11-5  12-1  12-2  12-3  12-4

BUCKET - 1    5.0   4.0   0.0   8.0   0.0   6.0   0.0   4.0  12.0
BUCKET - 2    5.0   1.0  10.0   8.0   5.0  13.0   7.0   2.0   0.0
BUCKET - 3    3.0   1.0   8.2   7.0   3.0  12.0   7.0   2.0   1.0
BUCKET - 4    0.0  12.0   0.8   7.0  10.0  13.0   5.0   3.0   1.0
PERIOD  8 PRODUCTION QUANTITIES
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 GRP#-ITEM#   1-1   1-2   1-3   1-4   2-1   2-2   2-3   2-4   2-5   2-6   2-7   2-8   2-9

BUCKET - 1    5.0   5.0   2.0   8.0   2.0   1.0   1.0   3.0   3.0   1.0   0.0   5.0   2.0
BUCKET - 2    7.0   4.0   1.0   8.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 3   10.0   8.0   2.0   0.0   0.0   2.0   1.0   3.0   1.0   2.0   3.0   3.0   3.0
BUCKET - 4    4.1   6.0   0.0   8.0   0.0   1.0   1.0   2.0   3.0   0.0   2.0   0.0   5.0

 GRP#-ITEM#   3-1   3-2   3-3   3-4   3-5   4-1   4-2   4-3   4-4   4-5   4-6   4-7   4-8

BUCKET - 1    3.0   2.0   1.0   4.0   5.0   2.0   1.0   1.0   3.0   6.0   1.0   0.0   3.0
BUCKET - 2    3.0   1.0   7.0   4.0   3.0   4.0   1.0   0.0   2.0   0.0   3.0   5.0   2.0
BUCKET - 3    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 4    0.0   4.0   0.0   1.0   4.0   5.0   4.0   2.0   0.0   0.0   2.0   0.0   4.0

 GRP#-ITEM#   5-1   5-2   5-3   5-4   5-5   5-6   6-1   6-2   6-3   6-4   6-5   6-6   6-7   6-8   6-9

BUCKET - 1    0.0   0.0   0.0   0.0   0.0   0.0   4.0   2.0   1.0   6.0   5.0   3.0   0.0   6.0   3.0
BUCKET - 2    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 3    3.0   1.0   2.0   0.0   3.0   0.0   1.0   3.0   1.0   3.0   4.0   2.0   4.0   4.0   3.0
BUCKET - 4    0.0   0.0   0.0   0.0   0.0   0.0   3.0   2.0   2.0   7.0   0.0   0.0   7.0   4.0   0.0

 GRP#-ITEM#   7-1   7-2   7-3   7-4   7-5   7-6   7-7   7-8   7-9   8-1   8-2   8-3   8-4   8-5   8-6

BUCKET - 1    3.0   1.0   2.0   4.0   4.0   2.0   0.0   5.0   4.0   9.0   6.0   3.0  12.0  16.0   7.0
BUCKET - 2    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0  13.0  15.0  12.0   7.0   2.0   1.0
BUCKET - 3    1.0   3.0   0.0   6.0   4.0   2.0   5.0   3.0   7.0   2.0  14.0   3.0  13.0  12.0   6.0
BUCKET - 4    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0  10.0   5.0  11.0   0.0  16.0   8.0

 GRP#-ITEM#   9-1   9-2   9-3   9-4   9-5  10-1  10-2  10-3  10-4  10-5  10-6  10-7  10-8  10-9

BUCKET - 1    2.0   2.0   1.0   0.0   5.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 2    0.0   1.0   4.0   3.0   2.0   1.0   2.0   1.0   8.0   2.0   3.0   3.0   4.0   9.0
BUCKET - 3    1.0   0.0   3.0   2.0   4.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BUCKET - 4    3.0   5.0   1.0   0.0   1.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
```

```
 GRP#-ITEM#  11-1   11-2   11-3   11-4   11-5   12-1   12-2   12-3   12-4

BUCKET - 1    5.0    0.0    2.0    0.0    8.0    7.0    5.0    3.0   10.0
BUCKET - 2    4.0    1.0    8.0    7.0    3.0   17.0   11.0    3.0   14.8
BUCKET - 3    3.0    1.0    8.0    5.0    1.5   11.0    7.0    2.0    3.2
BUCKET - 4    1.0    9.0    6.0    3.0    9.5   11.0    4.0    0.0    7.0

PERIOD  9 PRODUCTION QUANTITIES
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 GRP#-ITEM#   1-1    1-2    1-3    1-4    2-1    2-2    2-3    2-4    2-5    2-6    2-7    2-8    2-9

BUCKET - 1    6.0    4.0    2.0    8.0    3.0    0.0    1.0    4.0    0.0    0.0    1.0    5.0    4.0
BUCKET - 2    9.0    1.0    1.0    9.0    3.0    1.0    0.0    4.0    3.0    1.0    0.0    6.0    0.0
BUCKET - 3   11.0    4.0    3.0    2.0    3.0    5.0    1.0    8.0    1.0    5.0    5.0    4.0    6.1
BUCKET - 4    3.0    3.0    0.0    0.0    1.0    2.0    2.0    5.0    5.0    0.0    3.0    2.0    3.9

 GRP#-ITEM#   3-1    3-2    3-3    3-4    3-5    4-1    4-2    4-3    4-4    4-5    4-6    4-7    4-8

BUCKET - 1    2.0    1.0    1.0    2.0    3.0    3.0    1.0    0.0    3.0    5.0    2.0    0.0    3.0
BUCKET - 2    1.0    0.0    3.0    3.0    1.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 3    0.0    0.0    2.0    0.0    6.0    3.0    0.0    0.0    1.0    1.0    3.0    2.0    7.0
BUCKET - 4    1.0    2.0    3.0    2.0    1.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

 GRP#-ITEM#   5-1    5-2    5-3    5-4    5-5    5-6    6-1    6-2    6-3    6-4    6-5    6-6    6-7    6-8    6-9

BUCKET - 1    0.0    0.0    0.0    0.0    0.0    0.0    4.0    0.0    0.0    5.0    6.0    2.0    1.0    2.0    5.0
BUCKET - 2    0.0    0.0    0.0    0.0    0.0    0.0    2.0    1.0    0.0    4.0    7.0    1.0    0.0    5.0    5.0
BUCKET - 3    2.0    1.0    0.0    0.0    3.0    3.0    1.0    6.0    2.0    5.0    0.0    3.0    5.0    3.0    0.0
BUCKET - 4    0.0    1.9    0.0    1.1    0.0    1.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

 GRP#-ITEM#   7-1    7-2    7-3    7-4    7-5    7-6    7-7    7-8    7-9    8-1    8-2    8-3    8-4    8-5    8-6

BUCKET - 1    2.0    3.0    0.0    5.0    4.0    2.0    3.0    5.0    6.0   10.0   19.0    7.0   18.0   14.0    6.0
BUCKET - 2    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 3    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 4    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    4.0   13.0    3.0   14.0    7.0    9.0

 GRP#-ITEM#   9-1    9-2    9-3    9-4    9-5   10-1   10-2   10-3   10-4   10-5   10-6   10-7   10-8   10-9

BUCKET - 1    0.0    1.0    1.0    4.0    4.0    2.0    1.0    1.0    8.0    3.0    1.0    0.0    2.0    2.0
BUCKET - 2    2.0    0.0    3.0    3.0    2.0    1.0    2.0    0.0    0.0    2.0    2.0    5.0    5.0    3.0
BUCKET - 3    1.0    0.0    3.0    2.0    4.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 4    0.0    3.0    3.0    0.0    4.0    3.0    1.0    2.0    2.0    6.0    1.0    0.0    3.0    2.0

 GRP#-ITEM#  11-1   11-2   11-3   11-4   11-5   12-1   12-2   12-3   12-4

BUCKET - 1    4.0    0.0    0.0    5.0    6.0   11.0    8.0    4.0   15.0
BUCKET - 2    3.0    1.0    6.0    4.0    1.0   23.0   10.0    4.0   18.4
BUCKET - 3    0.0    0.0    0.0    0.0    0.0   16.0   10.0    2.0    4.2
BUCKET - 4    0.0    5.0    0.0   10.0    6.0   15.0    6.0    3.0    3.5

PERIOD 10 PRODUCTION QUANTITIES
 ------------------------------


 GRP#-ITEM#   1-1    1-2    1-3    1-4    2-1    2-2    2-3    2-4    2-5    2-6    2-7    2-8    2-9

BUCKET - 1   10.0    3.0    2.0    5.0    3.0    0.0    1.0    4.0    4.0    2.0    1.0    0.0    3.0
BUCKET - 2    0.0    0.0    0.0    0.0    2.0    1.0    0.0    3.0    1.0    1.0    0.0    6.0    4.0
BUCKET - 3   10.0    5.0    2.0    3.0    1.0    2.0    1.0    4.0    1.0    3.0    4.0    2.0    0.0
BUCKET - 4    0.0    0.0    0.0    0.0    1.0    1.0    0.0    4.0    4.0    0.0    0.0    0.0    3.0
```

```
GRP#-ITEM#   3-1    3-2    3-3    3-4    3-5    4-1    4-2    4-3    4-4    4-5    4-6    4-7    4-8

BUCKET - 1   2.0    1.0    0.0    2.0    3.0    2.0    1.0    1.0    3.0    6.0    1.0    0.0    3.0
BUCKET - 2   0.0    0.0    0.0    0.0    0.0    2.0    1.0    0.0    2.0    0.0    2.0    5.0    5.0
BUCKET - 3   0.0    2.0    2.0    1.0    3.0    5.0    2.0    1.0    0.0    0.0    2.0    0.0    0.0
BUCKET - 4   0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

GRP#-ITEM#   5-1    5-2    5-3    5-4    5-5    5-6    6-1    6-2    6-3    6-4    6-5    6-6    6-7    6-8    6-9

BUCKET - 1   1.0    1.0    1.0    2.0    2.0    2.0    3.0    4.0    1.0    4.0    4.0    2.0    0.0    5.0    2.0
BUCKET - 2   1.0    3.0    0.0    2.0    1.0    2.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 3   0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    1.0    5.0    4.0    2.0    3.0    3.0    9.0
BUCKET - 4   0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0

GRP#-ITEM#   7-1    7-2    7-3    7-4    7-5    7-6    7-7    7-8    7-9    8-1    8-2    8-3    8-4    8-5    8-6

BUCKET - 1   4.0    3.0    1.0    6.0    5.0    3.0    1.0    7.0    3.0   10.0    7.0    3.0   13.0   16.0    7.0
BUCKET - 2   0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0   14.0   20.0   15.0    8.0   15.0    2.0
BUCKET - 3   2.0    3.0    2.0    7.0    4.0    2.0    6.0    5.0    4.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 4   0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    4.0   10.0    4.0   14.0    5.0   11.0

GRP#-ITEM#   9-1    9-2    9-3    9-4    9-5   10-1   10-2   10-3   10-4   10-5   10-6   10-7   10-8   10-9

BUCKET - 1   3.0    2.0    1.0    4.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 2   3.0    1.0    5.0    6.0    3.0    1.0    2.0    0.0    4.0    2.0    2.0    3.0    5.0    1.0
BUCKET - 3   0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
BUCKET - 4   1.0    4.0    1.0    3.0    3.0    1.0    1.0    1.0    5.0    2.0    0.0    3.0    2.0    3.0

GRP#-ITEM#  11-1   11-2   11-3   11-4   11-5   12-1   12-2   12-3   12-4

BUCKET - 1   7.0    5.0    2.0    0.0    8.0    5.0    8.0    2.0    7.0
BUCKET - 2   5.0    2.0   11.0    9.0    6.0   14.0    3.0    2.0    8.0
BUCKET - 3   2.0    1.0    8.0    4.0    2.0    0.0    0.0    0.0    0.0
BUCKET - 4   0.0    9.0    1.0    2.0    9.0    8.0    5.0    0.0    3.0
```

```
TOTAL PRODUCTION
--------------------

GRP#-PERD#  1        2        3        4        5        6        7        8        9        10
  1       103.3     60.0     49.7     84.0     90.2     66.7     60.0     78.1     66.0     40.0
  2       216.0     53.4      0.0     39.0     31.3     58.3     52.0     50.0     98.0     67.0
  3        29.0     26.0     24.0     20.0     28.0     51.0     38.0     42.0     34.0     16.0
  4        51.0     34.0     35.0     34.0     44.0     41.0     39.0     51.0     34.0     44.0
  5        63.2     28.2     72.0     10.4     27.1     41.0     72.1      9.0     13.0     18.0
  6        56.0    144.0     60.0    112.0     60.0     50.0     73.0     80.0     75.0     52.0
  7        75.0     35.0     77.0     50.0     64.0     60.0     35.0     56.0     30.0     68.0
  8       168.0    160.0    233.0    150.0    119.0    124.0    221.0    203.0    124.0    178.0
  9        43.0     31.0     24.0     25.0     20.0     37.0     34.0     40.0     40.0     40.0
 10        48.0     57.0     65.0     60.0     80.0     20.0     40.0     33.0     60.0     38.0
 11        61.0     64.0    103.6     57.9    101.5    117.0     98.0     85.0     51.0     93.0
 12        61.1     83.9     68.0     66.0     90.0     88.0     88.0    116.0    153.1     65.0
```

APPENDIX D

This appendix contains programs listings, for the programs executed in the testing procedures.

```
//A223DAS  JOB  41792,SANCHOY,REGION=2048K,TIME=10
/*LONGKEY *******
/*PRIORITY IDLE
/*JOBPARM CARDS=2000,LINES=500
/*ROUTE PRINT VTVM1.INUD133
//  EXEC  $IPIII,TIME=10,REGION=800K
//EXEC.SYSIN DD *
NAME          MIPIII
*
*     PROGRAM TO EXECUTE THE MIP-III OPTIMIZER FOR THE MA-SCHED
*
*-----MIP SOLUTION STRATEGIES
*
        TABLE     T:STRATEGY = BP
                  PRINT      = 1
                  NODES      = 500
                  NBLOOK     = 100
                  DEGRADE    = 0.05
*
*-----MIP CONTROL PARAMETERS
*
        TABLE     Z:SYSTEM = NAMES
                  MATRIX   = INTEGER
                  CONVERT  = TESTONE
                  OBJ      = COST
                  RHS      = RH
*                 PICTURE
                  CONTSOL
                  MIN
                  SOLUTION = ACTIVE
*
*-----INTEGER VARIABLES
*
        TABLE     Z:IVL = DVT
ENDATA
*
* BEGIN DATA INPUT
*
NAME          TESTONE
/*
//
```

```
//A223DAS  JOB  41792,SANCHOY
/*LONGKEY *******
/*PRIORITY IDLE
/*JOBPARM LINES=1000
/*ROUTE PRINT VTVM1.INUD133
//STEP1 EXEC WATFIV
//SYSIN DD   DATA
//WATFIV         DAS,PAGES=400,TIME=10,NOLIST
C
C
C ===========================================================
C WATFIV CODE TO GENERATE THE MIXED INTEGER
C PROGRAM TO BE SOLVED ON THE MIP-3 MODULE OF MPS-3
C ===========================================================
C
C
C
C INITIALIZE VARIABLES
C
C
      REAL  P(20,4,20), C(20), Q(20), A(20), AQ(20),EF(20,20),QLTY(20)
      REAL  F(20,20), E(20,20), H(20,4), PSI,ID(20),L,LPHI(20),B(20)
      REAL  PHI(20),QF(20),QO(20),QW(20),QQ(20),QU(20),QB(20),QC(20)
      REAL  S(20), D(20), QOW(20),WOBJ(20,20),QD(20),MOVE(20),ZOBJ(20)
      REAL  PROCS(20,20),SUM1(20,20)/400*0.0/,SUM3(20)/20*0.0/
      REAL  SUM4(20)/20*0.0/, NEED(20)
      INTEGER  N,M,RO,TI,I,R,T,K,NB,PROB,TMIN,KA,KB,IA,IB,TA,TB,TC,TD
      INTEGER KC, KD, IDEN, BLOCK(20,20), TT
C
C
C -----------------------------------------------------------
C READ INPUT PARAMETERS FOR CURRENT SCHEDULING PROBLEM
C -----------------------------------------------------------
C
C
      READ, PROB
      READ, N
      READ, M
      READ, RO
      READ, TI
      DO 2 I=1,N
        DO 3 R=1,RO
          READ, (P(I,R,K), K=1,M)
    3   CONTINUE
    2 CONTINUE
      READ, BIG
      READ, (C(K), K=1,M)
      READ, (Q(K), K=1,M)
      READ, (A(K), K=1,M)
      READ, (MOVE(K), K=1,M)
      READ, (ID(I), I=1,N)
      DO 4 I=1,N
        READ, (F(I,T), T=1,TI)
        READ, (E(I,T), T=1,TI)
    4 CONTINUE
      DO 5 I=1,N
        READ, (H(I,R), R=1,RO)
    5 CONTINUE
      READ, PSI
      DO 6 K=1,M
        AQ(K) = A(K)/Q(K)
        C(K) = -1*C(K)
    6 CONTINUE
      DO 7 I=1,N
        DO 8 T=1,TI
          EF(I,T)= E(I,T) + F(I,T)
    8   CONTINUE
    7 CONTINUE
      READ, (PHI(I), I=1,N)
      READ, (QB(I), I=1,N)
      READ, (QC(I), I=1,N)
```

```
   READ, (QD(I), I=1,N)
   READ, (QF(K), K=1,M)
   READ, (QO(K), K=1,M)
   READ, (QW(K), K=1,M)
   READ, (QQ(K), K=1,M)
   READ, (QU(K), K=1,M)
   READ, (S(K), K=1,M)
   READ, (D(K), K=1,M)
   READ, L
   READ, NB
   READ, (B(J), J=1,NB)
   DO 9 I=1,N
     LPHI(I) = PHI(I)*L
 9 CONTINUE
   DO 1 K=1,M
     QLTY(K) = QQ(K)/Q(K)
     QOW(K) = QO(K) + QLTY(K)
     ZOBJ(K) = QF(K)
     DO 15 T=1,TI
       WOBJ(K,T) = QW(K) + QLTY(K)
       BLOCK(K,T) = 0
15 CONTINUE
 1 CONTINUE
   DO 16 J=1,NB
     K = B(J)
     ZOBJ(K) = ZOBJ(K) +(QU(K)*Q(K))
     DO 17 T=1,TI
       WOBJ(K,T) = WOBJ(K,T) - QU(K)
17   CONTINUE
16 CONTINUE
   TMIN =TI-1

--------------------------------------------------------------
DETERMINE CELLS/PERIODS WHICH WILL DEFINITELY BE ON
--------------------------------------------------------------


    DO 5000 K=1,M
    NEED(K) = 0
    DO 5001 I=1,N
      DO 5002 R=1,RO
        IF(P(I,R,K) .EQ. 0.0) NEED(K)=NEED(K)+1
2     CONTINUE
1   CONTINUE
    QQQ = RO*N
    QQQ = NEED(K)/QQQ
    IF(QQQ  .LE. 0.30) THEN
      DO 5003 T=1,TI
        BLOCK(K,T)=1
3     CONTINUE
    ENDIF
0 CONTINUE
  DO 5100 K=1,M
    DO 5110 I=1,N
      PROCS(I,K) = 100
      DO 5111 R=1,RO
        IF(P(I,R,K) .LE. PROCS(I,K)) PROCS(I,K)=P(I,R,K)
1     CONTINUE
0   CONTINUE
0 CONTINUE
  DO 5200 T=1,TI
    BLOCK(1,T)=1
    DO 5210 K=1,M
      DO 5230 I=1,N
        SUM2 = PROCS(I,K)*F(I,T)/(-1*C(K))
        SUM1(K,T) = SUM1(K,T) + SUM2
        SUM4(K) = SUM4(K) + (E(I,T)*PROCS(I,K)/(-1*C(K)))
        IF(SUM2 .GE. 0.30) BLOCK(K,T)=1
0     CONTINUE
      SUM3(K) = SUM3(K) + SUM1(K,T)
      IF(SUM1(K,T) .GE. 0.75) BLOCK(K,T)=1
      XX = T-1
      IF(SUM3(K) .GE. XX) THEN
```

```
            DO 5233 TT=1,T
              BLOCK(K,TT)=1
 5233       CONTINUE
          ENDIF
 5210   CONTINUE
 5200 CONTINUE
      DO 5300 K=1,M
        ADD = SUM3(K) + SUM4(K)
        IF (ADD .GE. (TI-1)) THEN
          DO 5333 TT=1,TI
            BLOCK(K,TT)=1
 5333     CONTINUE
        ENDIF
 5300 CONTINUE
C
C
C ---------------------------------------------------------------
C PRINT INTEGER VARIABLES
C ---------------------------------------------------------------
C
      DO 3000 K=1,M
        CALL MINT(K,KA,KB)
        DO 3010 T=1,TI
          CALL TINT(T,TA,TB)
          PRINT 3020,KA,KB,TA,TB
 3020     FORMAT(1X,19X,'Z',I1,I1,'.',I1,I1)
 3010   CONTINUE
 3000 CONTINUE
      DO 3030 I=1,N
        CALL NINT(I,IA,IB)
        DO 3040 T=1,TI
          CALL TINT(T,TA,TB)
          DO 3050 R=1,RO
            PRINT 3060,IA,IB,R,TA,TB
 3060       FORMAT(1X,19X,'Y',I1,I1,'.',I1,'.',I1,I1)
 3050     CONTINUE
 3040   CONTINUE
 3030 CONTINUE
C
C
C ---------------------------------------------------------------
C PRINT ROW TYPES. THAT IS L, G, E
C ---------------------------------------------------------------
C
C
      PRINT 1001
 1001 FORMAT (1X,'ROWS')
      PRINT 1002
 1002 FORMAT (1X,' N',T6,'COST')
      DO 1000 T=1,TI
        CALL TINT(T,TA,TB)
        DO 1010 I=1,N
          CALL NINT(I,IA,IB)
          DO 1020 R=1,RO
            PRINT 1030, IA,IB,R,TA,TB
 1030       FORMAT(1X,' L',T6,'T',I1,I1,'.',I1,'.',I1,I1)
            PRINT 1035, IA,IB,R,TA,TB
 1035       FORMAT(1X,' G',T6,'D',I1,I1,'.',I1,'.',I1,I1)
 1020     CONTINUE
          PRINT 1040, IA,IB,TA,TB
 1040     FORMAT (1X,' E',T6,'INV',I1,I1,'.',I1,I1)
          PRINT 1041, IA,IB,TA,TB
 1041     FORMAT (1X,' E',T6,'REQ',I1,I1,'.',I1,I1)
          PRINT 1050, IA,IB,TA,TB
 1050     FORMAT (1X,' G',T6,'PIV',I1,I1,'.',I1,I1)
          PRINT 1070, IA,IB,TA,TB
 1070     FORMAT (1X,' L',T6,'FXR',I1,I1,'.',I1,I1)
          PRINT 1075, IA,IB,TA,TB
 1075     FORMAT (1X,' E',T6,'IND',I1,I1,'.',I1,I1)
 1010   CONTINUE
        PRINT 1080, TA,TB
 1080   FORMAT (1X,' E',T6,'TRAP',I1,I1)
        PRINT 1090, TA,TB
 1090   FORMAT (1X,' L',T6,'TRNS',I1,I1)
```

```
1000 CONTINUE
     DO 1100 T=1,TI
       CALL TINT(T,TA,TB)
       DO 1110 K=1,M
       CALL MINT(K,KA,KB)
         PRINT 1120, KA,KB,TA,TB
1120     FORMAT (1X,' L',T6,'CAP',I1,I1,'.',I1,I1)
         PRINT 1130, KA,KB,TA,TB
1130     FORMAT (1X,' L',T6,'FXC',I1,I1,'.',I1,I1)
         PRINT 1140, KA,KB,TA,TB
1140     FORMAT (1X,' L',T6,'RGT',I1,I1,'.',I1,I1)
         PRINT 1150, KA,KB,TA,TB
1150     FORMAT (1X,' L',T6,'TRC',I1,I1,'.',I1,I1)
         PRINT 1155, KA,KB,TA,TB
1155     FORMAT (1X,' E',T6,'SRT',I1,I1,'.',I1,I1)
         IF (BLOCK(K,T) .GE. 1.0) THEN
           PRINT 1157, KA,KB,TA,TB
1157       FORMAT (1X,' E',T6,'CUT',I1,I1,'.',I1,I1)
         ENDIF
1110   CONTINUE
1100 CONTINUE
     DO 1160 I=1,N
       CALL NINT(I,IA,IB)
       PRINT 1170, IA,IB
1170   FORMAT (1X,' E',T6,'NINV',I1,I1)
1160 CONTINUE
     PRINT 1180
1180 FORMAT(1X,'COLUMNS')

 ----------------------------------------------------------------
 PRINT COLUMN COEFFICIENTS

 PRINT X(I,T) COEFFICIENTS
 ----------------------------------------------------------------

     DO 10 I=1,N
       CALL NINT(I,IA,IB)
       DO 11 T=1,TI
       CALL TINT(T,TA,TB)
         PRINT 101,IA,IB,TA,TB,IA,IB,TA,TB,IA,IB,TA,TB
 101 FORMAT (1X,T6,'X',I1,I1,'.',I1,I1,T16,'INV',I1,I1,'.',I1,I1,T26,
    C'1',T41,'PIV',I1,I1,'.',I1,I1,T51,'1')
         PRINT 102,IA,IB,TA,TB,IA,IB,TA,TB,LPHI(I)
 102 FORMAT (1X,T6,'X',I1,I1,'.',I1,I1,T16,'REQ',I1,I1,'.',I1,I1,T26,
    C'-1',T41,'COST',T51,F7.2)
  11   CONTINUE
  10 CONTINUE

 ----------------------------------------------------------------
 PRINT Z(K,T) COEFFECIENTS
 ----------------------------------------------------------------

     DO 20 K=1,M
       CALL MINT(K,KA,KB)
       DO 21 T=1,TMIN
         CALL TINT(T,TA,TB)
         PRINT 200, KA,KB,TA,TB,KA,KB,TA,TB,C(K),KA,KB,TA,TB
 200 FORMAT (1X,T6,'Z',I1,I1,'.',I1,I1,T16,'FXC',I1,I1,'.',I1,I1,T26,
    CF8.1,T41,'SRT',I1,I1,'.',I1,I1,T51,'-1')
         CALL TINT(T+1,TC,TD)
         PRINT 201, KA,KB,TA,TB,KA,KB,TC,TD,ZOBJ(K)
 201 FORMAT (1X,T6,'Z',I1,I1,'.',I1,I1,T16,'SRT',I1,I1,'.',I1,I1,T26,
    C'1',T41,'COST',T51,F9.1)
         IF (BLOCK(K,T) .GE. 1.0) THEN
           PRINT 205, KA,KB,TA,TB,KA,KB,TA,TB
 205 FORMAT (1X,T6,'Z',I1,I1,'.',I1,I1,T16,'CUT',I1,I1,'.',I1,I1,T26,
    C'1')
         ENDIF
 21    CONTINUE
       CALL TINT(T,TA,TB)
       PRINT 200, KA,KB,TA,TB,KA,KB,TA,TB,C(K),KA,KB,TA,TB
       PRINT 203, KA,KB,TA,TB,ZOBJ(K)
 203   FORMAT (1X,T6,'Z',I1,I1,'.',I1,I1,T16,'COST',T26,F9.1)
```

```
        IF (BLOCK(K,T) .GE. 1.0) THEN
          PRINT 205, KA,KB,TA,TB,KA,KB,TA,TB
        ENDIF
   20 CONTINUE
C
C ------------------------------------------------------------------
C PRINT R(I,R,T) COEFFICIENTS
C ------------------------------------------------------------------
C
      DO 30 I=1,N
        CALL NINT(I,IA,IB)
        DO 31 T=1,TI
          CALL TINT(T,TA,TB)
          DO 32 R=1,RO
            IDEN = 0
            DO 33 K=1,M
              IF (IDEN .EQ. 1) GO TO 34
              IF (K. EQ. M) THEN
                CALL MINT(K,KA,KB)
                PRINT 300, IA,IB,R,TA,TB,KA,KB,TA,TB,P(I,R,K)
 300 FORMAT (1X,T6,'R',I1,I1,'.',I1,'.',I1,I1,T16,'CAP',I1,I1,'.',I1,
    CI1,T26,F7.2)
              ELSE
                CALL MINT(K,KA,KB)
                CALL MINT(K+1,KC,KD)
     PRINT 304, IA,IB,R,TA,TB,KA,KB,TA,TB,P(I,R,K),KC,KD,TA,TB,
    CP(I,R,K+1)
 304 FORMAT (1X,T6,'R',I1,I1,'.',I1,'.',I1,I1,T16,'CAP',I1,I1,'.',I1,
    CI1,T26,F7.2,T41,'CAP',I1,I1,'.',I1,I1,T51,F7.2)
                IDEN = 1
              ENDIF
              GO TO 33
  34        IDEN=0
  33        CONTINUE
            PRINT 301, IA,IB,R,TA,TB,IA,IB,R,TA,TB,TA,TB,H(I,R)
 301 FORMAT (1X,T6,'R',I1,I1,'.',I1,'.',I1,I1,T16,'T',I1,I1,'.',I1,'.',
    CI1,I1,T26,'1',T41,'TRAP',I1,I1,T51,F5.2)
           PRINT 302, IA,IB,R,TA,TB,IA,IB,TA,TB,IA,IB,R,TA,TB
 302 FORMAT (1X,T6,'R',I1,I1,'.',I1,'.',I1,I1,T16,'REQ',I1,I1,'.',I1,
    CI1,T26,'1',T41,'D',I1,I1,'.',I1,'.',I1,I1,T51,'-1')
  32     CONTINUE
  31   CONTINUE
  30 CONTINUE
C
C ------------------------------------------------------------------
C PRINT Y(I,R,T) AND AP(I,R,T) COEFFICIENTS
C ------------------------------------------------------------------
C
      BIGN=BIG*(-1)
      DO 40 I=1,N
        CALL NINT(I,IA,IB)
        DO 41 T=1,TI
          CALL TINT(T,TA,TB)
          DO 42 R=1,RO
           PRINT 400, IA,IB,R,TA,TB,IA,IB,R,TA,TB,BIGN,IA,IB,TA,TB
 400 FORMAT (1X,T6,'Y',I1,I1,'.',I1,'.',I1,I1,T16,'T',I1,I1,'.',I1,
    C'.',I1,I1,T26,F9.2,T41,'FXR',I1,I1,'.',I1,I1,T51,'1')
           PRINT 401, IA,IB,R,TA,TB,IA,IB,R,TA,TB
 401 FORMAT (1X,T6,'Y',I1,I1,'.',I1,'.',I1,I1,T16,'D',I1,I1,'.',
    CI1,'.',I1,I1,T26,'1')
  42      CONTINUE
  41    CONTINUE
  40 CONTINUE
      DO 45 I=1,N
        CALL NINT(I,IA,IB)
        DO 46 T=1,TI
          CALL TINT(T,TA,TB)
          PRINT 405, IA,IB,TA,TB,IA,IB,1,TA,TB
 405 FORMAT (1X,T6,'A',I1,I1,'.',I1,I1,T16,'D',I1,I1,'.',I1,
    C'.',I1,I1,T26,'1',T41,'COST',T51,'0.001')
          IF(RO .EQ. 2) THEN
            PRINT 406, IA,IB,TA,TB,IA,IB,2,TA,TB
 406        FORMAT (1X,T6,'A',I1,I1,'.',I1,I1,T16,'D',I1,I1,'.',I1,
    C'.',I1,I1,T26,'1')
```

```
          ELSE
           PRINT 407, IA,IB,TA,TB,IA,IB,2,TA,TB,IA,IB,3,TA,TB
 407       FORMAT (1X,T6,'A',I1,I1,'.',I1,I1,T16,'D',I1,I1,'.',I1,
     C'.',I1,I1,T26,'1',T41,'D',I1,I1,'.',I1,'.',I1,I1,T51,'1')
          ENDIF
  47      CONTINUE
  46    CONTINUE
  45 CONTINUE
 ------------------------------------------------------------------
 PRINT O(K,T) COEFFICIENTS
 ------------------------------------------------------------------

      DO 50 K=1,M
        CALL MINT(K,KA,KB)
        DO 51 T=1,TI
          CALL TINT(T,TA,TB)
          PRINT 500, KA,KB,TA,TB,KA,KB,TA,TB,KA,KB,TA,TB
 500 FORMAT (1X,T6,'O',I1,I1,'.',I1,I1,T16,'CAP',I1,I1,'.',I1,I1,T26,
    C'-1',T41,'FXC',I1,I1,'.',I1,I1,T51,'1')
          PRINT 501, KA,KB,TA,TB,KA,KB,TA,TB,AQ(K),QOW(K)
 501 FORMAT (1X,T6,'O',I1,I1,'.',I1,I1,T16,'TRC',I1,I1,'.',I1,I1,T26,
    CF6.2,T41,'COST',T51,F7.2)
  51    CONTINUE
  50 CONTINUE

 ------------------------------------------------------------------
 PRINT W(K,T) COEFFICIENTS
 ------------------------------------------------------------------

      DO 60 K=1,M
        CALL MINT(K,KA,KB)
        DO 61 T=1,TI
          CALL TINT(T,TA,TB)
          PRINT 600,KA,KB,TA,TB,WOBJ(K,T)
 600 FORMAT (1X,T6,'W',I1,I1,'.',I1,I1,T16,'COST',T26,F7.2)
          PRINT 601, KA,KB,TA,TB,KA,KB,TA,TB,KA,KB,TA,TB
 601 FORMAT (1X,T6,'W',I1,I1,'.',I1,I1,T16,'CAP',I1,I1,'.',I1,I1,T26,
    C'-1',T41,'FXC',I1,I1,'.',I1,I1,T51,'1')
          PRINT 602, KA,KB,TA,TB,KA,KB,TA,TB,AQ(K),KA,KB,TA,TB
 602 FORMAT (1X,T6,'W',I1,I1,'.',I1,I1,T16,'TRC',I1,I1,'.',I1,I1,T26,
    CF7.2,T41,'RGT',I1,I1,'.',I1,I1,T51,'1')
  61    CONTINUE
  60 CONTINUE

 ------------------------------------------------------------------
 PRINT I(I,T) COEFFICIENTS
 ------------------------------------------------------------------

      DO 70 I=1,N
        CALL NINT(I,IA,IB)
        DO 71 T=1,TMIN
          CALL TINT(T,TA,TB)
          PRINT 700, IA,IB,TA,TB,QB(I),IA,IB,TA,TB
 700 FORMAT (1X,T6,'I',I1,I1,'.',I1,I1,T16,'COST',T26,F5.2,T41,
    C'PIV',I1,I1,'.',I1,I1,T51,'-1')
          CALL TINT(T+1,TC,TD)
          PRINT 701, IA,IB,TA,TB,IA,IB,TA,TB,IA,IB,TA,TB
 701 FORMAT (1X,T6,'I',I1,I1,'.',I1,I1,T16,'IND',I1,I1,'.',I1,I1,T26,
    C'1',T41,'INV',I1,I1,'.',I1,I1,T51,'-1')
          PRINT 702, IA,IB,TA,TB,IA,IB,TC,TD,IA,IB,TC,TD
 702 FORMAT (1X,T6,'I',I1,I1,'.',I1,I1,T16,'INV',I1,I1,'.',I1,I1,T26,
    C'1',T41,'PIV',I1,I1,'.',I1,I1,T51,'1')
  71    CONTINUE
          CALL TINT(T,TA,TB)
      PRINT 700, IA,IB,TA,TB,QB(I),IA,IB,TA,TB
          PRINT 701, IA,IB,TA,TB,IA,IB,TA,TB,IA,IB,TA,TB
  70 CONTINUE

 ------------------------------------------------------------------
 PRINT L(I,T) COEFFICIENTS
 ------------------------------------------------------------------
```

```
C
      DO 80 I=1,N
        CALL NINT(I,IA,IB)
        DO 81 T=1,TMIN
          CALL TINT(T,TA,TB)
          CALL TINT(T+1,TC,TD)
          PRINT 800, IA,IB,TA,TB,IA,IB,TA,TB,IA,IB,TC,TD
  800 FORMAT (1X,T6,'L',I1,I1,'.',I1,I1,T16,'INV',I1,I1,'.',I1,I1,T26,
     C'1',T41,'INV',I1,I1,'.',I1,I1,T51,'-1')
          PRINT 801, IA,IB,TA,TB,QC(I)
  801 FORMAT (1X,T6,'L',I1,I1,'.',I1,I1,T16,'COST',T26,F5.2)
   81   CONTINUE
          CALL TINT(T,TA,TB)
          PRINT 803, IA,IB,TA,TB,IA,IB,TA,TB
  803 FORMAT (1X,T6,'L',I1,I1,'.',I1,I1,T16,'INV',I1,I1,'.',I1,I1,
     CT26,'1')
        PRINT 801, IA,IB,TA,TB,QC(I)
        PRINT 802, IA,IB,TA,TB,IA,IB
  802 FORMAT (1X,T6,'L',I1,I1,'.',I1,I1,T16,'NINV',I1,I1,T26,'1')
   80 CONTINUE
C
C -----------------------------------------------------------------
C PRINT H(K,T) COEFFICIENTS
C -----------------------------------------------------------------
C
      DO 90 K=1,M
        CALL MINT(K,KA,KB)
        DO 91 T=1,TI
          CALL TINT(T,TA,TB)
          PRINT 900, KA,KB,TA,TB,KA,KB,TA,TB,TA,TB
  900 FORMAT (1X,T6,'H',I1,I1,'.',I1,I1,T16,'TRC',I1,I1,'.',I1,I1,T26,
     C'-1',T41,'TRNS',I1,I1,T51,'1')
          PRINT 901, KA,KB,TA,TB
  901 FORMAT (1X,T6,'H',I1,I1,'.',I1,I1,T16,'COST',T26,'0.001')
   91   CONTINUE
   90 CONTINUE
C
C -----------------------------------------------------------------
C PRINT OM(T) COEFFICIENTS
C -----------------------------------------------------------------
C
      DO 92 T=1,TI
          CALL TINT(T,TA,TB)
        PRINT 910, TA,TB,TA,TB,TA,TB
  910 FORMAT (1X,T6,'OM',I1,I1,T16,'TRAP',I1,I1,T26,'-1',T41,'TRNS',I1,
     CI1,T51,'1')
   92 CONTINUE
C
C -----------------------------------------------------------------
C PRINT ZS(K,T) AND ZD(K,T) COEFFICIENTS
C -----------------------------------------------------------------
C
      DO 110 T=1,TI
          CALL TINT(T,TA,TB)
        DO 111 K=1,M
        CALL MINT(K,KA,KB)
          PRINT 112, KA,KB,TA,TB,KA,KB,TA,TB,S(K)
  112 FORMAT(1X,T6,'ZS',I1,I1,'.',I1,I1,T16,'SRT',I1,I1,'.',I1,I1,T26,
     C'1',T41,'COST',T51,F7.0)
  111   CONTINUE
  110 CONTINUE
      DO 115 T=1,TI
          CALL TINT(T,TA,TB)
        DO 116 K=1,M
        CALL MINT(K,KA,KB)
          PRINT 117, KA,KB,TA,TB,KA,KB,TA,TB,D(K)
  117 FORMAT(1X,T6,'ZD',I1,I1,'.',I1,I1,T16,'SRT',I1,I1,'.',I1,I1,T26,
     C'-1',T41,'COST',T51,F7.0)
  116   CONTINUE
  115 CONTINUE
C
C -----------------------------------------------------------------
C PRINT IY(I,T) AND IZ(I,T) COEFFICIENTS
C -----------------------------------------------------------------
C
```

```
      DO 120 T=1,TI
          CALL TINT(T,TA,TB)
        DO 121 I=1,N
        CALL NINT(I,IA,IB)
          PRINT 122, IA,IB,TA,TB,IA,IB,TA,TB,QD(I)
  122 FORMAT(1X,T6,'IY',I1,I1,'.',I1,I1,T16,'IND',I1,I1,'.',I1,I1,T26,
     C'-1',T41,'COST',T51,F5.2)
  121   CONTINUE
  120 CONTINUE
      DO 124 T=1,TI
          CALL TINT(T,TA,TB)
        DO 125 I=1,N
        CALL NINT(I,IA,IB)
          PRINT 123, IA,IB,TA,TB,IA,IB,TA,TB,QD(I)
  123 FORMAT(1X,T6,'IZ',I1,I1,'.',I1,I1,T16,'IND',I1,I1,'.',I1,I1,
     CT26,'1',T41,'COST',T51,F5.2)
  125   CONTINUE
  124 CONTINUE
C
C
C ------------------------------------------------------------------
C PRINT RIGHT HAND SIDE VALUES
C ------------------------------------------------------------------
C
C
      PRINT 2001
 2001 FORMAT (1X,'RHS')
      DO 2000 T=1,TI
        CALL TINT(T,TA,TB)
        DO 2010 I=1,N
          CALL NINT(I,IA,IB)
          PRINT 2040, IA,IB,TA,TB,EF(I,T),IA,IB,TA,TB,F(I,T)
 2040 FORMAT (1X,T6,'RH',T16,'INV',I1,I1,'.',I1,I1,T26,F7.2,T41,'PIV',
     CI1,I1,'.',I1,I1,T51,F7.2)
          PRINT 2060, IA,IB,TA,TB,ID(I),IA,IB,TA,TB
 2060 FORMAT (1X,T6,'RH',T16,'IND',I1,I1,'.',I1,I1,T26,F7.2,T41,'FXR',
     CI1,I1,'.',I1,I1,T51,'1')
 2010   CONTINUE
        PRINT 2080, TA,TB,PSI
 2080 FORMAT (1X,T6,'RH',T16,'TRNS',I1,I1,T26,F9.2)
 2000 CONTINUE
      DO 2100 T=1,TI
          CALL TINT(T,TA,TB)
        DO 2110 K=1,M
        CALL MINT(K,KA,KB)
          PRINT 2120, KA,KB,TA,TB,KA,KB,TA,TB
 2120 FORMAT (1X,T6,'RH',T16,'CAP',I1,I1,'.',I1,I1,T26,'0',T41,'FXC',I1,
     CI1,'.',I1,I1,T51,'0')
          PRINT 2140, KA,KB,TA,TB,Q(K),KA,KB,TA,TB,MOVE(K)
 2140 FORMAT (1X,T6,'RH',T16,'RGT',I1,I1,'.',I1,I1,T26,F7.2,T41,'TRC',
     CI1,I1,'.',I1,I1,T51,F8.2)
          IF (BLOCK(K,T) .GE. 1.0) THEN
            PRINT 2142, KA,KB,TA,TB
 2142       FORMAT (1X,T6,'RH',T16,'CUT',I1,I1,'.',I1,I1,T26,'1')
          ENDIF
 2110   CONTINUE
 2100 CONTINUE
C
C
C ------------------------------------------------------------------
C PROGRAM TERMINATION TO OCCUR
C ------------------------------------------------------------------
C
C
      STOP
      END
C
C
C ------------------------------------------------------------------
C SUBROUTINES TO ACCOUNT FOR TWO DIGIT IDENTIFIERS
C ------------------------------------------------------------------
C
```

```
    SUBROUTINE MINT(K1,K2,K3)
    INTEGER  K1,K2,K3

    IF (K1 .LE. 9) THEN
      K2 = 0
      K3 = K1
    ELSE
      K2 = 1
      K3 = K1-10
    ENDIF
    RETURN
    END

    SUBROUTINE TINT(T1,T2,T3)
    INTEGER  T1,T2,T3

    IF (T1 .LE. 9) THEN
      T2 = 0
      T3 = T1
    ELSE
      T2 = 1
      T3 = T1-10
    ENDIF
    RETURN
    END

    SUBROUTINE NINT(I1,I2,I3)
    INTEGER  I1,I2,I3

    IF (I1 .LE. 9) THEN
      I2 = 0
      I3 = I1
    ELSE
      I2 = 1
      I3 = I1-10
    ENDIF
    RETURN
    END


DATA
ENDWAT
```

```
//A223DAS  JOB  41792,SANCHOY
/*LONGKEY *******
/*PRIORITY IDLE
/*JOBPARM LINES=2000
/*ROUTE PRINT VTVM1.INUD133
//STEP1 EXEC WATFIV
//SYSIN DD   DATA
//WATFIV        DAS,PAGES=400,TIME=10
C
C
C ====================================================================
C THIS PROGRAM STORES THE LPROG DECISIONS, ASSIGNS INSPECIFIED
C ITEM PRODUCTION AND PRINTS THE PRESCRIBED DECISION POLICY
C ====================================================================
C
C
C
C INITIALIZE VARIABLES
C
C
      REAL  BET(10,20), ALF(10,20), EOQ(20), X(20,20),QDEL(20),QB(20)
      REAL  LV(10,4,20)/800*0.0/,DH(20)/20*0.0/,VCOST(20)/20*0.0/
      REAL  ICOST(20)/20*0.0/, IM(20)/20*0.0/, LM(20)/20*0.0/
      REAL  QCOST(20)/20*0.0/,PCOST(20)/20*0.0/,TOTAL(20,20)/400*0.0/
      INTEGER  N,M,TI,TT,Q,KK,K,NB,PROB,TAUM,K1,K2,TR,TAU,T,G(20)
      INTEGER  KA,KB,VARX, VARY,TMIN,TP
      COMMON  Y(10,4,20,20), YP(10,4,20,20), YG(4,20,20), TP(20)
C
C
C -----------------------------------------------------------------
C READ INPUT PARAMETERS FOR CURRENT SCHEDULING PROBLEM
C -----------------------------------------------------------------
C
      READ, PROB
      READ, N
      READ, M
      READ, TI
      READ, TAU
      READ, (G(I), I=1,N)
      DO 1999 T=1,TI
        DO 2000 I=1,N
          KK=G(I)
          DO 2002 TT=1,4
            READ 2005, (Y(Q,TT,I,T), Q=1,KK)
 2005       FORMAT(1X,10(F6.1,1X))
            READ 2005, (YP(Q,TT,I,T), Q=1,KK)
 2002     CONTINUE
          READ 2005, (YG(TT,I,T), TT=1,4)
 2000   CONTINUE
        READ, ICOST(T), QCOST(T), PCOST(T)
 1999 CONTINUE
C
C -----------------------------------------------------------------
C ASSIGN YP VALUES TO YG VALUES
C -----------------------------------------------------------------
C
      DO 200 I=1,N
        TP(I) = 1
        KK=G(I)
        DO 205 T=2,TI
          DO 207 TT=1,4
            DO 209 Q=1,KK
              IF (YP(Q,TT,I,T) .GT. 0.0) THEN
                CALL ASSIGN(Q,TT,I,T)
              ENDIF
 209        CONTINUE
 207      CONTINUE
 205    CONTINUE
 200  CONTINUE
```

```
C
C -------------------------------------------------------------------
C PRINT DECISION TABLE FOR CURRENT CP1-SCHEDULING PROBLEM
C -------------------------------------------------------------------
C
      PRINT 550
  550 FORMAT('1'/)
      PRINT 551, PROB
  551 FORMAT ('0',4X,'CP1-SCHEDULE DECISIONS FOR PROBLEM - ',I2/5X
     C,99('='),/)
      DO 5001 T=1,TI
      K1=1
      K2=2
      PRINT 552 ,T
  552 FORMAT('0'/,4X,'PERIOD ',I2,' PRODUCTION QUANTITIES',/,
     C5X,32('-'))
  559 IF (G(K1)+G(K2) .LE. 15) THEN
        KA=G(K1)
        KB=G(K2)
        PRINT 553, (K1,Q, Q=1,KA), (K2,Q, Q=1,KB)
  553   FORMAT('0'/,6X,'GRP#-ITEM#',T19,15(I2,'-',I1,3X))
        PRINT, ' '
        DO 554 TT=1,TAU
          PRINT 556,TT,(Y(Q,TT,K1,T),Q=1,KA),(Y(Q,TT,K2,T),Q=1,KB)
  556     FORMAT (' ',4X,'BUCKET - ',I1,T18,18(F5.1,2X))
  554   CONTINUE
        K1=K2+1
        K2=K2+2
      ELSE
        KA=G(K1)
        PRINT 553, (K1,Q, Q=1,KA)
        PRINT, ' '
        DO 558 TT=1,TAU
          PRINT 556,TT,(Y(Q,TT,K1,T),Q=1,KA)
  558   CONTINUE
        K1=K2
        K2=K2+1
      ENDIF
      IF (K2 .GT. N) G(K2) =100
      IF (K1 .LE. N) GO TO 559
5001  CONTINUE
      DO 600 I=1,N
        KK=G(I)
        DO 601 T=1,TI
          DO 602 TT=1,4
            DO 603 Q=1,KK
             TOTAL(I,T) = TOTAL(I,T) + Y(Q,TT,I,T)
  603       CONTINUE
  602     CONTINUE
  601   CONTINUE
  600 CONTINUE
      PRINT 752
  752 FORMAT('1',4X,'CP1-SCHEDULE COSTS',/,5X,20('-'))
      PRINT 753, (T, T=1,TI)
  753 FORMAT('0'/,8X,'PERIOD #',T19,12(I2,7X))
      PRINT 755, (ICOST(T), T=1,TI)
  755 FORMAT('0',5X,'INVTRY COST',T19,12(F8.1,1X))
      PRINT 756, (PCOST(T), T=1,TI)
  756 FORMAT('0',5X,'PROD DIF COST',T19,12(F8.1,1X))
       PRINT 757, (QCOST(T), T=1,TI)
  757 FORMAT('0',5X,'QNTY DIF COST',T19,12(F8.1,1X))
      PRINT 852
  852 FORMAT('1',4X,'TOTAL PRODUCTION',/,5X,20('-'))
      PRINT 853, (T, T=1,TI)
  853 FORMAT('0'/,6X,'GRP#-PERD#',T19,12(I2,7X))
      DO 800 I=1,N
        PRINT 855, I, (TOTAL(I,T), T=1,TI)
  855   FORMAT('0',5X,I3,T14,12(F8.1,1X))
  800 CONTINUE
```

```
C
C ---------------------------------------------------------------
C PROGRAM TERMINATION TO OCCUR
C ---------------------------------------------------------------
C
 1114 STOP
      END
C
C
C ---------------------------------------------------------------
C SUBROUTINES TO ASSIGN THE YP REQUIREMENTS
C ---------------------------------------------------------------
C
C
      SUBROUTINE ASSIGN(Q,TT,IX,TX)
      INTEGER  T2,Q,TT,TX,IX,T1,TZ,TV,TY,TP
      REAL Y,YP,YG
      COMMON  Y(10,4,20,20), YP(10,4,20,20), YG(4,20,20), TP(20)
C
      T1 = TP(IX)
      TV=TX-1
      DO 1000 TZ=T1,TV
        DO 1010 TY=1,4
          IF (YG(TY,IX,TZ) .GE. YP(Q,TT,IX,TX)) THEN
            Y(Q,TY,IX,TZ) = Y(Q,TY,IX,TZ) + YP(Q,TT,IX,TX)
            YG(TY,IX,TZ) = YG(TY,IX,TZ) - YP(Q,TT,IX,TX)
            YP(Q,TT,IX,TX) = 0
            TP(IX) = TZ
            QUIT 3
          ELSE IF (YG(TY,IX,TZ) .GT. 0.0) THEN
            Y(Q,TY,IX,TZ) = Y(Q,TY,IX,TZ) + YG(TY,IX,TZ)
            YP(Q,TT,IX,TX) = YP(Q,TT,IX,TX) - YG(TY,IX,TZ)
            YG(TY,IX,TZ) = 0
          ENDIF
 1010   CONTINUE
 1000 CONTINUE
C
      RETURN
      END
C
C
//DATA
//ENDWAT
/*
//
```