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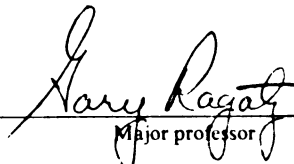
A PRODUCTION SCHEDULING MODEL FOR
REPETITIVE MANUFACTURING SYSTEMS

presented by

Bret Joseph Wagner

has been accepted towards fulfillment
of the requirements for

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Major professor

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**A PRODUCTION SCHEDULING MODEL FOR
REPETITIVE MANUFACTURING SYSTEMS**

By

Bret Joseph Wagner

A DISSERTATION

**Submitted to
Michigan State University
in partial fulfillment of the requirements
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ABSTRACT

A PRODUCTION SCHEDULING MODEL FOR REPETITIVE MANUFACTURING SYSTEMS

By

Bret Joseph Wagner

This dissertation presents the Machine State Scheduling (MSS) model, a production planning and scheduling model for repetitive manufacturing systems. The MSS model was evaluated using data from an actual production facility.

Although production planning and scheduling has received a great deal of attention in the past 40 years, surprisingly few models or techniques have been applied in actual manufacturing environments. In varying degrees, three problems have plagued most models:

1. The models make simplifying assumptions or constrain the problem so that it has limited applicability in real world environments.
2. The models are difficult to solve.
3. The models are hard for the typical practitioner to understand.

The MSS model addresses real-world production problems, including labor and machine constraints, sequence-dependent setups, component part commonality and transfer batches. It is a zero-one integer programming model that does not involve the large number of integer variables typical of most models. While the model itself is not simple, the underlying logic is easily explained. Further, the results of the model can be directly translated into shop floor instructions. Thus, the model lends itself to implementation in real production environments.

The computer program MSS Plan was developed to implement the MSS model and demonstrate how the model could be used in an actual production environment. Two solution methods--integer programming using GAMS/OSL and a single-pass finite loading (SPFL) heuristic--were evaluated using production data from Walker Manufacturing's Newark, Ohio exhaust system production facility. While it proved difficult to find optimal solutions to the MSS model for real-world sized problems, both the integer programming and SPFL heuristic solutions compared favorably to the scheduling decisions of Walker Manufacturing.

The MSS Model provides a means to schedule production in a repetitive manufacturing environment that currently does not exist. Future research that finds solution techniques that quickly find better solutions will enhance the usefulness of the MSS model.

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To Cindy, Emily and Robert, who gave up
so much for me to complete this work

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1.0 INTRODUCTION

A repetitive manufacturing system intermittently produces a fixed set of relatively high volume products and is a common and important type of manufacturing system. The production scheduling problem in this environment is complex and effective scheduling techniques do not exist. Numerous models and techniques have been proposed for this problem, all of which have weaknesses and limitations. This dissertation presents the Machine State Scheduling (MSS) model, a comprehensive production planning and scheduling model that provides an improved capability to schedule production in repetitive manufacturing environments. The MSS model was evaluated by applying it to the scheduling problem faced by Walker Manufacturing, a major automotive supplier that provides an assembled product according to the customer's demand schedule.

To define the production planning and scheduling problem, it is necessary to classify the production environment and describe the traditional approach to the problem, then describe how this model differs from the traditional approach.

1.1 CLASSIFICATION OF PRODUCTION-INVENTORY SYSTEMS

A number of researchers (Buffa and Taubert [1972], Buffa and Miller [1979] and Johnson and Montgomery [1974]) suggest that production-inventory systems be classified into four categories:

1. Pure inventory systems
2. Continuous production systems
3. Intermittent production systems
4. Project management

Intermittent production systems are characterized by batch production of many products using shared production equipment. A repetitive manufacturing system is a special case of the intermittent production system in which a fixed and usually limited set of products is produced. Repetitive production systems may be composed of a combination of machines, workcenters, assembly stations or assembly lines and usually exhibit a flow-shop-like work flow as opposed to the random flow of the general job shop. Since product demand typically varies, production batches may vary in size or timing, equipment may be operated intermittently, dedicated machines may be idled and labor may be transferred among different pieces of equipment.

Intermittent production systems are the least understood category of production system. Inventory theory was well developed by the 1960's, and many practical techniques have been applied by industry and the military. Continuous production systems have also been studied extensively, and again research has resulted in tools for industry. Many of the factors in successful project management are hard to quantify, but PERT and CPM have simplified the coordination of tasks and resources in a project. Research on intermittent production systems, while voluminous, has produced few practical tools and techniques.

Intermittent production of unique products has been the domain of job shop research, which now is typically conducted using computer simulation. Most of this research has centered around the evaluation of dispatching rules. Researchers have

developed a surprisingly large number of ways to select jobs for processing. Blackstone, Phillips and Hogg (1982) provided a state-of-the-art evaluation of 34 dispatching rules while Panwalker and Iskander (1977) provided a survey of over 100 dispatching rules from the literature. A number of researchers have studied the dual resource constrained problem (see Fredendall, 1991) in which both machines and labor constrain production options. This research has used dual dispatching rules (labor assignment and job selection) to solve the problem. McKay, Safayeni and Buzacott (1988) point out that little job shop research has been applied, stating that in job shop research "the problem definition is so far removed from job-shop reality that perhaps a different name for the research should be considered."

Material Requirements Planning (MRP) is a practical, practitioner-developed approach to order launching and due date maintenance that requires skilled planners for successful implementation. In 1982, Anderson, Schroeder, Tupy and White estimated that 62% of manufacturing firms used MRP systems and in 1989 MRP systems accounted for almost one-third of the total market for computer services.¹ Yet MRP systems have not been very successful in scheduling repetitive manufacturing systems. According to the APICS Repetitive Manufacturing Group:

The history of floor control for repetitive manufacturing has been very different from that of job shops. Very few companies have successfully adapted an MRP system designed to generate shop orders to operate a repetitive manufacturing floor. When they did, they buried themselves in transactions and paperwork. Consequently, most repetitive manufacturing companies have

¹Newscope Column, "Competition in Manufacturing Leads to MRP II", *Industrial Engineering*, 1991, Vol. 23, No. 7, p. 10.

developed their own planning and control systems. Their need is to provide visibility and control of a flow of parts.²

The Japanese have developed Kanban systems to be used in conjunction with the Just-In-Time (JIT) approach to manufacturing. A Kanban system is essentially an advanced reorder-point inventory system that works well if production equipment requires minimal setups and production managers are willing to set level production schedules, two factors that appear to be in short supply in U.S. manufacturing firms.

In conclusion, repetitive manufacturing systems are an important form of production systems for which effective production planning and scheduling techniques do not exist. By taking a different approach to the problem, the MSS model provides a means for converting an end-item production schedule into detailed shop floor instructions. Because the MSS model considers the critical parameters of the real-world repetitive manufacturing problem (sequence-dependent setups, machine capacity, labor assignments, assembly, component commonality, etc.), this research is of importance to the repetitive manufacturing practitioner. The next two sections describe how the MSS model differs from the traditional modeling approach to production planning and scheduling for repetitive manufacturing systems.

1.2 TRADITIONAL APPROACHES TO PRODUCTION PLANNING AND SCHEDULING IN REPETITIVE MANUFACTURING SYSTEMS

The traditional approach to production planning and scheduling in repetitive manufacturing systems is to treat the problem in a hierarchical fashion. Figure 1.1

²APICS Repetitive Manufacturing Group, "Repetitive Manufacturing", *Production and Inventory Management*, Second Quarter, 1982, p. 81.

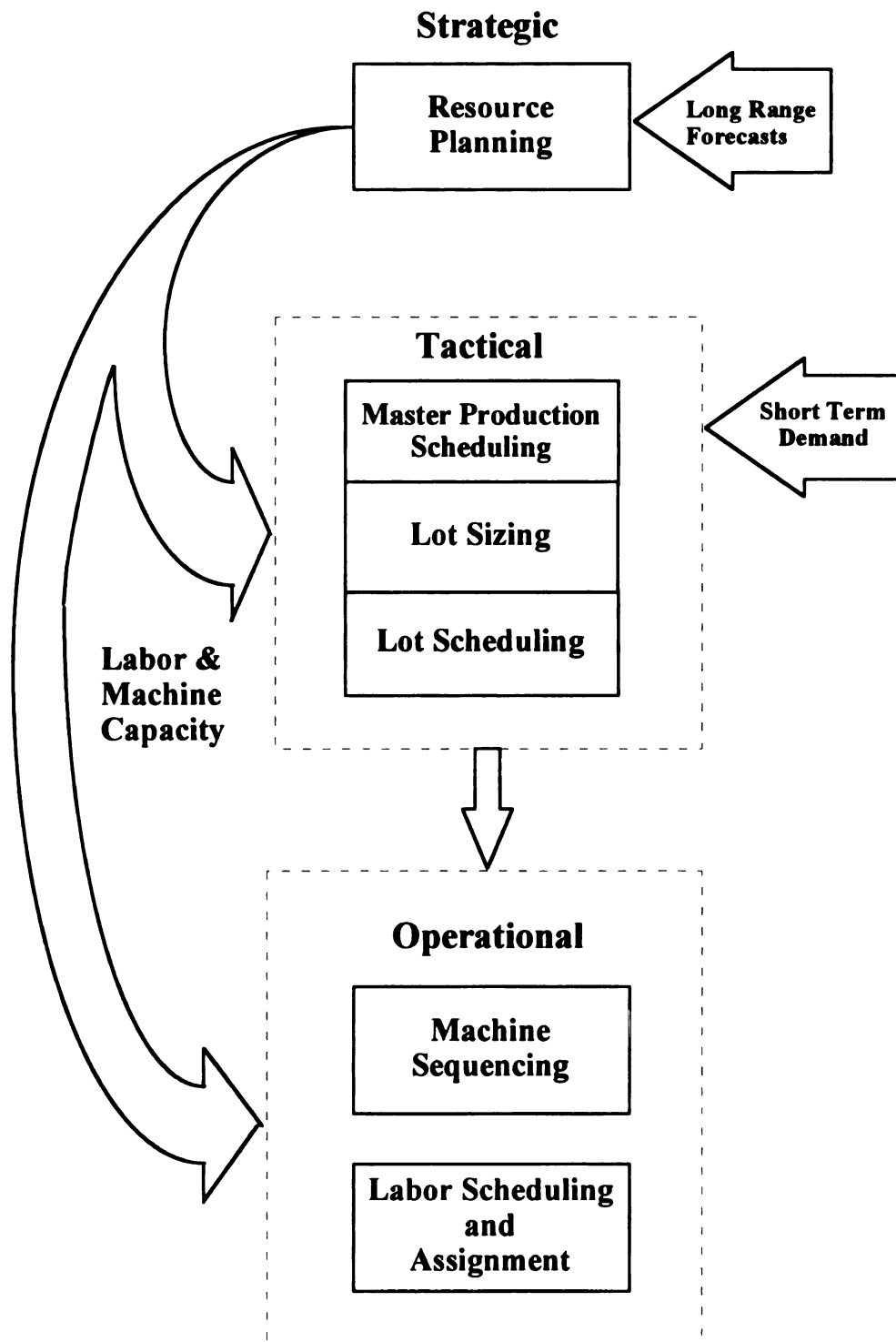


FIGURE 1.1 TRADITIONAL PRODUCTION PLANNING AND SCHEDULING

illustrates this traditional view. Long range production planning involves determining labor and machine capacity requirements to meet long range product demand. These strategic decisions are typically made for a one- to two-year planning horizon and constrain lower level decisions.

The first tactical problem is master production scheduling, which is determining which finished products to manufacture to best meet short term demand, given labor and machine capacity constraints. In many environments, there is no master production scheduling decision. For example, automotive suppliers must meet dictated schedules or face severe penalties. General Motor's Saturn division charges suppliers \$500 per minute of assembly line production delay due to tardy shipments.³

Given a master production schedule, the next problem in the traditional approach is deciding how big production lots should be (lot sizing) and when these lots should be released to the shop floor (lot scheduling). Ideally, these decisions should be made simultaneously for all components. In MRP systems, lot sizing and scheduling decisions are made separately for each component and constrain the decision for components at lower levels in the bill of material. The lot sizing and sequencing decisions should be made recognizing labor and machine constraints and many planning models incorporate at least one constraint. MRP systems incorporate capacity planning as a separate process that must be used iteratively with the MRP lot sizing and scheduling logic.

³Raia, Ernest, "Saturn: Rising Star", *Purchasing*, Vol. 115, No. 3, September 9, 1993, p. 45.

With production lots sized and scheduled, the shop floor supervisor must determine how to manage machines and workers to process production lots so that demand is satisfied at minimum cost. The shop floor supervisor decides which production lot to process next (the sequencing or dispatching decision) and where to assign workers (the labor assignment decision). Although the sequencing problem has been studied extensively, in practice this decision is made using dispatching rules. In some cases, dispatching heuristics include behavioral parameters, e.g., which supervisor is most convincing in his demand that his batch of parts be produced next.

While the traditional hierarchical approach attempts to simplify the production planning and scheduling problem by sacrificing global optimality, the resulting tactical and operational problems are still complex, and integrated solutions are not available. Von Lanzenauer (1970) observed that "The production scheduling and the job-lot sequencing problem remain separate in theory while being closely interrelated in practice."⁴ More recently, Sum and Hill (1993) "take the position that order sizing and scheduling should be considered simultaneously (or at least iteratively) because they are tightly interdependent."⁵

1.3 THE MACHINE STATE SCHEDULING APPROACH

The MSS model is a zero-one integer programming model that integrates tactical and operational decisions by focusing on the state of production equipment, i.e., which

⁴Von Lanzenauer, Christoph Haehling, "A Production Scheduling Model by Bivalent Linear Programming", *Management Science*, Vol. 17, No. 1, 1970, p. 105.

⁵Sum, Chee-Chuong and Arthur V. Hill, "A New Framework for Manufacturing Planning and Control Systems", *Decision Sciences*, Vol. 24, No. 4, July/August 1993, p. 740.

component are machines, workcenters and assembly lines producing in a given time period. By constraining production to fixed time intervals, the model can determine schedules for machines and labor in a dependent demand repetitive manufacturing system with sequence-dependent setups. The model formulation requires a reasonable number of integer variables. If c_i is the number of components produced on workcenter i and T is the number of periods in the planning horizon, then the number of zero-one integer variables in the problem (N_z) is:

$$N_z = T \sum_i c_i \quad (1-1)$$

This model takes a desired end item demand schedule and converts it into a set of shop floor production decisions that can be easily implemented by shop floor supervisors. The shop floor supervisor, freed from the intractable shop floor scheduling problem, can concentrate on ensuring that labor and equipment are performing to plan.

Constraining production to a single component at a workcenter in a period is consistent with management practice in repetitive manufacturing firms. According to the APICS Repetitive Manufacturing Group, repetitive manufacturers use "daily run schedules, not work orders, for control of production. Master schedules culminate in serialized control of production which covers specific lengths of time, which is the development of schedules, not orders."⁶

⁶APICS Repetitive Manufacturing Group, "Repetitive Manufacturing", *Production and Inventory Management*, Second Quarter, 1982, p. 81.

1.4 FORMAT OF THE DISSERTATION

Section 2 reviews the literature on production planning and scheduling models. Section 3 presents the Machine State Scheduling (MSS) model. Section 4 presents the single-pass finite loading (SPFL) heuristic that gives good solutions to MSS problems. Section 5 presents the production environment at Walker Manufacturing, the firm that was used to evaluate the MSS model. In Section 6, the quality of the integer programming and SPFL heuristic solutions is evaluated and the MSS model solutions are compared to the production scheduling decisions made at the Walker Manufacturing. Section 7 presents a discussion of the results and Section 8 gives conclusions and recommendations for future research. Appendix A describes the methods and computer programs used to generate solutions to the MSS model.

2.0 LITERATURE REVIEW

2.1 PRODUCTION PLANNING AND SCHEDULING MODELS AND METHODS

Most production planning and scheduling models/methods make use of at least one of the following techniques to make the problem tractable:

1. **Hierarchical Structure:** The problem is solved in a hierarchical fashion, with each solution in the hierarchy providing restrictions on the lower level problems.
2. **Aggregation/Disaggregation:** The products are aggregated to reduce the size of the problem. The solution to the aggregate problem must then be disaggregated to provide detailed production plans.
3. **Limited Scope:** A limited portion of the production planning and scheduling problem is addressed or some of the factors of production are ignored. For example, machine capacity constraints may be considered but labor capacity ignored.
4. **Simplifying assumptions/restrictions:** For example, component part commonality may not be allowed or production lot sizes may be restricted to be integer multiples of the parent component lot size.
5. **Local logic:** Heuristics may be applied using a limited set of information in isolation from other decisions in the production facility. Local logic produces solutions to the scheduling problem which are locally optimal at best. Dispatching rules and Kanban systems are examples of local logic.

MRP is the most common production planning and scheduling technique in use today. MRP systems develop production schedules for component parts based on a time-phased "parts explosion" using the bill of material. Figure 2.1 shows the main components of an MRP system. The MRP lot sizing logic requires a master production schedule as an input. Capacity requirements can be approximated at the master production schedule level using rough-cut capacity planning techniques, or more accurately after the parts explosion

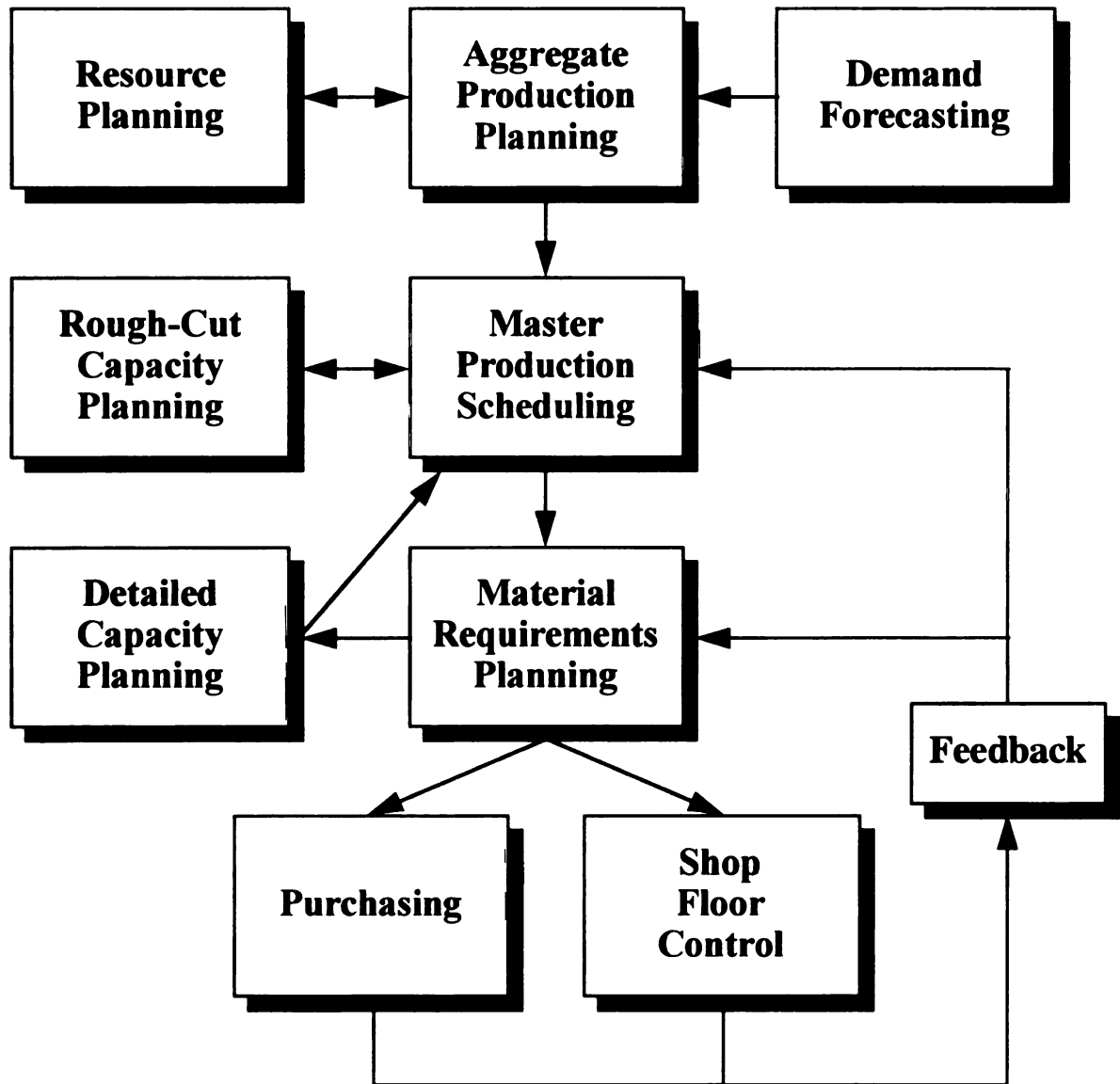


FIGURE 2.1 COMPONENTS OF AN MRP SYSTEM

process using capacity requirements planning techniques. MRP systems use a hierarchical structure (the bill of material) with simplifying assumptions and a limited scope to generate production plans. MRP systems have a number of weaknesses as a result of the techniques used to make the production planning and scheduling problem tractable:

- 1) The production planning decisions are made independent of the shop floor. MRP systems only provide batch sizes, release dates, due dates and priority information to the shop floor, but they do not provide shop floor production schedules.
- 2) The time phasing process assumes a known and constant lead time for component part production--usually with significant slack.
- 3) The MRP logic assumes infinite capacity (capacity planning techniques are separate from the explosion process).
- 4) Lot sizing decisions are performed level by level according to the BOM. Lot sizing decisions at one level constrain the decisions at a lower level, producing less than optimal lot sizes.

2.1.1 Lot Sizing Models

A number of lot sizing models have been developed since F.W. Harris proposed the EOQ model. Bahl, Ritzman and Gupta (1987) evaluate lot sizing models and provide the classification scheme shown in Figure 2.2. To solve practical problems in a repetitive production system, a lot sizing model must consider dependent demand and constraints, so this discussion will focus primarily on MLCR models.

A second means of classifying lot sizing models is to consider the nature of demand. Many of the earlier models were developed in the inventory theory field, and considered demand as stochastic. Others are extensions of the EOQ model and consider demand known and constant. More recent models use the concept of a master production

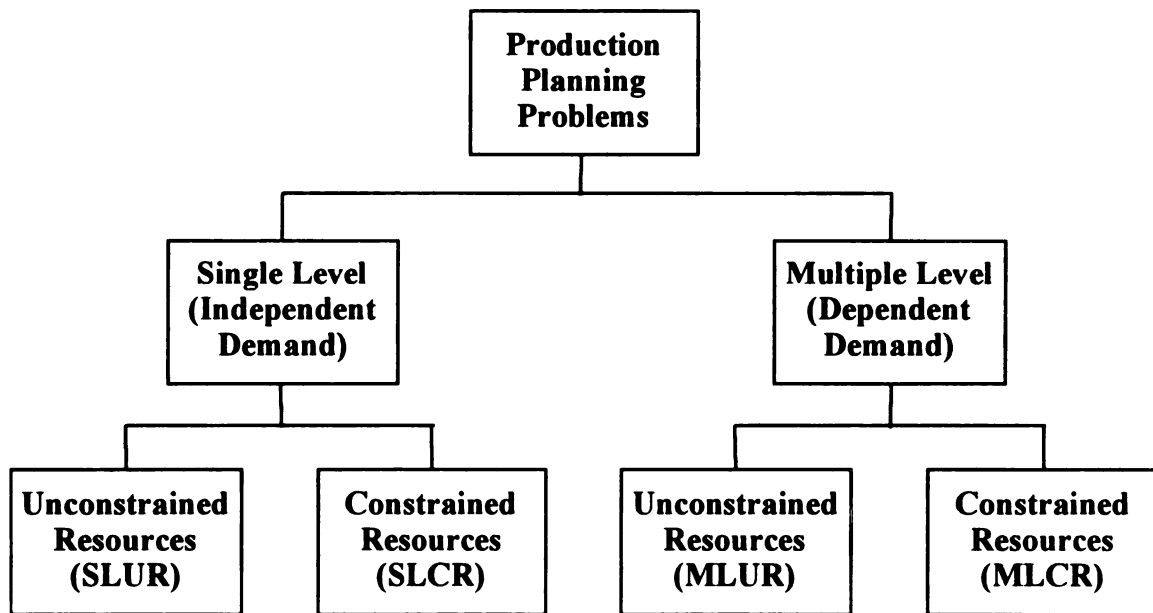


FIGURE 2.2 LOT SIZING MODEL CLASSIFICATION SCHEME

schedule--a varying but known production schedule for end items. The MSS model assumes demand is known and fixed but that it may vary from period to period.

The single-level constrained resource (SLCR) problem has received considerable attention. Elmaghraby (1978) provides a survey of the research on the economic lot scheduling problem (ELSP), which allows multiple items but assumes only one constrained resource and constant demand. Many heuristics have been developed for the ELSP problem when the constant demand constraint is relaxed (Eisenhut (1975), Vanderveken (1978), Karni and Roll (1982) among them), but these methods assume that setups result in a cost but not in reduced capacity. In the repetitive manufacturing environment, the setup costs are typically the labor costs associated with performing the setup, but the loss in production capacity may be more important. A second problem with these models is that they assume that production of an item in a period requires a setup. It is possible that an item may be the last one produced in one period and the first one produced in the next period, eliminating the need for a setup.

Manne (1958), in his seminal piece, defined a zero-one integer variable for each possible production sequence. Although this approach resulted in a large number of zero-one integer variables, Manne showed that the large majority of these variables would be integer when the problem was solved as a linear program. Thus, good solutions could be achieved by rounding LP relaxations. A disadvantage of the model is that by defining production sequences, variable lot sizes are not allowed.

The multiple-level unconstrained resource (MLUR) problem has been studied, but a number of assumptions are usually made in addition to the assumption that resources are

unlimited. Component commonality is usually not allowed, constant end-item demand rates are typically assumed and production is assumed to be instantaneous. Crowston, Wagner and Williams (1973) proved that in this environment component lot sizes should be integer multiples of the parent component's lot size, a proof that was later shown to be incorrect (Williams, 1982). Unfortunately, the Crowston, Wagner and Williams paper is frequently quoted and used to justify the assumption of integer multiple lot sizes.

As Bahl, Ritzman and Gupta point out, "A casual look at practitioner-oriented literature such as the *Production and Inventory Management* journal and *APICS Conference Proceedings* strongly suggests that most real-life environments are MLCR problems."⁷

Von Lanzenauer (1970) formulated a zero-one integer programming model that considered machine capacity in the multi-level production environment. Like the Von Lanzenauer model, the MSS model divides the production horizon into periods. Von Lanzenauer's model considers setups, but only as a fixed cost independent of the production sequence. The production environment is considered to be a flowshop, with no assembly operations. Von Lanzenauer's model contains the basic structure used in this proposal to address a less constrained, more realistic environment. Surprisingly little has been done with this approach since Von Lanzenauer's original paper. Bruvold and Evans (1985) use the fixed time period concept in the single level problem to consider sequencing multiple products on multiple production lines where setups are sequence-

⁷Bahl, Harish C., Larry P. Ritzman and Jatinder N. D. Gupta, "Determining Lot Sizes and Resource Requirements: A Review", *Operations Research*, Vol. 35, No. 3, May-June 1987.

dependent. Setups are considered to result in both a fixed cost and a capacity loss. A disadvantage of their model is the number of variables required. Bruvold and Evans define the zero-one integer variable δ_{ijk} to determine if product i is produced on production line j in period k . If there are N products produced on J machines in T time periods, then NJT zero-one integer variables are required to define the production schedule. To determine which setups occur, Bruvold and Evans define the continuous variables ϕ_{ijk} , θ_{ijk} and γ_{iljk} , which are continuous variables but only take on binary values due to constraint relationships with the variable δ_{ijk} . Since the subscript i and l in γ_{iljk} refer to product, there are $2NJT + N^2JT$ added variables in the problem. In the MSS model presented in Section 3, a production variable δ_{ijt} is defined similarly to Bruvold and Evans, except the sequence-dependent setups are determined using only one continuous variable γ_{ijt} , resulting in NJT additional continuous variables with a corresponding reduction in added constraints.

Smith-Daniels and Smith-Daniels (1986) developed a mixed integer programming model for lot sizing and sequencing in packaging lines which include both major and minor setups. A major setup may be required for changing products, while a minor setup may be required to change package size (or vice-versa). Their model only allows major setups to occur between fixed time periods (over the weekend, for example), and restricts production in a period to one product family. Item production in a period can have sequence-dependent setups, and not all items need to be produced. Item sequencing is handled via a traveling-salesman binary variable V_{imt} which equals one if item i is an

immediate predecessor of item m in period t . Thus, the number of zero-one variables is proportional to the square of the number of items.

A variety of other approaches have been used to model MLUR and MLCR problems. Prabhakar (1974) modeled a two-stage chemical processing problem using traveling salesman binary variables. His continuous time model allowed for sequence-dependent setups, but no assembly. While his model constrains aggregate production and inventory in the first stage to be at least as great as aggregate production in the second stage, his model does not require first stage production to precede second stage production. Thus, the model could produce a schedule where the second stage production of a product is scheduled before the first stage production is started.

Gabbay (1979) formulated a discrete time, multi-stage, multi-item planning model with one constraint per stage. He presented a one-pass algorithm and a hierarchical solution procedure, however, the problem could be solved with a linear program since the model does not consider setups.

Steinberg and Napier (1980) proposed a model that considers commonality. While it is presented as having a network structure, the problem is solved with a mixed integer linear programming code.

A number of researchers have considered the multi-stage problem assuming constant end item demand as in Crowston, Wagner and Williams (1973). Blackburn and Millen (1982) considered the multistage problem assuming child component lot sizes to be integer multiples of the parent lot size in the context of a lot sizing procedure for an MRP system. They developed a single pass heuristic that considers the impact of lot sizing

decisions at one level of the bill of material on lower level components. Moily (1986) considered the same problem assuming lot splitting (an integer number of child component lots is required to satisfy the demand created by a parent component lot) and provides both an optimal and a heuristic solution procedure.

Billington, McClain and Thomas (1983) present an integer programming model that considers sequence-independent setups. The contribution of their paper is product structure compression--an optimized production technology (OPT) concept by which the problem size is reduced by solving the problem for the few capacity-constrained facilities and lot-for-lot lot sizing is used at unconstrained facilities.

Bahl and Ritzman (1984) present a model that combines the Manne concept of production sequences with an integer programming lot sizing model. They develop a solution heuristic that iterates between a production sequencing problem with fixed lot sizes and a lot sizing model with fixed production sequences. The model only considers 2 levels--component and end-item--and assumes that assemblies are produced lot-for-lot and have no capacity constraints. Sum and Hill (1993) propose the integrated manufacturing planning in continuous time (IMPICT) framework, which is a late-start, capacity constrained operation scheduling network, similar to a project scheduling network. They present three heuristics based on order merging, order splitting and order merging and splitting.

The production planning and scheduling literature is broad and varied. Table 2.1 provides an analysis of the more relevant models described above. This comparison clearly shows that all of these models have significant limitations that make them

TABLE 2.1 COMPARISON OF MODEL CAPABILITIES

Author(s)	Year	Multiple end items	Depend. demand	Assembly	Common.	External Comp. Demand	Transfer Delays	Machine capacity	Labor	Setups	Sequence Depend. Setups
Bahl and Ritzman	1984	✓	✓	✓	✓			✓		✓	
Billington, McClain and Thomas	1983	✓	✓	✓	✓	✓	✓	✓		✓	
Blackburn and Millen	1982		✓	✓		✓	Possible			Cost	
Bruvold and Evans	1985	✓						✓		✓	✓
Crowston, Wagner and Williams	1973	Possible	✓	✓						Cost	
Gabbay	1979	✓				✓		✓			
Moily	1986	✓	✓	✓						Cost	
Prabhakar	1974	✓	2 levels			Possible		✓		✓	✓
Steinburg and Napier	1980	✓	✓	✓	✓	✓	Possible	✓		Cost	
Sum and Hill	1993	✓	✓	✓	✓	Possible	✓	✓		✓	
Von Lanzanauer	1970	✓						✓	Possible	Cost	

unsuitable as a general modeling approach for repetitive manufacturing systems.

Commonality frequently has been excluded from model formulations. Machine capacity is frequently modeled, but labor constraints (constraints based on the actual workers and not aggregate labor levels) have been excluded. Only Von Lanzenauer's model could be easily extended to consider labor. Many models consider setups as a cost and ignore the capacity loss. Sequence-dependent setups have only been considered in the single level case (Bruvold and Evans) and the two level case of Prabhakar, although Prabhakar's model incorrectly relates the timing of production quantities at each level.

The MSS model includes all of the model capabilities given in Table 2.1.

Furthermore, it includes these capabilities while only making three simplifying assumptions:

1. Only one component is produced at a workcenter in a period
2. Labor cannot be transferred between workcenters in a period.
3. Setups are performed either during a period when the workcenter is idle or at the beginning of a period in which there is production.

The next section presents the MSS model.

3.0 THE MACHINE STATE SCHEDULING (MSS) MODEL

In the following description, **component** refers to components, subassemblies, assemblies or end items. A **workcenter** is a collection of tools, a machine or a group of machines operated by one or more workers that produces one or more components using purchased components or components produced by other workcenters. A workcenter is buffered by inventory; that is, components used and produced by a workcenter can be stored in work-in-process (WIP).

The fundamental concept behind the MSS model is that the production planning and scheduling problem for repetitive manufacturing systems can be made manageable by dividing the planning horizon into periods, then producing no more than one component at each workcenter in the period. The zero-one integer production variable δ_{ijt} is used to determine whether component i is being produced at workcenter j in period t . Knowing which components are being produced at each workcenter, it is possible to determine production quantities and labor requirements. By assuming setups are performed either during periods when the workcenter is idle or at the beginning of a production period, it is possible to include sequence-dependent setups in the model. A machine state variable γ_{ijt} is used to keep track of which component a workcenter is set up to produce. This variable takes on a value of one when a workcenter is set up to produce component i in workcenter j in period t and zero if not. The machine state variable is continuous and can take on fractional values when the workcenter is idle to represent a setup that is performed over more than one (idle) period. The following example demonstrates the logic behind the MSS model.

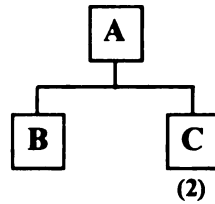
3.1 AN EXAMPLE PROBLEM

Figure 3.1 presents the data for the example problem and Figure 3.2 presents the MSS solution. The problem requires 300 units of component A by the end of period 4. Component A is assembled using one unit of component B and two units of component C, where components B and C are produced in the same workcenter. Production of components A and C require one worker, while production of component B requires two. Two workers are available each period; thus, labor limits production to either component B or components A and C in any period. Production periods are two hours long, resulting in four periods in a standard eight hour day. If component C is produced in a period, up to 150 units can be transferred in the same period to workcenter 1 for use in assembling component A. If a setup is required to produce component C in a period, the maximum units that can be transferred is reduced from 150 to 100 due to the production loss from the setup.

Units of component B cannot be transferred to workcenter 1 in the same period they are produced--the entire quantity becomes available in the next period. Workcenter 2 starts period 1 set up to produce component B and a setup is required to switch from production of component B to component C. These setups are sequence-dependent, expressed in terms of the units of production lost at the beginning of a period.

The MSS solution in Figure 3.2 shows that component B is produced in the first period, components A and C are produced in periods 2 and 3 and component A is produced in period 4. The initial inventory of 25 units of component B, plus 50 of the units produced in the first period are used in the assembly of component A in period 2.

Bill of Material



Production Information

Period Length

2 Hrs

Inventory Holding Cost

20%/unit/yr

Demand

300 units of end item A by the end
of Period 4

Available Workers

2

Initial Setup, Workcenter 2

Component B

Component Data

Comp.	Center	Prod. (hour)	Periods Delay	Max Transfer	Number Workers	Initial Inventory	Unit Cost (\$)
A	1	50	0	-	1	25	\$30
B	2	125	1	-	2	25	\$20
C	2	150	-	150	1	50	\$10

Production Loss from Setups

(production loss in units of the component
switched to.)

		To	
		B	C
Switching From	B	—	50
	C	40	—

FIGURE 3.1 MACHINE STATE SCHEDULING EXAMPLE PROBLEM

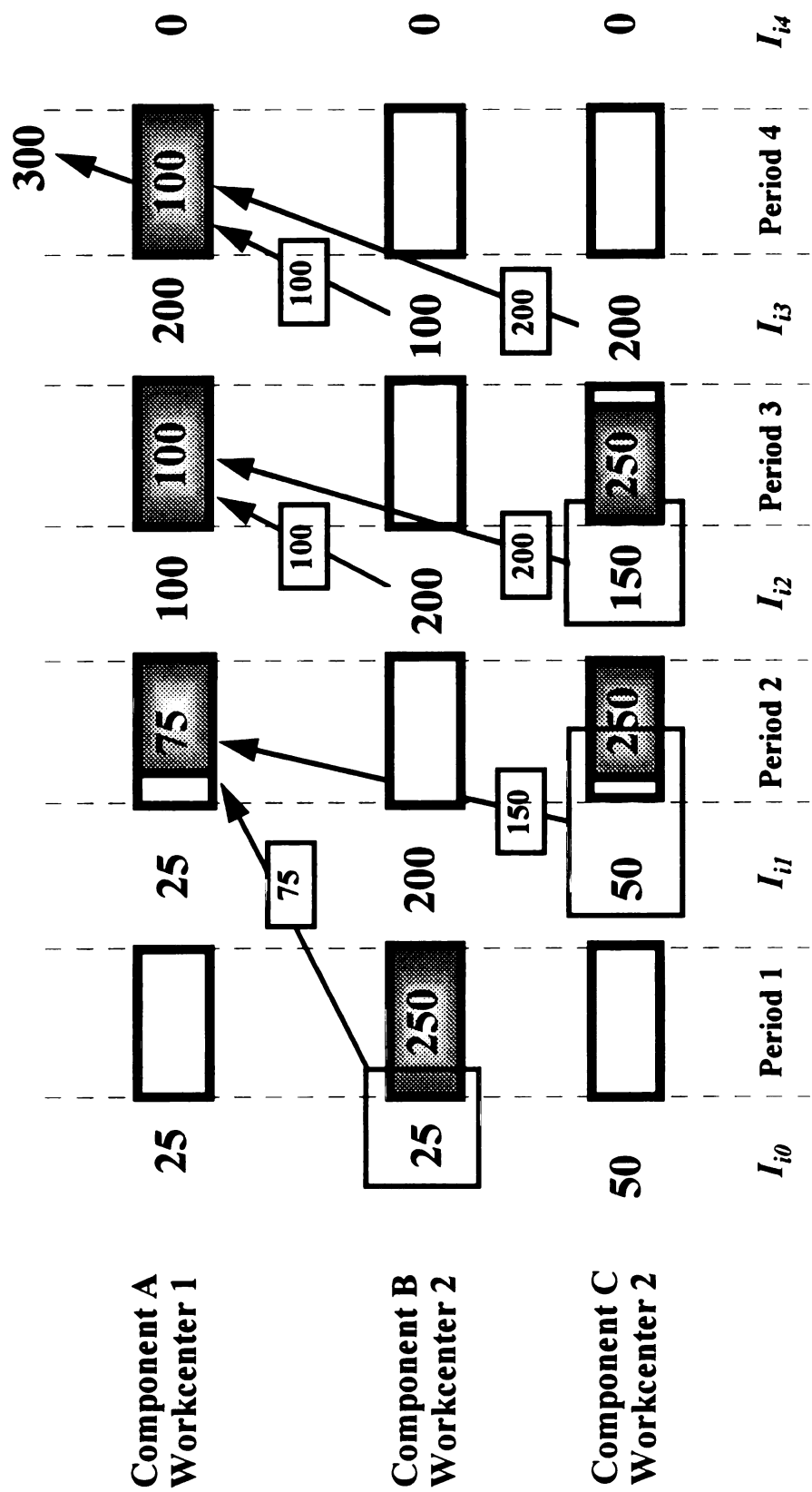


FIGURE 3.2 GRAPHICAL REPRESENTATION OF THE MSS SOLUTION

Units of component B used to assemble component A in periods 3 and 4 are satisfied from inventory.

In period 2, workcenter 2 is switched from production of component B to production of component C. The setup of workcenter 2 in period 2 means that only 250 units of component C can be produced in period 2 and the maximum number of units of period 2 production that can be transferred to workcenter 1 in period 2 is 100 units. The transfer of 100 units of period 2 production plus the initial inventory of 50 units is sufficient to support the assembly of component A in period 2. Workcenter 2 produces 250 units of component C in period 3, 50 of these units are used in period 3 for assembly of component A. After period 3, sufficient inventory of component C is available to support assembly of component A in period 4.

The example of Figures 3.1 and 3.2 illustrate the logic behind the MSS model, which is presented in the next section.

3.2 THE MACHINE STATE SCHEDULING INTEGER PROGRAMMING MODEL

In the following model, production periods are assumed to be of equal length with no loss in generality.

SUBSCRIPTS:

- i, i' - component
- j - workcenter
- t - time period
- d - labor division

VARIABLES:**Binary:**

- δ_{ijt} = 1 if workcenter j is producing component i in time period t .
0 if not.
- λ_{ijt} = 1 if an intraperiod transfer of component i can occur from workcenter j in period t .
0 if not.

Continuous:

- γ_{ijt} = 1 if workcenter j is set up to produce component i in time period t
0 if not.
- X_{ijt} = Number of units of production of component i at workcenter j in period t available after period t .
- Y_{ijt} = number of units of production of component i at workcenter j in period t available for intraperiod transfer.
- I_{it} = Units of component i in inventory at the end of period t .
- Z_{ijt} = Production loss (in units) of component i in a workcenter j in period t due to a setup (assumed to be less than the period production rate p_{ij}).

Parameters:

- b_d = Wage rate for a worker in labor division d (\$/period).
- c_i = Per period holding costs for a unit of component i .
- d_{it} = External demand for component i during period t .
- f_{ij} = The maximum number of units of component i produced at workcenter j that can be transferred to and used at another workcenter in the period in which they are produced.
- l_{ij} = Number of periods of delay between production of component i at workcenter j and its availability at another workcenter. If $l_{ij} > 0$, then $f_{ij} = 0$.

- $m_{i'ij}$ = $\max(f_{ij}, u_{i'ij})$ where $u_{i'ij}$ is defined below. This is only required if setups are sequence-dependent and some but not all $u_{i'ij}$ are greater than f_{ij} .
- n_{dt} = Number of workers in labor division d in period t .
- p_{ij} = Production rate of component i at workcenter j (units/period).
- $q_{ii'}$ = Number of units of component i used to produce a unit of component i' .
- $u_{i'ij}$ = Production loss (in units) when changing production from component i' to component i at workcenter j if setups are sequence-dependent.
- U_{ij} = $\max_{i'}(u_{i'ij})$ = maximum production loss (in units) in switching to product i at workcenter j if setups are sequence-dependent.
- $v_{i'ij}$ = $U_{ij} - u_{i'ij}$.
- w_{ijd} = Number of workers in labor division d required to staff workcenter j when producing component i .
- y_j = Production loss (in units) when changing the setup at workcenter j if setups are not sequence-dependent.

OBJECTIVE:

$$\text{Minimize } \sum_i \sum_t c_i I_{it} + \sum_i \sum_j \sum_d \sum_t b_d w_{ijd} \delta_{ijt}$$

CONSTRAINTS:

Production/Inventory Balance:

$$(1) \quad I_{i,t-1} + \sum_j X_{ij,t-l_0} \sum_j Y_{ijt} - I_{it} = d_{it} + \sum_{i'} \sum_j q_{ii'} X_{i'jt} \quad \forall it$$

Labor Capacity:

$$(2) \quad \sum_i \sum_j w_{ijd} \delta_{ijt} \leq n_{dt} \quad \forall d, t$$

Intraperiod transfer limit:

If $f_{ij} \geq$ all setup losses ($u_i'_{ij}$), then:

$$(3) \quad Y_{ijt} + Z_{ijt} \leq f_{ij} \quad \forall i, t \text{ where } l_y = 0$$

If $f_{ij} <$ any $u_i'_{ij}$, then:

$$(3a) \quad Y_{ijt} + Z_{ijt} + M(\lambda_{jt} - 1) \leq f_{ij} \quad \forall i, j, t \text{ where } l_y = 0$$

$$(3b) \quad Y_{ijt} \leq f_{ij} \lambda_{jt} \quad \forall i, j, t \text{ where } l_y = 0$$

Definition of the setup state variable γ_{ijt} :

$$(4) \quad \gamma_{ijt} \geq \delta_{ijt} \quad \forall i, j, t$$

$$(5) \quad \sum_i \gamma_{ijt} = 1 \quad \forall j, t$$

If setups are not allowed during idle periods, then constraint (6) is included:

$$(6) \quad \gamma_{ijt} \geq \gamma_{ij,t-1} - \sum_{i'} \delta_{i'jt} \quad \forall i, j, t$$

Define setup production loss Z_{ijt} :

$$(7) \quad Z_{ijt} \geq U_{ij} \delta_{ijt} - \sum_{i'} v_{i'ij} \gamma_{i'j,t-1} \quad \forall i, j, t$$

Define period production X_{ijt}

$$(8) \quad X_{ijt} + Y_{ijt} \leq p_{ij} \delta_{ijt} - Z_{ijt} \quad \forall i, j, t$$

The objective function of the MSS model minimizes the sum of inventory holding and labor costs. If a workcenter is producing a component in a period, then the labor required to operate the workcenter for the entire period is charged even if only one part is produced.

The first constraint in the model is the production/inventory balance equation. In any period, the beginning inventory plus the production available in the period (both $X_{ij,t-l_{ij}}$ and Y_{ijt}) minus the ending inventory must equal the external demand for the component plus the dependent demand for the component from workcenters that use the component. The parameter q_{ij} can be set to allow for scrap losses, but this does result in fractional production quantities.

A workcenter may require more than one worker. For example, an assembly line may require a number of workers from different labor divisions (e.g. welders, assemblers, etc.). The second constraint is the labor capacity constraint which limits the number of workers assigned to workcenters in a period.

The model allows two types of delay in the transfer and use of components. If components produced at a workcenter are not available for use by another workcenter in the same period they are produced, then parameter l_{ij} is the number of periods of delay before they are available. This delay might be due to material handling restrictions (parts transferred by forklift, time for paint to dry or steel to cool) or it may be due to an external process like electroplating by a supplier. Components delayed in this fashion are not included in the inventory variable for the periods of the delay and the entire period's production is available l_{ij} periods later.

If components can be transferred to a workcenter during the same period in which they are produced, it is unlikely that all components can be transferred and used within the period. The parameter f_{ij} is the maximum number of components that can be effectively transferred in the period. If the intraperiod transfer limit is always greater than or equal to the setup loss ($f_{ij} \geq u_{i'ij} \quad \forall i'$), then the intraperiod material transfer is handled by constraint (3). If the setup loss can be greater than the intraperiod transfer limit ($f_{ij} < \text{any } u_{i'ij}$) then an addition binary variable λ_{jt} is required and constraints (3a) and (3b) are used. These constraints are illustrated graphically in Figure 3.3.

To determine when setups occur, it is necessary to know the state of each workcenter in every period (i.e., what component a workcenter is set up to produce). The production variable δ_{ijt} indicates the state of a workcenter when it is operating but not when it is idle. The machine state variable γ_{ijt} is defined in terms of the production variable δ_{ijt} . Constraint (4) requires the state variable to be one when the production variable is one. Constraint (5) requires the sum of the state variables for a workcenter in a period to be one. Together, constraints (4) and (5) limit a workcenter to production of only one component in a period, making a constraint on the production variable δ_{ijt} unnecessary. If there are no setups, then $\sum_j \delta_{ijt} \leq 1 \quad \forall i, t$ replaces constraints (4) and (5).

If the workcenter setup can be changed only during an operating period, then constraint (6) is added. Constraint (6) requires the state variable for state i in period t to be one if the workcenter was in state i in period $t-1$ unless there is production of a

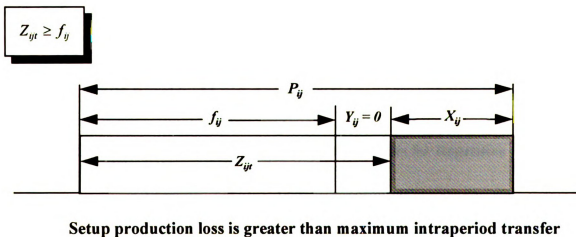
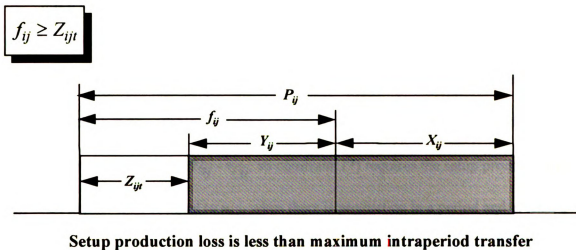


FIGURE 3.3 GRAPHIC REPRESENTATION OF THE TRANSFER LIMIT CONSTRAINT

different component i' in period t . Constraints (4), (5) and (6) will force the machine state variable γ_{ijt} to be binary even though it is defined as a continuous variable.

If n components can be produced in a workcenter, then $n(n-1)$ state changes are possible each period. Rather than defining a variable for each of the $n(n-1)$ possible state changes, constraint (7) defines the setup loss Z_{ijt} in terms of the production variable δ_{ijt} and the machine state variable γ_{ijt} . Since $v_{i'ij} = U_{ij} - u_{i'ij}$, the sequence-dependent setup loss $u_{i'ij}$ can be expressed as $U_{ij} - v_{i'ij}$, so constraint (7) requires the setup production loss Z_{ijt} to be greater than or equal to $u_{i'ij}$ when there is production in a period and at least a nonpositive number when there is no production. Note that sequence-independent setup losses are a special case of the sequence-dependent setup loss.

Constraint (8) defines the period production $X_{ijt} + Y_{ijt}$ in terms of the production variable δ_{ijt} , production rate parameter p_{ij} and setup loss variable Z_{ijt} .

The MSS model addresses two of the seven needs of repetitive manufacturing cited by the APICS Repetitive Manufacturing Group:

1. Conversion of MRP Explosions to Run Schedules for Repetitive Manufacturing.

Most companies control repetitive manufacturing by daily schedules, but schedules covering other lengths of time are more appropriate for some products. Floor control of repetitive manufacturing has not been addressed in a systematic way in the United States. Every company has developed its own in-house system. More detailed systems of planning are needed for repetitive manufacturing. Planning should lead to improved control of a flow of material through a sequence of operations. This would result in obvious savings by reducing parts banks between operations.

2. Planning Capacity During Production Planning and Master Scheduling.

This seems to be much more a problem with some companies than others, and is most severe in multi-plant planning. If production is planned through several stages and into final assembly, the assembly rates and parts fabrication rates must be balanced to avoid shortfalls or excessive parts banks between operations. A shortfall of parts is most serious, and it should be revealed as early as possible in the planning process.⁸

⁸APICS Repetitive Manufacturing Group, "Repetitive Manufacturing", *Production and Inventory Management*, Second Quarter, 1982, p. 85.

4.0 FINITE LOADING HEURISTIC

Although the MSS model does not require the large number of zero-one integer variables of typical production planning and scheduling models with sequence-dependent setups, the model is difficult to solve. Even for problems with good solutions, the time required to find solutions with integer programming software prevents using the model iteratively. Thus, a simple heuristic solution procedure, the single-pass finite loading heuristic (SPFL), was developed to provide an effective solution technique so that production planners could use the model in a trial-and-error manner.

The SPFL heuristic does not schedule setups during idle periods. Scheduling setups during an idle period in the heuristic could result in a significant loss of capacity since it is not possible to determine *a priori* which periods are idle. Allowing for setups during an idle period requires a multiple-pass or iterative approach. The heuristic procedure ignores cost or productivity differences at workcenters that can produce the same component.

The following parameters are used in the SPFL heuristic and are identical to the parameters of the MSS model in Section 3. The parameters and subscripts are not presented in italics in this section (except for the parameter l_{ij} and the subscript l) to clearly distinguish the heuristic procedure from the MSS model.

Parameters

- d_{it} = External demand for component i during period t .
- f_{ij} = The maximum number of units of component i produced at workcenter j that can be transferred to and used at another workcenter in the period in which they are produced.

- l_{ij} = Number of periods of delay between production of component i at workcenter j and its availability at another workcenter.
- n_{dt} = Number of workers in labor division d in period t .
- P_{ij} = Production rate of component i at workcenter j (units/period).
- $q_{ii'}$ = Number of units of component i used to produce a unit of component i' .
- $u_{i'ij}$ = Production loss (in units) when changing production from component i' to component i at workcenter j .
- $U_{ij} = \max_i(u_{iij})$ = maximum production loss (in units) in switching to product i at workcenter j .
- $v_{iij} = U_{ij} - u_{iij}$
- w_{ijd} = Number of workers in labor division d required to staff workcenter j when producing component i .

The variables used in the heuristic are defined below.

Variables

- $STATE(j, t)$ = i if workcenter j is producing component i in period t .
= 0 if not.
- $PROD(i, j, t)$ = Production of component i scheduled at workcenter j in period t .
- $POT(i, j, t)$ = Best known upper bound on the units of component i that can be produced at workcenter j in period t . If $STATE(j, t-1)$ is not known, then $POT(i, j, t) = P_{ij} - U_{ij} \forall i$.
- $WORK(t, d)$ = # of workers in labor division d in period t who are not yet assigned to a workcenter.
- $BAL(i, t)$ = Units of component i available in period t . $BAL(i, t)$ will take on negative values during processing of the heuristic to represent the need for production. If a feasible solution is found by the heuristic all $BAL(i, t)$ must be ≥ 0 .

The subscript i represents the component and ranges from 1 to I . The subscript j represents the workcenter and ranges from 1 to J . The time periods t are numbered from 1 to T . The component indices are assigned first in order of ascending low-level code, then in order of descending inventory holding cost. Figure 4.1 illustrates the low-level code concept, which was developed for MRP record processing. For example, component B is a level 2 component because it appears at level 1 for end item A but also appears at level 2 as a component of item H in end item G. Numbering components in low level code order allows the SPFL heuristic to schedule production in a single pass while considering dependent demand relationships. Numbering components in order of descending inventory holding costs should result in relatively low inventory costs since the SPFL heuristic will schedule production of higher holding cost components closer to the period in which they are used. It should be noted that low-level codes are generally negatively correlated to inventory holding costs because components with lower low-level codes have had more processing and are frequently assembled from components with numerically higher low-level codes.

Figure 4.2 shows how the major routines in the heuristic are related. The initial variable values are set in the Initialize routine. The Increment routine uses the $BAL(i,t)$ variable to determine when component production is needed. When the Increment routine finds a period that requires component production, control is passed to the Production routine which determines when the components should be produced. The Production routine passes control to the Schedule routine, which updates the variables $STATE(j,t)$, $PROD(i,j,t)$ and $POT(i,j,t)$. The routine Adjust updates the $BAL(i,t)$ variable to reflect the

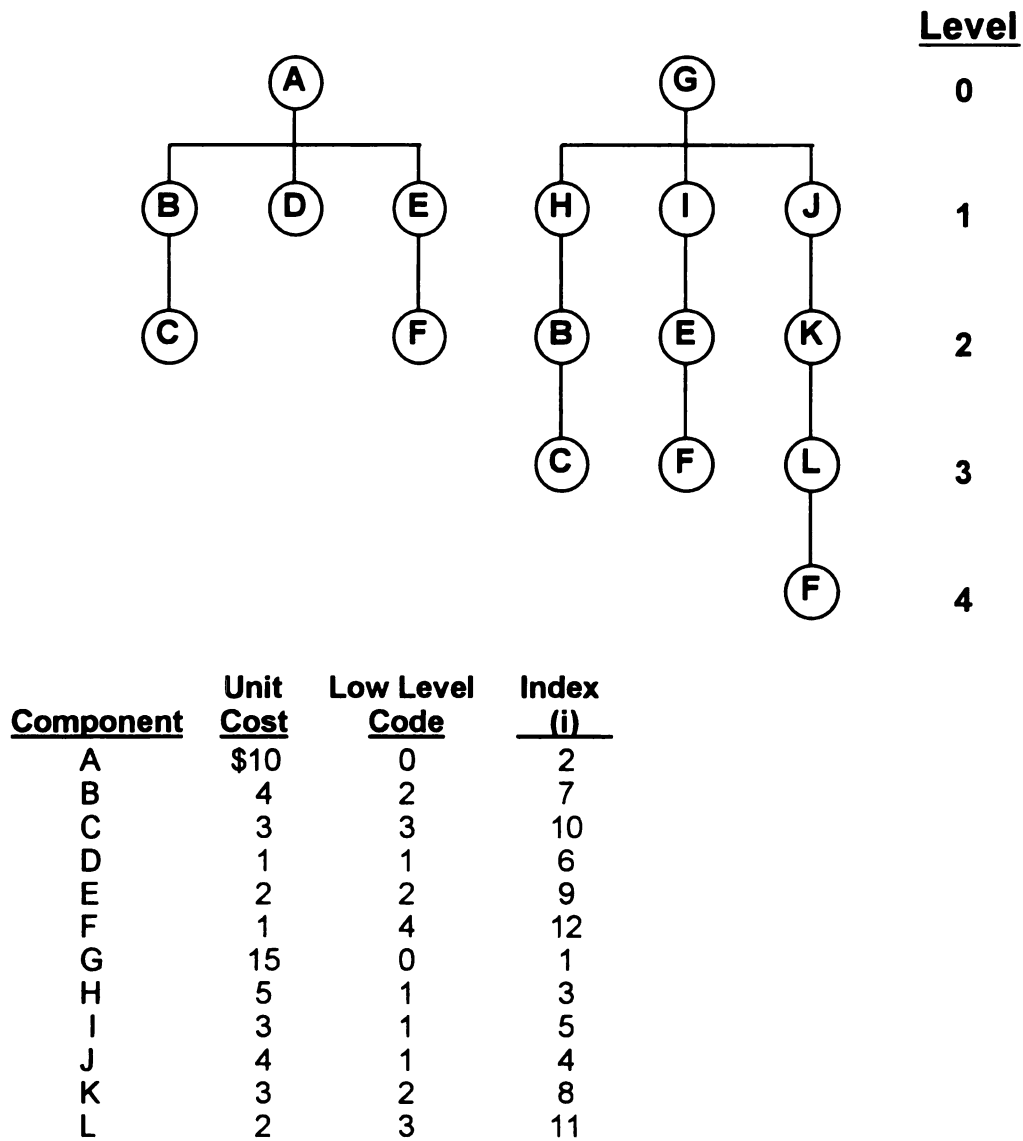
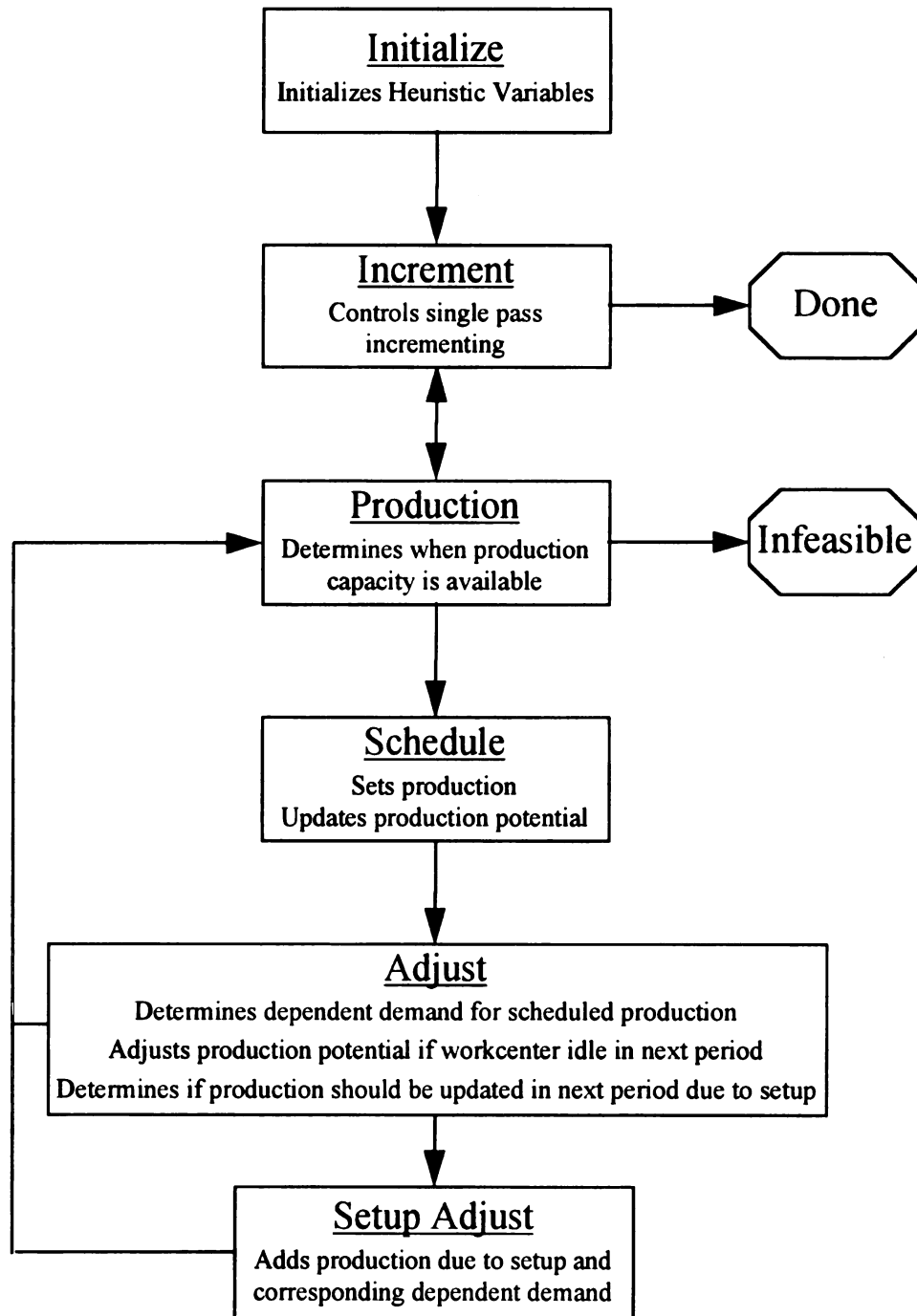


FIGURE 4.1 LOW LEVEL CODING

**FIGURE 4.2 SPFL HEURISTIC - OVERVIEW OF ROUTINES**

dependent demand for the component production that was just scheduled. Since the decision to schedule production in period t determines the state of the workcenter, adjustments may need to be made in period $t+1$. If the workcenter is idle in period $t+1$, the production potential can be adjusted since the workcenter's state is now known in period t . If the workcenter was scheduled to produce component i in period t and was already scheduled to produce component i in period $t+1$, a setup is not required in period $t+1$. Since the heuristic assumed the worst-case production potential when scheduling production in period $t+1$, production in period $t+1$ can be increased (if needed). This is accomplished in the Setup Adjust routine. Control returns to the Production routine either from the Adjust or Setup Adjust routine. The Production routine then checks if the scheduled production is sufficient to cover the need identified in the Increment routine. If not, additional production is scheduled. Otherwise, control is passed back to the Increment routine, which continues the single pass search for periods requiring component production. The heuristic either ends successfully if all component requirements are satisfied in the Increment routine, or unsuccessfully if the production routine cannot schedule sufficient production to satisfy the demand for a component.

The six SPFL heuristic routines are presented in detail in Figures 4.3 to 4.8. Important steps are identified by circled numbers to facilitate the following discussion. In Step 1, the Initialize routine (Figure 4.3) sets the variables $STATE(j,t)$ and $PROD(i,j,t)$ to zero. The $POT(i,j,t)$ variable is set to the minimum production potential for periods $t > 1$ since the previous production states are not known. The initial state for each workcenter is known for period 0, so the exact production potential for $t = 1$ is known and set

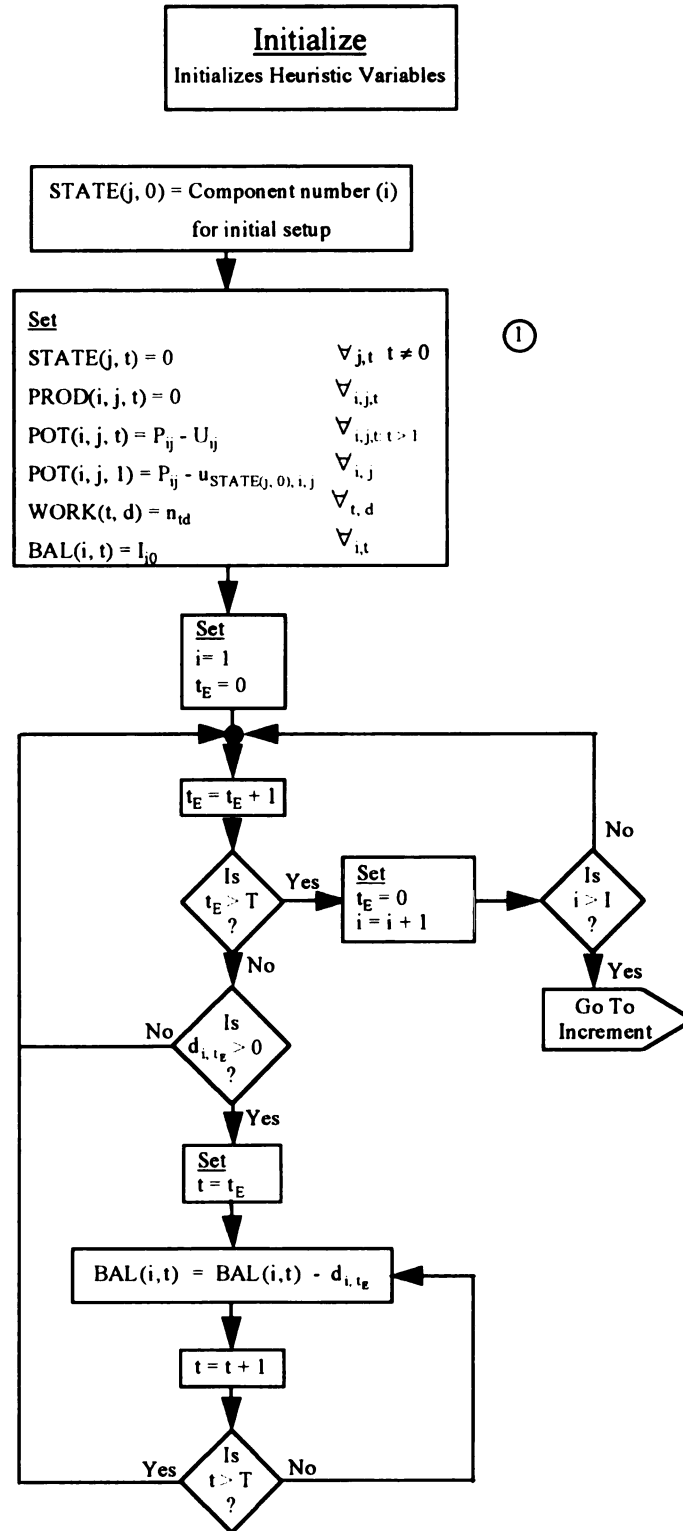


FIGURE 4.3 SPFL HEURISTIC - INITIALIZE ROUTINE

Increment
Controls single pass
incrementing

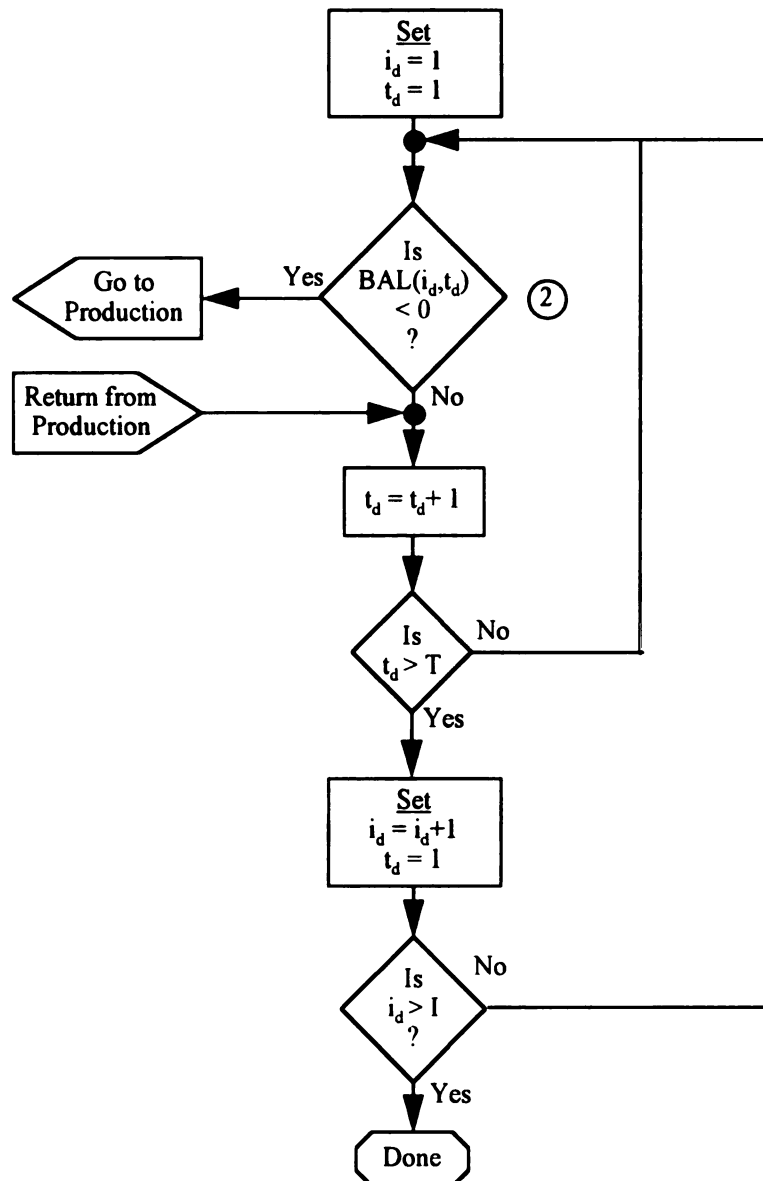


FIGURE 4.4 SPFL HEURISTIC - INCREMENT ROUTINE

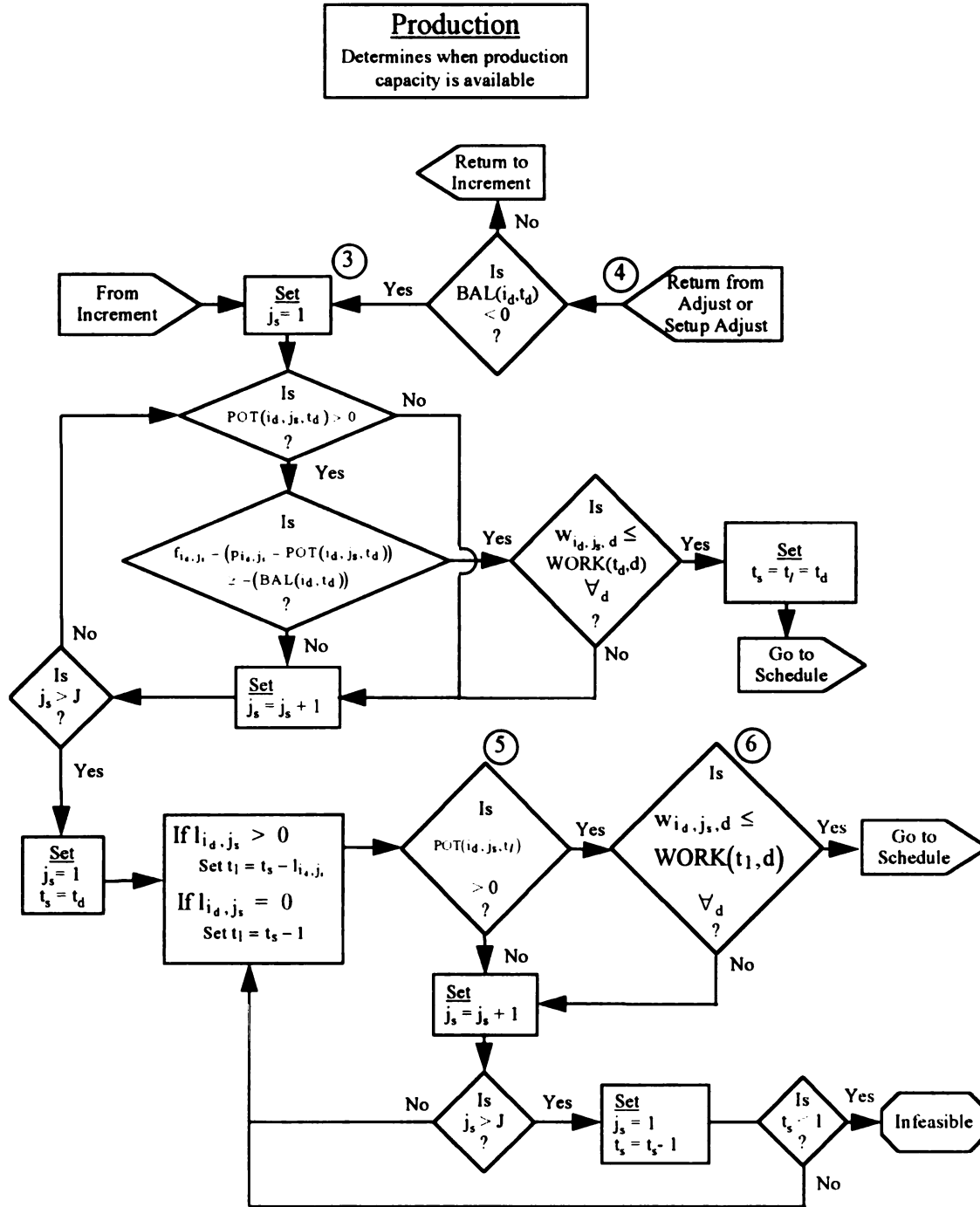


FIGURE 4.5 SPFL HEURISTIC - PRODUCTION ROUTINE

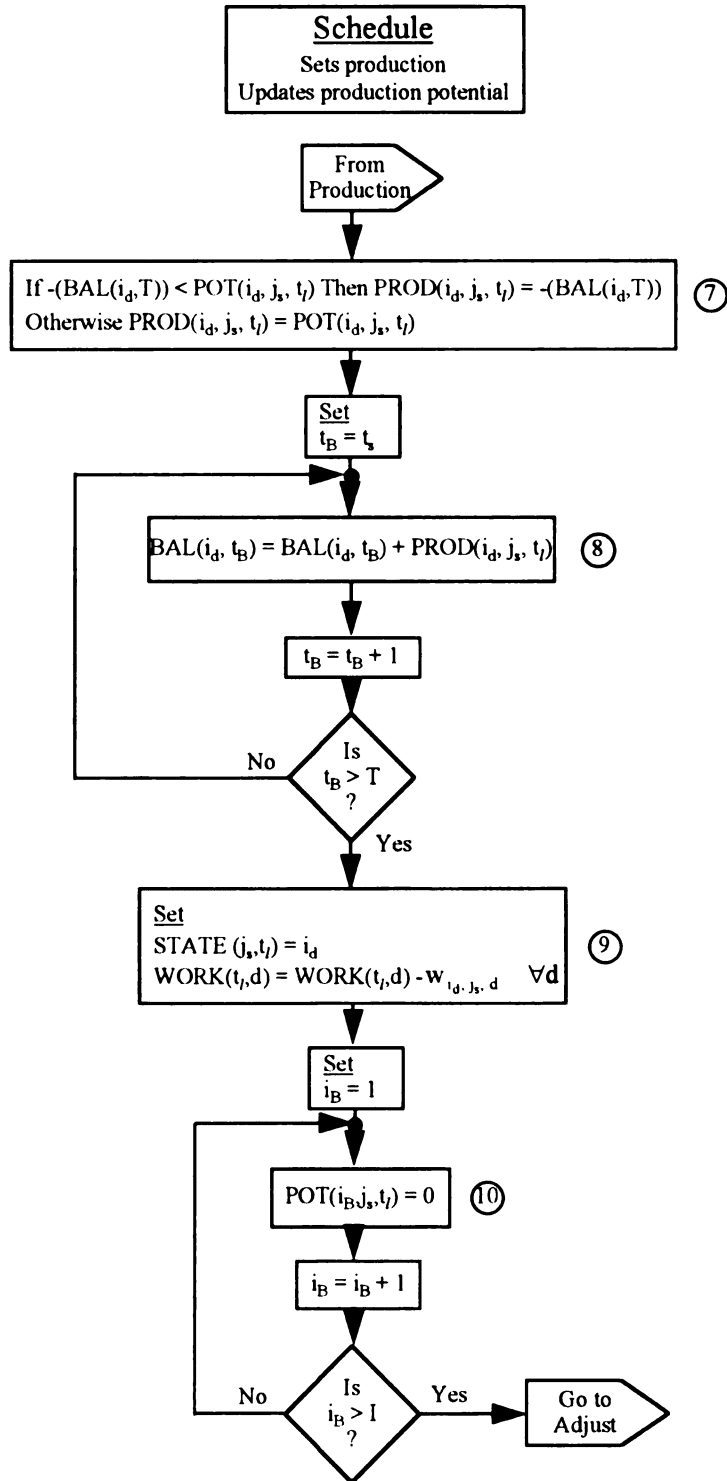


FIGURE 4.6 SPFL HEURISTIC - SCHEDULE ROUTINE

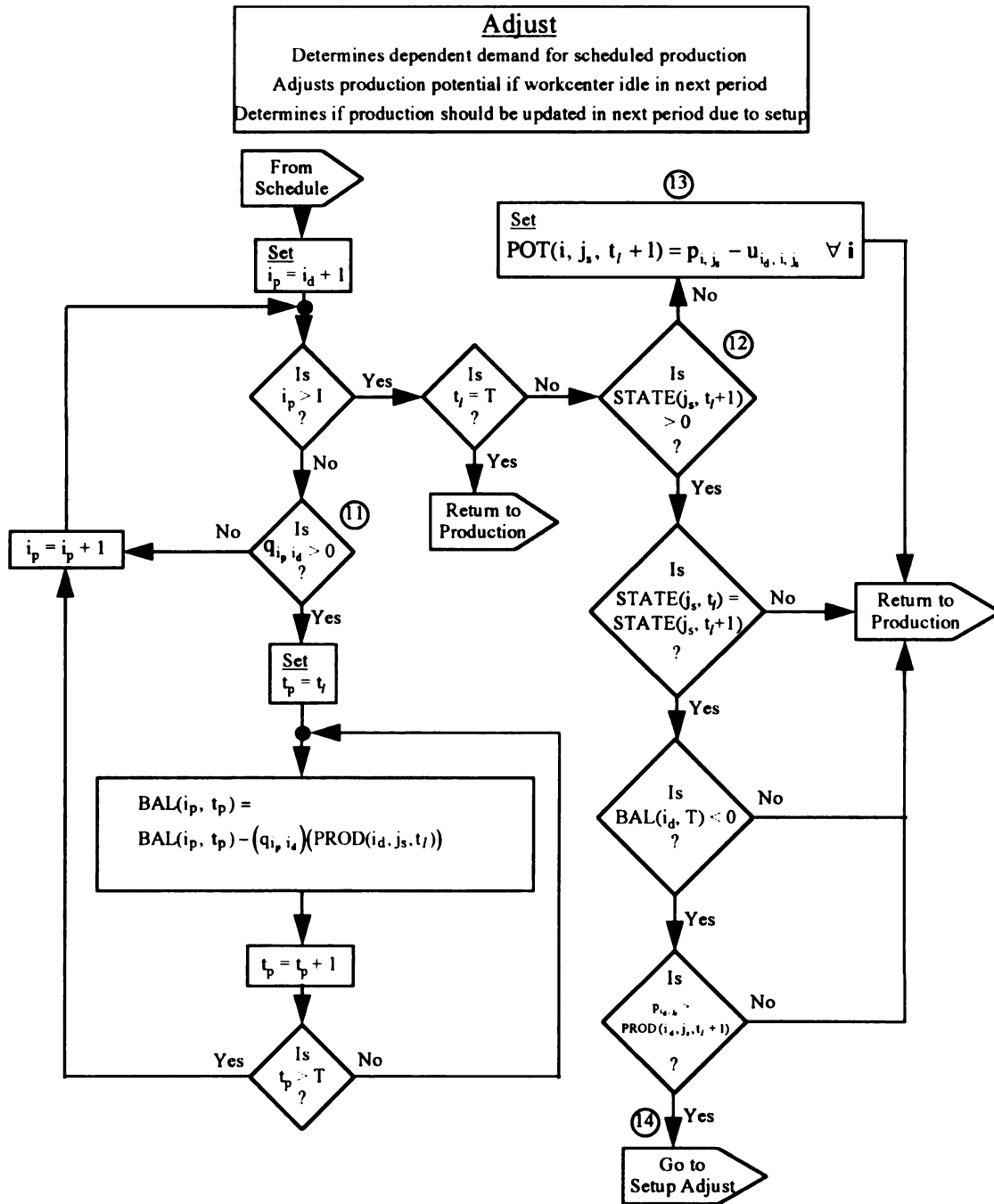


FIGURE 4.7 SPFL HEURISTIC - ADJUST ROUTINE

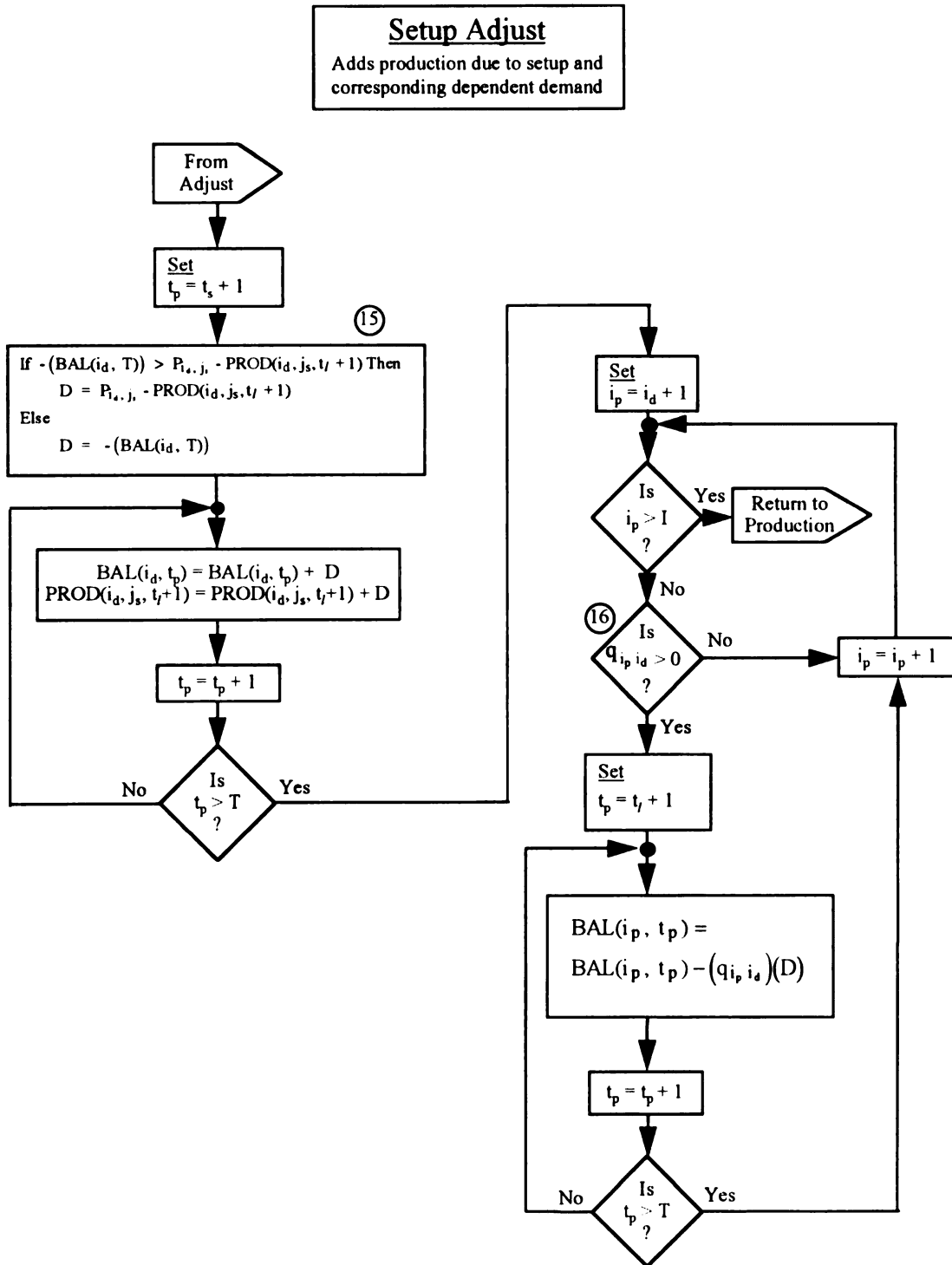


FIGURE 4.8 SPFL HEURISTIC - SETUP ADJUST ROUTINE

accordingly. The $WORK(t,d)$ variable keeps track of the number of workers available for assignment to a workcenter, so it is initialized to be n_{td} for all t . The $BAL(i,t)$ variable keeps track of the number of components at the end of each period. In Step 1 it is set equal to the initial inventory balance I_{i0} . The rest of the Initialize routine subtracts external component demand (d_{it}) from $BAL(i,t)$ for the period in which it occurs and all following periods. A negative value for $BAL(i,t)$ represents the need for component production.

Figure 4.4 shows the Increment routine. This routine increments i_d and t_d to determine when components are needed, which is indicated by a negative value of $BAL(i_d,t_d)$ in Step 2. Because the components are numbered in order of ascending low level code, the $BAL(i,t)$ array can be checked in a single pass.

Figure 4.5 shows the Production routine, which determines when production should be scheduled to eliminate a negative value in the $BAL(i_d,t_d)$ variable. The production routine tries to schedule production as close to the period in which it is needed to minimize inventory holding costs. The routine first checks if the entire demand in period t_d can be satisfied using intraperiod transfer (Step 3). If it can and there are sufficient workers available then control is passed to the Schedule routine. If not, the routine searches for the workcenter that can produce the desired component closest to the period needed (Step 5) and if there are sufficient workers to man the workcenter (Step 6) then control is passed to the Schedule routine. After production is scheduled, $BAL(i_d,t_d)$ may still be negative and additional production may need to be scheduled.

The Schedule routine (Figure 4.6) first checks the ending component balance (Step 7) and sets the production quantity in the $PROD(i,j,t)$ variable so that the ending inventory balance will be zero. If a nonzero ending balance were desired, the desired ending inventory could be subtracted from the last period of $BAL(i,t)$ in the initialize routine. In Step 8 the scheduled production is added to the $BAL(i,t)$ variable for the period in which it is available (t_s) and all later periods. Step 9 sets the $STATE(j,t)$ variable to the component number i_d and adjusts the $WORK(t,d)$ variable for the workers needed to staff the workcenter. With production assigned at workcenter j_s in period t_l , the workcenter is not available to produce other components and the $POT(i,j,t)$ variable is set to zero for all components at workcenter j_s in period t_l (Step 10).

If the component that has just been scheduled for production (i_d) is an assembly that requires other components in its production, then $BAL(i,t)$ must be adjusted to reflect the need for these components. This is done in the Adjust routine (Figure 4.7). If a component is used in the production of component i_d (Step 11), then the $BAL(i,t)$ variable is adjusted to reflect this dependent demand.

The state of workcenter j_s is known in period t_l because production was just scheduled. If the workcenter j_s has not been scheduled for production in period t_l+1 (Step 12) then the production potential will be adjusted for period t_l+1 at workcenter j_s (Step 13) since the setup losses are now known.

If workcenter j_s is producing component i_d in period t_l+1 , then the production scheduled can be increased in period t_l+1 since no setup will be required. Step 14 sends control to the routine Setup Adjust if additional production is needed and available. Note

that if production has been scheduled for a component other than i_d in period t_s+1 , then due to the single pass approach of the SPFL heuristic, sufficient production has already been scheduled to meet demand and there is no need to increase output.

The Setup Adjust routine sets the additional production D (due to the setup being performed in period t_s) as $\text{Minimum}\{\text{Potential Production, Component Deficit}\}$ in Step 15. If additional production is scheduled, then dependent demand for subcomponents must be reflected in the $\text{BAL}(i,t)$ variable (Step 16). When all dependent demand has been accounted for, control returns to the Production routine.

The SPFL heuristic provides a simple means to generate good solutions to the MSS model. The quality of the SPFL heuristic solutions is evaluated in Section 6.

5.0 PRODUCTION SYSTEM FOR MODEL EVALUATION

The MSS model was evaluated using Walker Manufacturing's 7-inch light truck exhaust system production line at its manufacturing facility in Newark, Ohio. Eight versions of the 7-inch exhaust system are produced at the facility. A drawing of a typical 7-inch exhaust system is shown in Figure 5.1. The typical exhaust system consists of a muffler, inlet and outlet pipes, a heat shield and hangers. Since hangers and heat shields are purchased components, they were not considered in the evaluation of the model. It would be easy, however, to incorporate a purchased material ordering capability in an implementation of the MSS model. Inlet and outlet pipes also were excluded from the model as they are produced on pipe benders that service a number of different products.

The 7-inch exhaust system mufflers are produced using a number of components--heads, partitions, bushings, louver tubes and tuning tubes--as illustrated in Figure 5.2. These components are produced in the pipe and press area of the Walker plant and are combined with a stamped steel sheet to produce a finished muffler on the muffler assembly line. Table 5.1 provides bill of material data for the 7-inch mufflers.

Production of 7-inch exhaust systems involves additional manufacturing processes including: the production of steel tubing sheet steel, bending of steel tubing, stamping of steel blanks for heads and partitions, stamping of perforated steel blanks for louver tubes and stamping muffler shell blanks. Since products from these processes are used in the production of other exhaust systems and components, they were not included in the evaluation.

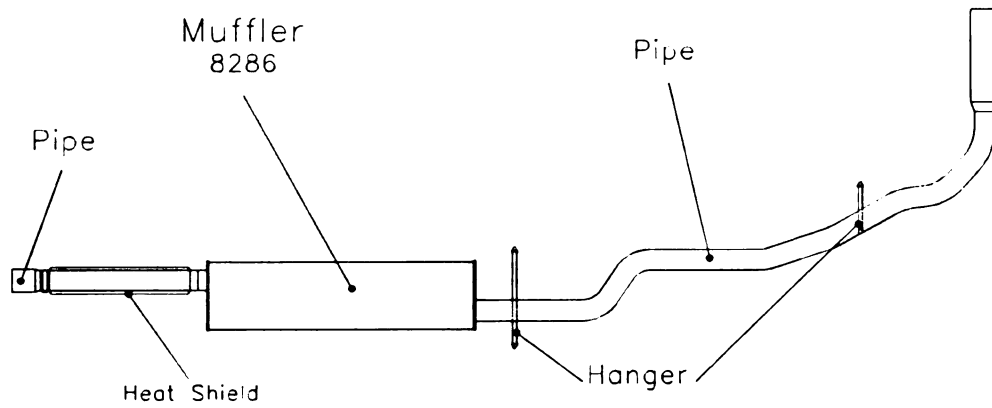


FIGURE 5.1 TYPICAL 7-INCH EXHAUST SYSTEM

Muffler #8286

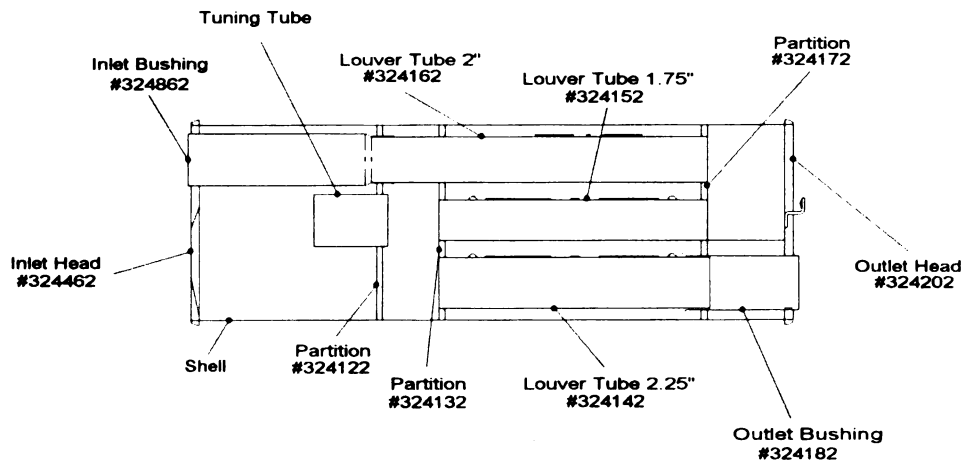


FIGURE 5.2 TYPICAL 7-INCH MUFFLER

TABLE 5.1 MUFFLER BILL OF MATERIAL DATA

Mufflers								
	8285	8286	8289	8290	8291	8297	8298	8329
Inlet Bushings								
324102	1							1
324282							1	
324782						1		
324862		1						
324912			1					
325792				1	1			
Outlet Bushings								
324182	1	1				1		1
324292							1	
325802				1	1			
326672			1					
Louver Tubes								
324142	1	1						
324152	1	1						
324162	1	1						
324372							1	
324392							1	
324442						1		
324722						1		
324732			2					
324742						1		
324952			1					
325852				1	1			
325862				1	1			
325872				1	1			
330022								1
330032								1
Partitions								
324122	1	1						
324132	1	1						
324172	1	1						
324322							1	
324332							1	
324342						1	1	
324352							1	
324752						1		
324762						1		
324922			1					
324972			1					
324982			1					
325812				1	1			
325822				1	1			
325832				1	1			
327782								1
327792								1
330002								1
Inlet Heads								
324302						1	1	
324462	1	1	1	1	1			1
Outlet Heads								
117417								1
324202	1	1				1	1	
324702			1					
325782				1	1			

5.1 THE WALKER MANUFACTURING ENVIRONMENT

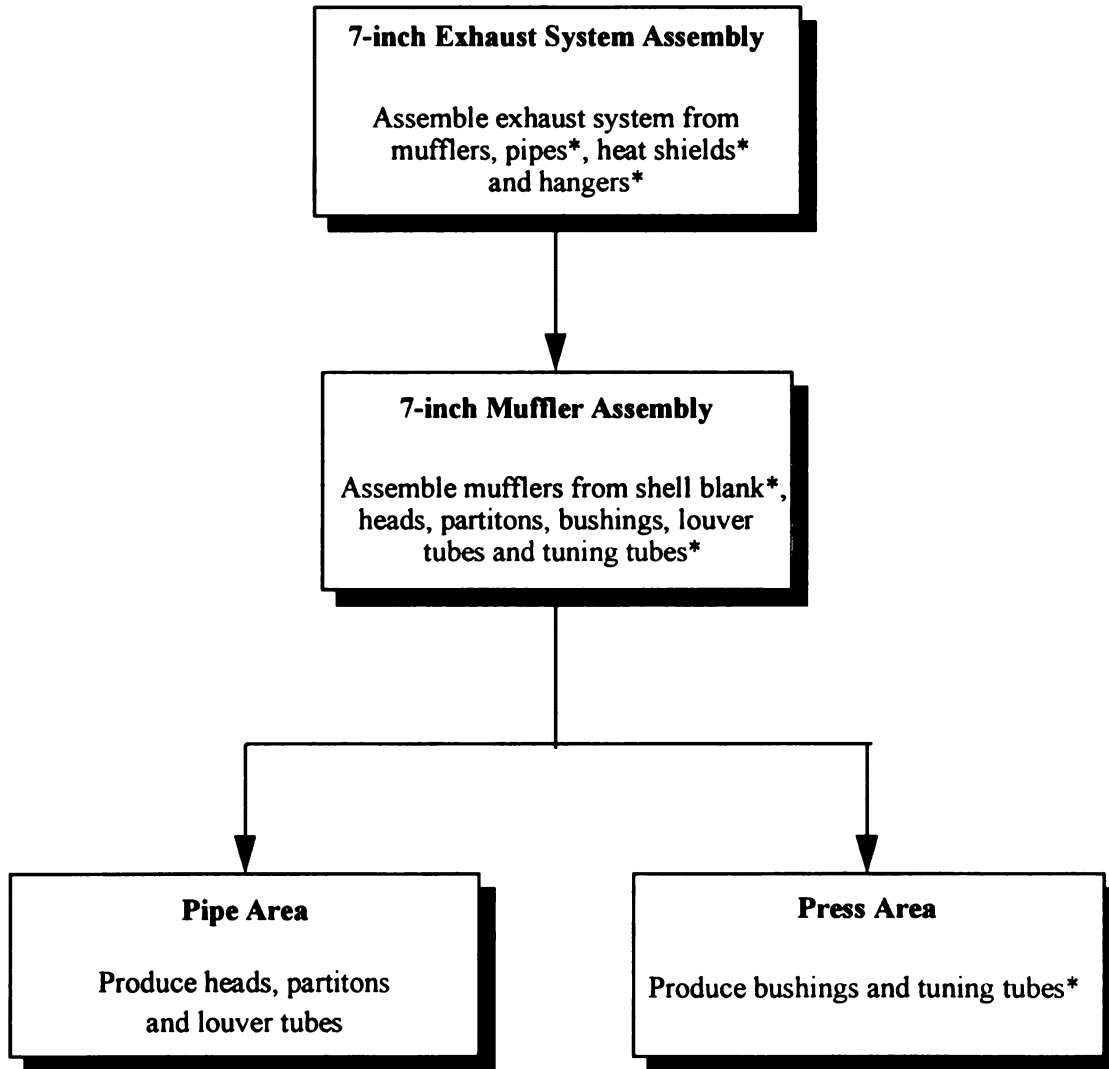
The 7-inch exhaust manufacturing system has a hierarchical structure which is illustrated in Figure 5.3. Exhaust system assembly is performed in dedicated work cells. The arrangement of the exhaust system work cells is shown in Figure 5.4. Eight different 7-inch exhaust systems are produced on seven dedicated workcenters, primarily by welders, although two C-classification machine operators are required for production of exhaust system #8297. A negligible setup is required to switch between the #8290 and #8291 exhaust systems; all other products are produced in dedicated assembly cells which do not require setups. The assembly cell for exhaust system #8289 is shown in Figure 5.5.

All 7-inch mufflers are produced on a single muffler line which is staffed with C-classification operators. Normally the muffler line produces 125 mufflers per hour and operates for two 8-hour shifts each day. A 1-hour setup (sequence-independent) is required to switch between different mufflers. The number of C-operators required to operate the muffler line depends on the muffler being produced as shown in Table 5.2.

TABLE 5.2 WORKERS REQUIREMENTS FOR MUFFLER ASSEMBLY

<u>Muffler</u>	<u># C-Operators</u>
8285	13
8286	11
8289	13
8290/91	11
8297	11
8298	14
8329	13

Some of the workstations on the muffler assembly line are shown in Figure 5.6



*not included in evaluation.

FIGURE 5.3 THE 7-INCH EXHAUST SYSTEM PRODUCTION STRUCTURE

8298 3 Welders 54 parts/hr.	8286 3 Welders 56 parts/hr.
8297 3 Welders 47.5 parts/hr. 2 C-Operators	Open 8285 2 Welders 52.5 parts/hr.

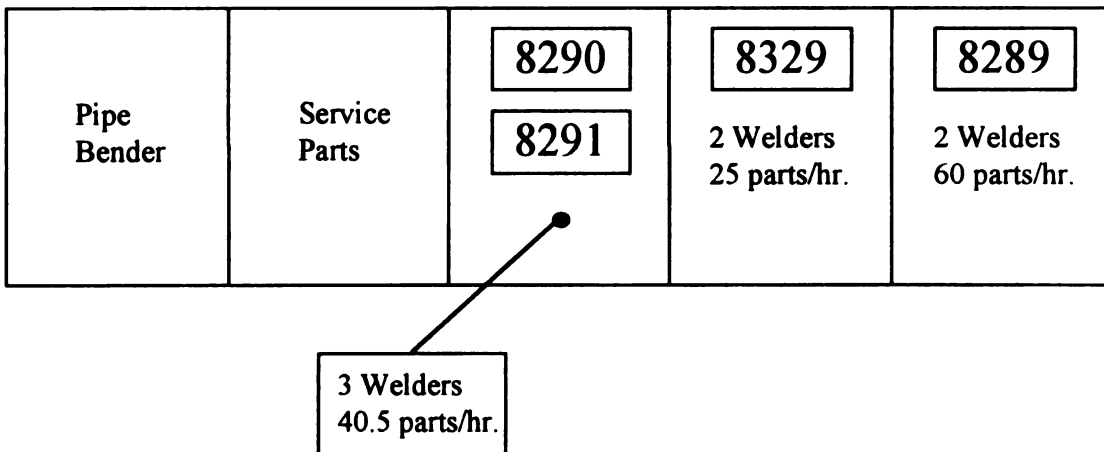
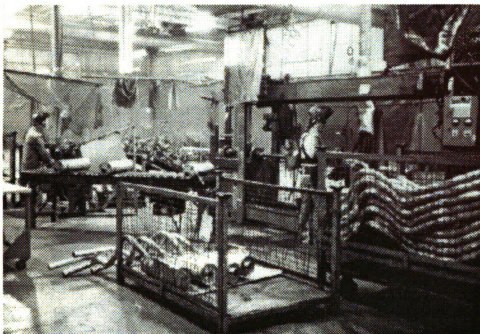
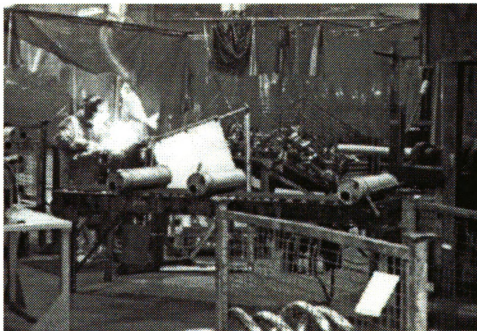


FIGURE 5.4 7-INCH EXHAUST SYSTEM ASSEMBLY AREA ARRANGEMENT

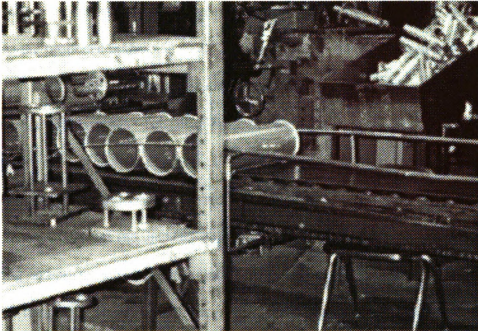


View showing both workstations

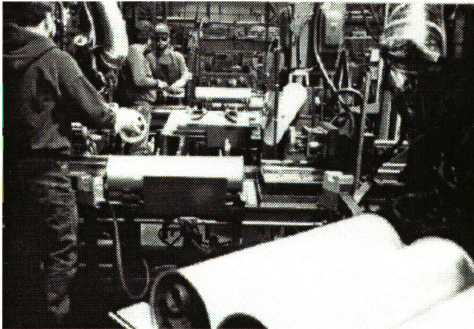


First workstation and conveyor to second workstation

FIGURE 5.5 ASSEMBLY CELL FOR EXHAUST SYSTEM #8289



View showing muffler shells in queue for component insertion



View of workstations where components are inserted

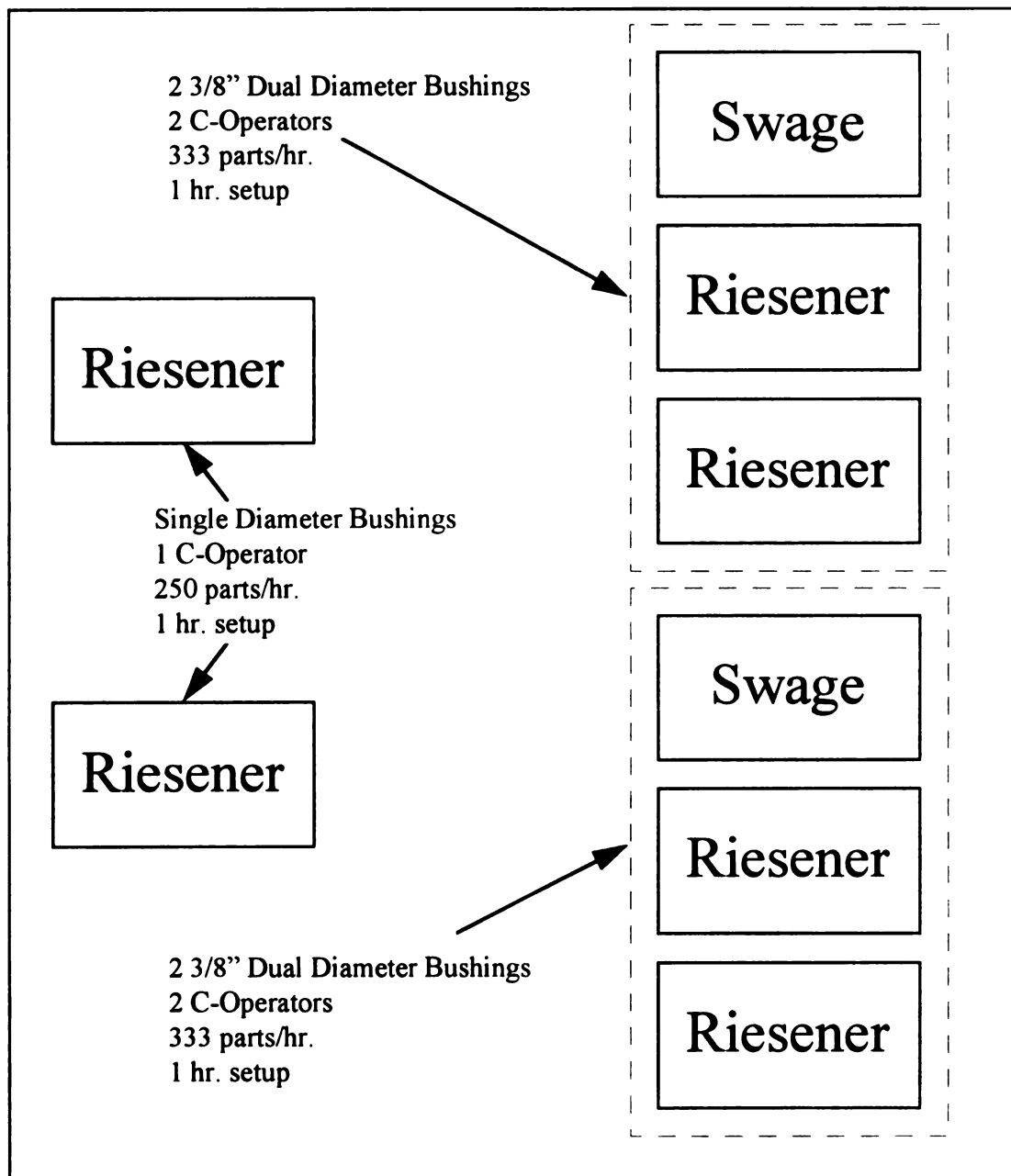
FIGURE 5.6 MUFFLER ASSEMBLY LINE WORKSTATIONS

Pipe components used in muffler production--inlet tubes, outlet tubes and bushings--are produced in the pipe area. The arrangement of the pipe area is shown in Figure 5.7. Production of these components begins by cutting steel tubing to length on one of two cutoff machines. The cutoff machines were not included in the problem since they produce components for products other than the 7-inch exhaust system. Since tuning tubes do not require additional processing, they were not included in the evaluation. Single diameter bushings (no diameter changes over the length of the bushing) require processing on both ends by a riesener machine, a metal forming machine that ensures that the end of the pipe is exactly round. The single diameter bushings listed below are produced in two diameters (2-3/8-inch and 2-5/8-inch) at one of two single-riesener workcenters as shown in Table 5.3.

TABLE 5.3 SINGLE DIAMETER BUSHINGS

<u>Inlet Bushings</u>
324912
325792
<u>Outlet Bushings</u>
324182
324292

Dual diameter bushings are produced by taking tubing that has been cut to length and reducing the diameter of one end with a swage machine. Each end must be processed on a riesener to ensure roundness, and since the pipe now has a different diameter on each end, a riesener is dedicated to each diameter. A swage with two riesener machines is set up in one workcenter dedicated to 2-3/8-inch dual diameter bushings, while another workcenter

**FIGURE 5.7 PIPE AREA LAYOUT**

composed of a swage with two risers is dedicated to 2-5/8-inch dual diameter bushings.

The bushings produced at each dual diameter bushing workcenter are listed in Table 5.4.

TABLE 5.4 DUAL DIAMETER BUSHING WORKCENTERS

2-3/8" Dual Diameter Bushings

Inlet Bushings

324102

324862

2-5/8" Dual Diameter Bushings

Inlet Bushing

324282

324782

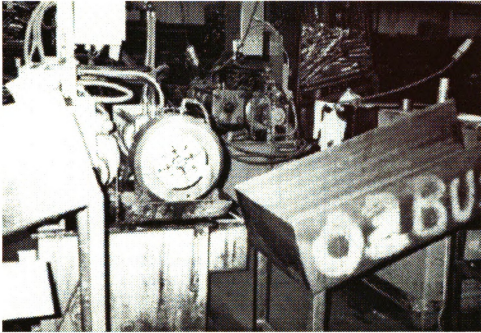
Outlet Bushing

325802

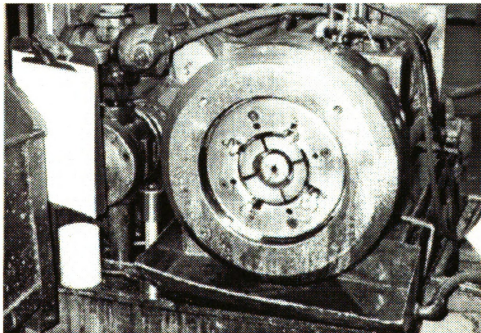
326672

A workstation at the 2 5/8" dual diameter bushing workcenter is shown in Figure 5.8.

The other muffler components--louver tubes, partitions and heads--are produced in the press area. The layout of the press area is shown in Figure 5.9. Louver tubes are formed from perforated steel blanks on three stolp machines (one for each louver tube diameter). See Figure 5.10. The louver tubes produced on each stolp machine are listed in Table 5.5.

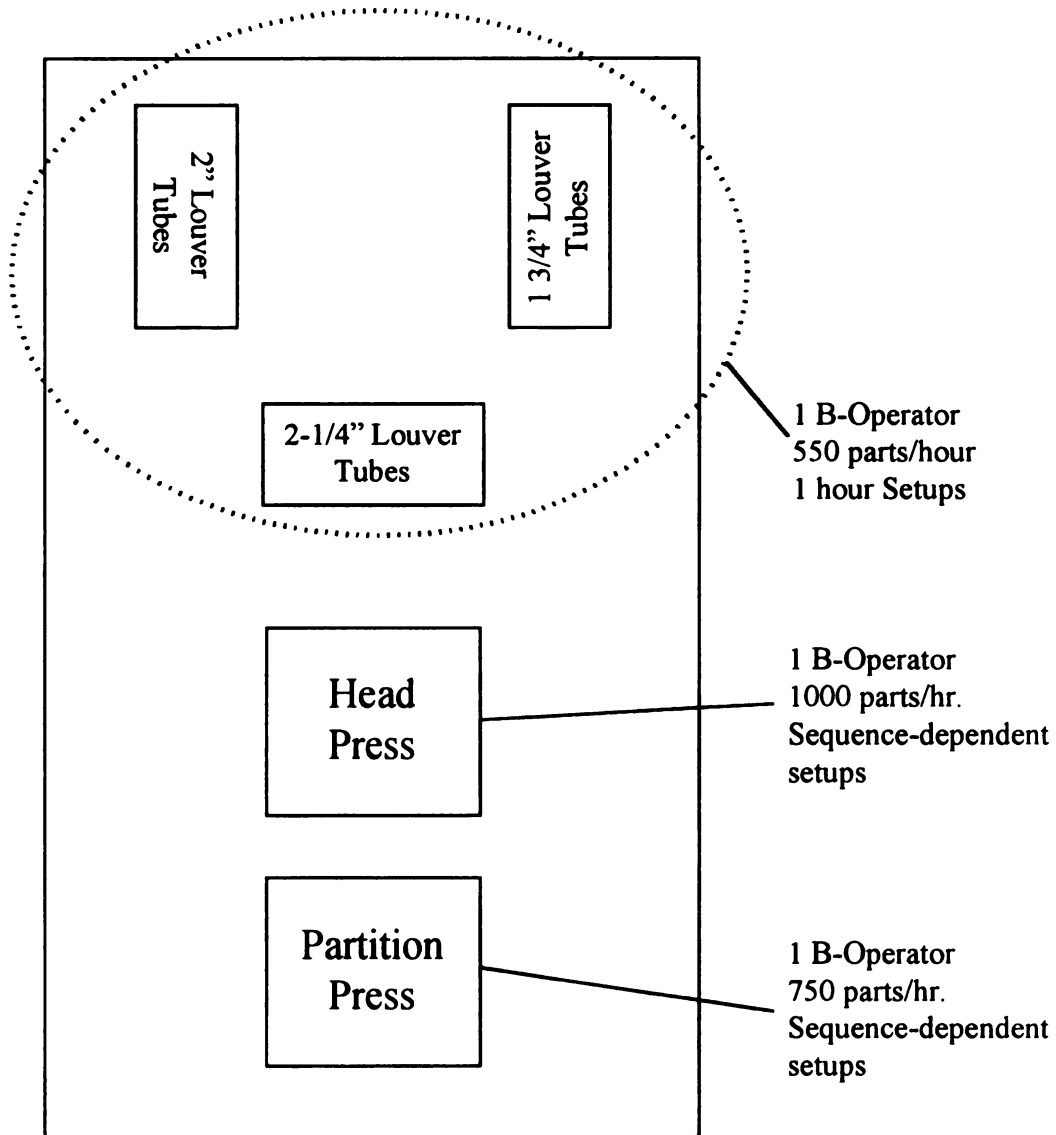


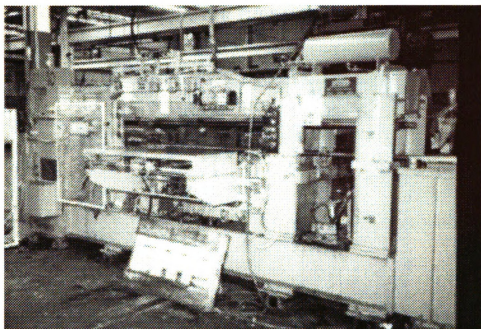
Workstation showing intermediate component storage



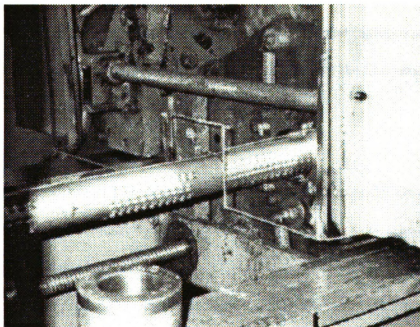
Close-up view of a riesener

FIGURE 5.8 A DUAL DIAMETER BUSHING WORKSTATION

**FIGURE 5.9 PRESS AREA LAYOUT**



Stolp machine for 2" louver tubes



Close up view of completed louver tubes on stolp machine

FIGURE 5.10 STOLP MACHINES

TABLE 5.5 LOUVER TUBE WORKCENTERS

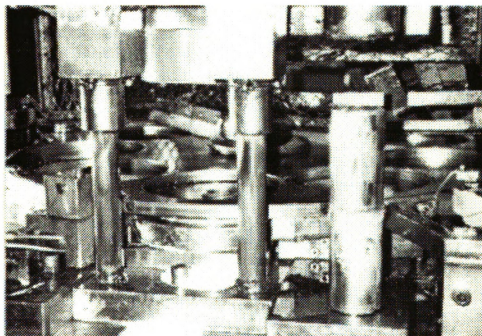
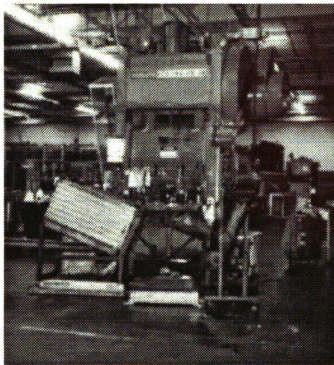
1-3/4" Stolp	2-1/4" Stolp
324152	324142
330032	324372
2" Stolp	324722
324162	324732
324392	324742
324442	324952
330022	325852
	325862
	325872

Partitions and heads are produced on dedicated dial presses(Figure 5.11). Many heads and partitions are similar, requiring only a change in a die insert to switch from one to the other. Others require a complete die change, so setups for the head and partition dial presses are sequence-dependent. Setup times for the head and partition presses are shown in Tables 5.6 and 5.7, respectively. The characteristics of the four production areas are summarized in Table 5.8.

5.2 WALKER PRODUCTION DATA

Walker Manufacturing production schedule data was obtained for the period from November 15, 1993 to February 3, 1994. Daily reports of exhaust system and muffler production were obtained, as well as copies of the shipment schedule, which recorded daily exhaust system production, shipments and inventory balances. Table 5.9 summarizes daily exhaust system demand.

Special records were made in the pipe and press area by the area supervisor to record daily production quantities and their sequence on a workcenter. The plant's



Close-up view of dial press tool

FIGURE 5.11 PARTITION DIAL PRESS

TABLE 5.6 SETUP TIMES FOR THE HEAD PRESS IN MINUTES

FROM	TO					
	117417	324202	324302	324462	324702	325782
117417		30	30	30	30	15
324202	30		30	10	30	30
324302	30	30		30	10	10
324462	30	10	30		30	30
324702	30	30	15	30		10
325782	30	30	10	30	10	

[illegible]

TABLE 5.8 SUMMARY OF 7-INCH MUFFLER PRODUCTION AREAS

Production Area	# of Wctr	# of Comp	Setups	Other
Exhaust Systems Assembly	7	8	None	
Muffler Assembly	1	8	Sequence-independent	2 shifts/day
Pipe Area	4	16	Sequence-independent	
Press Area	5	38	Sequence-dependent	Some Overtime Used

TABLE 5.9 WALKER EXHAUST SYSTEM DEMAND SCHEDULE

Exhaust System	1	2	3	4	5	6	7	8	9	10
	11/15/93	11/16/93	11/17/93	11/18/93	11/19/93	11/22/93	11/23/93	11/24/93	11/29/93	11/30/93
8285	180	300	180	270		420	120	330	61	510
8286	390	270	390	300		570	240	451	270	570
8289		175		175		150	150		175	175
8290		270		270		360		300		270
8291	25	120	30	120		180	60	90	60	180
8297	120	120	121	120	160	160	160			
8298	300	300	300	300	300	300	200			
8329		25		25		50		25		25

Exhaust System	11	12	13	14	15	16	17	18	19	20
	12/1/93	12/2/93	12/3/93	12/6/93	12/7/93	12/8/93	12/9/93	12/10/93	12/13/93	12/14/93
8285	210	60	360	270	240	210	210	240	300	210
8286	60	270	360	270	600	30	570	330	1050	30
8289		150		150	150		150	175	125	
8290	270		240	270	30	270	60	300	90	300
8291	60	90	180	150	150	60	120	120	210	30
8297		160		160	160		160	120	120	120
8298		300		300	300		300	350	350	350
8329			25	25		25	25			25

Exhaust System	21	22	23	24	25	26	27	28	29	30
	12/15/93	12/16/93	12/17/93	12/20/93	12/21/93	12/22/93	12/23/93	1/4/94	1/5/94	1/6/94
8285	270	480	300	180	525	270	210	360	330	90
8286	630	690	270	330	1140	600	300	390	570	210
8289	150	175	150		175	150	175		125	150
8290		300	330		360		420	330		30
8291	120	210	90	30	210	150	60	90	120	90
8297		120	120	200	200	240	160	200	320	
8298		350	351	200	200	100	400		600	
8329			25	25	25			25		

TABLE 5.9 (CONT'D)

Exhaust System	31	32	33	34	35	36	37	38	39	40
	1/7/94	1/10/94	1/11/94	1/12/94	1/13/94	1/14/94	1/17/94	1/18/94	1/19/94	1/20/94
8285	330	300	180	270	210	330		510	90	420
8286	30	630	30	600	360	630		840	300	405
8289		150		151	150	125			150	
8290	180	30	300	30	270	30		330	30	405
8291	30	30	60	90	90	60		90	30	180
8297	160	160	160	160	200			160	200	
8298	300	300	300	300	200			300	200	
8329	25		25	25	50					25

Exhaust System	41	42	43	44	45	46	47	48	49	50
	1/21/94	1/24/94	1/25/94	1/26/94	1/27/94	1/28/94	1/31/94	2/1/94	2/2/94	2/3/94
8285	90		600	60	390	210	390	90	390	90
8286	300		690	300	360	240	990	210	450	330
8289	100		150	125		150	100	100		125
8290	30		180		270	330	60		330	90
8291	60		120	30	120	90	120	60	90	30
8297	200	160	200	160	160	200	200		160	160
8298	200	300	200	300	300	200	200		300	300
8329			25		25	25				

accounting department provided cost data for all components. Accurate inventory data for November 15, 1993 (the beginning inventory for the planning period) for components other than finished exhaust systems was unavailable. Since the goal was to compare MSS model schedules to actual production decisions, the initial inventory levels were assumed to be the lowest value that would result in a non-negative inventory balance over the period of data availability. This resulted in a conservative (minimum cost) estimate of the scheduling decisions made by the company. Table 5.10 summarizes the component cost and beginning inventory data.

5.3 HIGH AND LOW CAPACITY DEMAND SCHEDULES

A high-capacity utilization test problem was developed based on the Walker Manufacturing environment by keeping all parameters the same as the Walker problem and increasing the demand. Exhaust system demand over the period November 15, 1993 to February 3, 1994 occurred in the proportions shown in column two of Table 5.11 (relative to the lowest demand exhaust system #8329). These proportions were used to develop the lot sizes shown in column three of Table 5.11. Demand was randomly added to the Walker demand schedule of Table 5.9 using the following procedure. Beginning with the first day of the schedule, an exhaust system was randomly selected and demand was increased by the lot size in the table above. The SPFL heuristic with an 8-hour period length was used to determine if the demand schedule was still feasible. If it was, then the additional demand was kept in the high capacity demand schedule. If not, it was removed and another exhaust system was randomly selected. This process continued until either all

TABLE 5.10 COMPONENT COST AND BEGINNING INVENTORY DATA

Exhaust Systems		
Part#	Unit Cost	Initial Inv.*
8285	\$27.27	1710
8286	\$33.09	2310
8289	\$33.14	475
8290	\$29.38	240
8291	\$33.62	25
8297	\$51.50	1560
8298	\$33.35	650
8329	\$40.59	0
Mufflers		
8285	\$17.31	2048
8286	\$16.56	0
8289	\$17.76	125
8290/91	\$16.30	696
8297	\$17.54	54
8298	\$18.00	1538
8329	\$18.93	47
Inlet Bushings		
324102	\$1.59	987
324282	\$1.23	1685
324782	\$1.62	769
324862	\$1.35	4968
324912	\$1.80	0
325792	\$1.52	551
Outlet Bushings		
324182	\$0.80	8032
324292	\$1.34	1011
325802	\$0.97	1844
326672	\$0.97	882
Inlet Heads		
324302	\$0.82	2663
324462	\$0.82	13704
Outlet Heads		
117417	\$0.94	228
324202	\$0.82	20229
324702	\$0.94	2275
325782	\$0.82	4993

Partitions		
Part#	Unit Cost	Initial Inv.*
324122	\$0.55	7238
324132	\$0.42	9840
324172	\$0.55	5813
324322	\$0.42	4520
324332	\$0.55	5076
324342	\$0.55	3238
324352	\$0.55	6596
324752	\$0.42	2187
324762	\$0.55	1579
324922	\$0.59	1493
324972	\$0.59	1753
324982	\$0.55	503
325812	\$0.42	1551
325822	\$0.42	1551
325832	\$0.55	1551
327782	\$0.55	1007
327792	\$0.59	611
330002	\$0.59	703
Louver Tubes		
324142	\$0.79	16561
324152	\$0.66	4161
324162	\$0.82	6952
324372	\$1.38	1611
324392	\$0.66	4452
324442	\$0.63	4089
324722	\$0.68	3068
324732	\$0.64	1824
324742	\$0.80	3557
324952	\$0.76	1841
325852	\$0.76	2666
325862	\$0.64	2064
325872	\$0.64	4984
330022	\$0.57	228
330032	\$1.26	405

*Initial inventory was known for exhaust systems. For all other components it was set at the minimum feasible level.

TABLE 5.11 LOT SIZES USED FOR HIGH CAPACITY DEMAND SCHEDULE

Exhaust System	Proportion	Lot Size
8285	20.3	200
8286	32.1	320
8289	7.1	70
8290	12.1	120
8291	6.7	70
8297	9.8	100
8298	16.7	170
8329	1.0	10

components during a day had been evaluated for additional capacity or three exhaust systems had been selected with the result being an infeasible schedule, whereupon the process was repeated for the next day in the schedule. The result was the development of a demand schedule that used a high percentage of the available capacity, yet remained feasible and had a demand pattern that was roughly proportional to that typically experienced by Walker Manufacturing. The resulting demand schedule is shown in Table 5.12.

A low capacity problem was also developed by taking the Walker Manufacturing demand schedule of Table 5.9 and reducing the demand by one half.

5.4 LABOR COSTS AND SCHEDULES

Three job classifications were used in the production of 7-inch exhaust systems. Welders were used solely in the assembly of exhaust systems. C-classification machine operators were used in the assembly of #8297 exhaust systems, muffler assembly and the pipe production areas. B-classification machine operators are a higher classification of

TABLE 5.12 HIGH CAPACITY DEMAND SCHEDULE

Exhaust System	1	2	3	4	5	6	7	8	9	10
	11/15/93	11/16/93	11/17/93	11/18/93	11/19/93	11/22/93	11/23/93	11/24/93	11/29/93	11/30/93
8285	380	500	380	470	200	620	320	530	61	510
8286	710	590	710	300	320	890	560	771	270	570
8289	70	175	70	245	70	220	220	70	175	175
8290	120	270	120	270		360		300	120	270
8291	95	190	200	120	70	250	130	160	60	180
8297	220	120	121	120	260	160	260			
8298	470	470	470	300	470	470	370	170	170	
8329		35	10	25	10	60	10	35		25

Exhaust System	11	12	13	14	15	16	17	18	19	20
	12/1/93	12/2/93	12/3/93	12/6/93	12/7/93	12/8/93	12/9/93	12/10/93	12/13/93	12/14/93
8285	210	60	360	270	240	210	210	240	300	210
8286	60	270	360	270	600	30	570	330	1050	30
8289		150		150	150		150	175	125	
8290	270		240	270	30	270	60	300	90	300
8291	60	90	180	150	150	60	120	120	210	30
8297		160		160	160		160	120	120	120
8298		300		300	300		300	350	350	350
8329			25	25		25	25			25

Exhaust System	21	22	23	24	25	26	27	28	29	30
	12/15/93	12/16/93	12/17/93	12/20/93	12/21/93	12/22/93	12/23/93	1/4/94	1/5/94	1/6/94
8285	270	480	300	180	525	270	210	360	330	90
8286	630	690	270	330	1140	600	300	390	570	210
8289	150	175	150		175	150	175		125	150
8290		300	330		360		420	330		30
8291	120	210	90	30	210	150	60	90	120	90
8297		120	120	200	200	240	160	200	320	
8298		350	351	200	200	100	400		600	
8329			25	25	25			25		

TABLE 5.12 (CONT'D)

Exhaust	31	32	33	34	35	36	37	38	39	40
System	1/7/94	1/10/94	1/11/94	1/12/94	1/13/94	1/14/94	1/17/94	1/18/94	1/19/94	1/20/94
8285	330	300	180	270	210	330		510	90	420
8286	30	630	30	600	360	630		840	300	405
8289		150		151	150	125			150	
8290	180	30	300	30	270	30		330	30	405
8291	30	30	60	90	90	60		90	30	180
8297	160	160	160	160	200			160	200	
8298	300	300	300	300	200			300	200	
8329	25		25	25	50					25

Exhaust	41	42	43	44	45	46	47	48	49	50
System	1/21/94	1/24/94	1/25/94	1/26/94	1/27/94	1/28/94	1/31/94	2/1/94	2/2/94	2/3/94
8285	90		600	60	390	210	390	90	390	90
8286	300		690	300	360	240	990	210	450	330
8289	100		150	125		150	100	100		125
8290	30		180		270	330	60		330	90
8291	60		120	30	120	90	120	60	90	30
8297	200	160	200	160	160	200	200		160	160
8298	200	300	200	300	300	200	200		300	300
8329			25		25	25				

operator who can perform machine setups entirely on their own. They were used in the press area to produce louver tubes, partitions and heads. Wage rates for the job classifications are given in Table 5.13.

TABLE 5.13 WAGE RATES

Job Classification	Hourly Wage Rate (\$/hr)
Welder	12.00
C operator	11.16
B operator	12.00

For the MSS model of the production facility, the number of workers available was assumed to be the same each day according to the schedule in Table 5.14.

TABLE 5.14 LABOR AVAILABILITY

Model	Shift	Classification	Number of Workers
Exhaust Assembly	1	Welder	12
		C operator	2
Muffler Assembly	1&2	C operator	14
Pipe Area	1	C operator	4
Press Area	1	B operator	3
	2	B operator	2(3*)
All Areas	1	Welder	12
	1	B operator	3
	1	C operator	20
All Areas	2	Welder	0
	2	B operator	2(3*)
	2	C operator	14

*During some days a second shift was used for head production with a second B classification operator.

A second shift for head production was assumed to be available on the days shown in Table 5.15.

TABLE 5.15 DAYS WITH SECOND SHIFT HEAD PRODUCTION

11/16/93	11/23/93	11/30/93	12/7/93
12/14/93	12/21/93	1/5/94	1/11/94
1/18/94	1/25/94	2/1/94	

The next section discusses the results of the MSS model evaluation.

6.0 EVALUATION OF THE MODEL

Two experiments were run using models of the Walker Manufacturing production facility. In the first experiment, models were developed for each of the four production areas (exhaust system assembly, muffler assembly line, pipe area and press area) and for the entire production process. Three period lengths--eight, four and two hours--were evaluated for planning horizons ranging from 10 to 50 days. The first experiment allowed for the comparison of the MSS model results to actual production schedules used at Walker Manufacturing.

A second experiment evaluated the impact of production system capacity utilization on the solution procedures. This experiment was run using the Walker Manufacturing environment with three demand schedules: Walker Manufacturing's demand schedule and the high and low capacity demand schedules described in Section 5.3. This experiment also evaluated hierarchical decomposition of the problem. In hierarchical decomposition, the scheduling problem is solved one level at a time. In the Walker Manufacturing environment, hierarchical decomposition means that the exhaust system assembly problem is solved first, with the resulting exhaust system assembly schedule used to generate demand for the muffler assembly problem. The solution to the muffler assembly problem then can be used to generate demand for the pipe and press areas, which in turn are solved in isolation. In the second experiment, models were evaluated using 30 and 50 day planning horizons with 8 hour periods. Table 6.1 summarizes the two experiments used to analyze the MSS model.

TABLE 6.1 EXPERIMENTAL DESIGN**Walker Manufacturing Comparison**

Production System	8-hr. Days	4-hr. Days	2-hr. Days
Assembly	10-50	10, 30, 50	10, 30, 50
Muffler	10-50	10, 30, 50	10, 30, 50
Pipe	10-50	10, 30, 50	10, 30, 50
Press	10-50	10, 30, 50	10, 30, 50
Entire System	10-50	10, 30, 50	10, 30, 50

Capacity Evaluation

Production System	High Capacity Demand	Walker Demand	Low Capacity Demand
Assembly	30, 50	30, 50	30, 50
Muffler	30, 50	30, 50	30, 50
Pipe	30, 50	30, 50	30, 50
Press	30, 50	30, 50	30, 50
Entire System	30, 50	30, 50	30, 50

KEY

Assembly: Exhaust system assembly area, 7 workcenters, 8 components, no setups
Muffler: Muffler assembly line, 1 workcenter, 7 components, seq. ind. setups, 2 shifts
Pipe: Inlet and outlet bushings, 4 workcenters, 16 components, seq. ind. setups
Press: Partitions and louver tubes, 5 workcenters, 38 components, seq. dep. setups

10-50: Model evaluated for 10, 20, 30, 40 and 50 day planning horizons

10, 30, 50: Model evaluated for 10, 30 and 50 day planning horizons

30, 50: Model evaluated for 30 and 50 day planning horizons

6.1 WALKER MANUFACTURING COMPARISON

6.1.1 Walker Manufacturing Cost Estimates

The first experiment compared the performance of the integer programming and the SPFL heuristic solutions to the actual schedules used at Walker Manufacturing. A number of real-life factors (machine breakdowns, worker absences, setup difficulties, low employee performance, etc.) can affect the implementation of a production schedule and are difficult to include in the evaluation of the model. The approach used here was to calculate costs for Walker Manufacturing based on production quantities, inventory levels and setup decisions assuming the same parameters used in the MSS model.

To calculate costs for Walker Manufacturing, a spreadsheet was developed to calculate the daily production-inventory balances based on the production data described in Section 5.2. Daily inventory levels were calculated and inventory costs assessed accordingly. In the MSS model, when a workcenter is activated ($\delta_{ijt}=1$), labor costs are charged for the entire period whether parts are being made, a setup is being changed or the workcenter is idle for part of the period. For Walker Manufacturing, production costs were calculated in two parts: direct production costs and setup costs. Letting X_{ijt} be the units of component i produced at workcenter j in period t , the direct production cost CP_{ijt} was calculated as:

$$CP_{ijt} = \sum_d b_d w_{ijd} \frac{X_{ijt}}{p_{ij}}$$

where:

$$b_d = \text{Wage rate for a worker in labor division } d \text{ (\$/period)}$$

p_{ij} = Production rate of component i at workcenter j (units/period).

w_{ijd} = Number of workers in labor division d required to staff workcenter j when producing component i

as defined in Section 3.2. Based on the production data gathered at Walker

Manufacturing it was possible to determine when setups occurred. The cost for a setup at

a workcenter with sequence-independent setups CS_{ij} was calculated using:

$$CS_{ij} = \sum_d b_d w_{ijd} \frac{y_j}{p_{ij}}$$

where y_j is the production loss (in units) when changing the setup at workcenter j . If the setups are sequence-dependent, then the cost for changing the setup from component i to component i' , $CS_{i'ij}$ was calculated as:

$$CS_{i'ij} = \sum_d b_d w_{ijd} \frac{u_{i'ij}}{p_{ij}}$$

where $u_{i'ij}$ is the production loss (in units) when changing production from component i' to component i at workcenter j . Note that calculating labor costs in this fashion assumes no idle labor.

6.1.2 Lower Bound on Costs

A lower bound on production costs was calculated to aid in the comparisons. A perfect schedule would carry zero inventory while minimizing setups. Although it is impossible to determine the minimum number of setups required for a particular demand schedule, a lower bound is zero. Thus, a zero-setup, zero inventory (ZSZI) bound on production costs can be calculated assuming zero inventory levels (once the initial

inventory is “consumed” by the demand schedule) and including only direct production costs. This bound is quite good when there are no setups involved (e.g. exhaust system assembly) and not as good when setups are significant (e.g. muffler assembly), but in either case it can aid in comparing the MSS model results with Walker Manufacturing’s production decisions.

6.2 SOLUTION OF MSS INTEGER PROGRAMMING MODELS

The integer programming models were solved using IBMs Optimization Subroutine Library (OSL) release 2 on a Sun Microsystems SPARCcenter 2000 consisting of eight 50mhz TI SuperSPARC CPUs with 2 MB of Supercache. Problems were submitted to OSL using GAMS version 2.25.073 requesting 300 MB of core memory.

The branching strategy used in evaluating models was the standard OSL strategy with the addition of supernode processing and the SPFL heuristic solution (if available) as an incumbent. The OSL branching strategy first estimates two values for the solution degradation (rounding up and rounding down) in satisfying integrality for each 0-1 variable that does not take on an integer value in LP relaxation at the current node. It then branches on the variable with the worst of the best solution degradation estimates.

6.3 EXHAUST SYSTEM ASSEMBLY COMPARISON

For the exhaust system assembly problem, the GAMS/OSL integer programming software was unable to find optimal solutions, even for a 10 period model with 8 hour periods (80 integer variables). In these cases, the GAMS/OSL software ran out of memory (300 MB available) after over 24 CPU hours. The SPFL heuristic found solutions in under 1 minute. The difficulty in finding integer programming solutions to the

MSS model is likely due to the failure of the LP relaxation to provide tight bounds in the branch and bound procedure.

One problem with the LP relaxation is the term:

$$\sum_i \sum_j \sum_d \sum_t b_d w_{ijd} \delta_{ijt}$$

in the objective function. This term defines the labor cost as a fixed cost if a workcenter is operating in a period, no matter how many units are being produced. Since production at a workcenter is defined as $p_{ij} \delta_{ijt}$, in the LP relaxation the variable δ_{ijt} can take on fractional values so that the labor cost for production is not a fixed quantity but proportional to the quantity produced. When the term $\sum_i \sum_j \sum_d \sum_t b_d w_{ijd} \delta_{ijt}$ is removed from the model, the ten day assembly problem can be solved to optimality in minutes, although larger problems are much harder to solve.

Tables 6.2 and 6.3 show the results for the exhaust system assembly models.

Table 6.2 shows that for this model (with no setups), better solutions can be obtained with smaller period lengths for both the SPFL heuristic and integer programming solutions.

This is somewhat surprising for the integer programming solution since cutting the period length in half doubles the number of integer variables in the model. Apparently the increase in the ability to fit production to the demand schedule with shorter period lengths more than offsets the increase in problem size. Smaller periods also improve the lower bound on the optimal solution of the integer programming solution. For the 50 period model with 2 hour periods, the best integer solution can be no more than 2.68% better than the best integer solution found. There is some indication that the bound on the

TABLE 6.2 SOLUTIONS FOR EXHAUST SYSTEM ASSEMBLY**IP Solutions**

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	5,858	15,857	27,649	37,831	47,481
4	5,555		26,598		46,001
2	5,249		25,907		44,472

SPFL Solutions

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	5,925	15,609	27,042	36,489	46,541
4	5,587	14,447	26,502	35,853	45,545
2	5,191	14,027	26,287	35,438	44,926

IP Solution % of Lower Bound on Optimal

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	11.93	15.83	9.36	10.83	9.36
4	13.14		5.87		6.20
2	7.11		3.13		2.68

TABLE 6.3 COMPARISON OF COSTS FOR EXHAUST SYSTEM ASSEMBLY**COMPARISON OF COSTS - 8 hr. Period**

Solution	Planning Horizon (days)				
	10	20	30	40	50
Walker	12,480	23,849	34,585	45,409	57,860
IP	5,858	15,857	27,649	37,831	47,481
SPFL	5,925	15,609	27,042	36,489	46,541
ZSZI Bound	4,880	13,263	23,799	32,088	40,577

% OVER ZSZI BOUND - 8 hr. Period

Solution	Planning Horizon (days)				
	10	20	30	40	50
Walker	155.7%	79.8%	45.3%	41.5%	42.6%
IP	20.0%	19.6%	16.2%	17.9%	17.0%
SPFL	21.4%	17.7%	13.6%	13.7%	14.7%

COMPARISON OF COSTS - 4 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	12,480	34,585	57,860
IP	5,555	26,598	46,001
SPFL	5,587	26,502	45,545
ZSZI Bound	4,880	23,799	40,577

% OVER ZSZI BOUND - 4 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	155.7%	45.3%	42.6%
IP	13.8%	11.8%	13.4%
SPFL	14.5%	11.4%	12.2%

TABLE 6.3 (CONT'D)**COMPARISON OF COSTS - 2 hr. Period**

Solution	Planning Horizon (days)		
	10	30	50
Walker	12,480	34,585	57,860
IP	5,249	25,907	44,472
SPFL	5,191	26,287	44,926
ZSZI Bound	4,880	23,799	40,577

% OVER ZSZI BOUND - 2 hr. Period

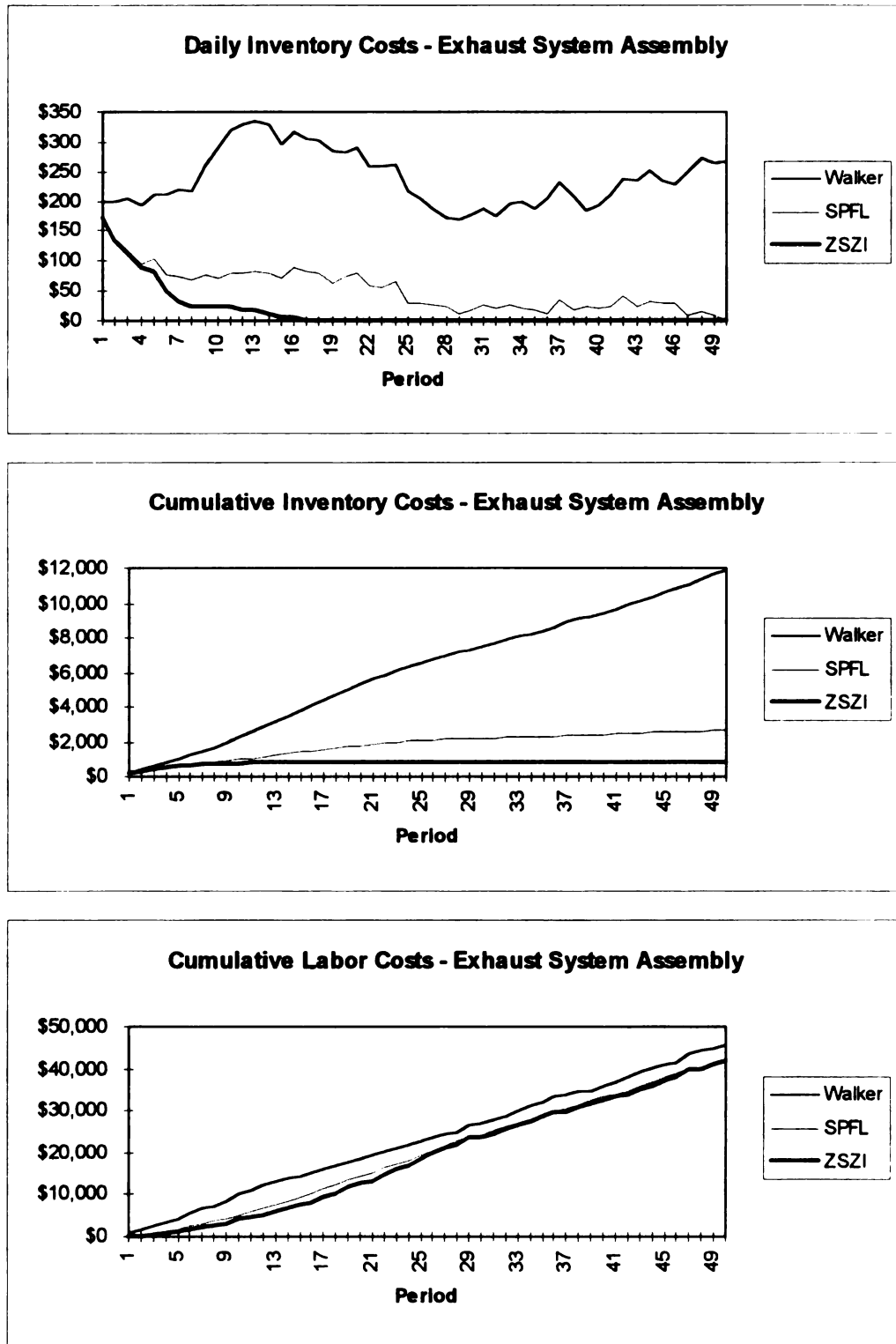
Solution	Planning Horizon (days)		
	10	30	50
Walker	155.74%	45.32%	42.59%
IP	7.56%	8.86%	9.60%
SPFL	6.37%	10.45%	10.72%

optimal solution is tighter for models with longer planning horizons, but this result is not consistent for all period lengths.

In Table 6.3, the integer programming and SPFL solutions are compared to the Walker Manufacturing schedule and the ZSZI lower bound. In all cases, the integer programming and SPFL solutions are better than the Walker Manufacturing schedule. Since there are no setups, the ZSZI lower bound is reasonably tight, and provides a good way to compare the MSS model solutions to the Walker Manufacturing schedules. The Walker Manufacturing schedule costs are extremely high compared to the ZSZI bound for short planning horizons. This is because the initial inventory levels are relatively high and demand can be met in the early periods by "consuming" the inventory to satisfy demand. For planning horizons of 30 days and longer, the Walker Manufacturing schedules have costs around 42-45% over the ZSZI bound, whereas the MSS solutions are in the range of 8-20% over the ZSZI bound. Thus, the MSS model can provide schedules that reduce costs by up to 80% of the maximum possible cost reduction.

Interestingly, the SPFL heuristic is superior to the integer programming solutions for planning horizons of over 10 days when the period length was over two hours.

Figure 6.1 presents the cost data graphically for the 50 day, two hour period SPFL solution. These graphs show that the SPFL heuristic operates at a much lower inventory level than the Walker Manufacturing schedule, resulting in significantly lower labor costs early in the planning horizon. Once the initial inventory is "consumed," the labor costs for the SPFL solution parallel those of the Walker Manufacturing schedule, until the end of the horizon, when the SPFL solution allows the ending inventory to go to zero, which reduces labor costs even further.

**FIGURE 6.1 DAILY COSTS FOR EXHAUST SYSTEM ASSEMBLY**

The graphs of Figure 6.1 show that comparing the total costs for the entire planning horizon overestimates the cost reduction from the MSS model schedule. The MSS model solution requires much less labor since the inventory levels are reduced, yet in practice both methods require the same amount of labor to produce the same number of parts. Because there are no setups in this model, the only true cost savings are due to operating at lower inventory levels. Looking at the daily inventory cost graph in Figure 6.1, it appears that the MSS model could reduce finished goods inventory costs by \$100-\$250 per day depending on how much of the finished goods inventory is due to uncertainty in how well the manufacturing system can meet schedules and how much is used to buffer demand uncertainty.

6.4 MUFFLER ASSEMBLY COMPARISON

The Muffler assembly line was evaluated using Walker Manufacturing's exhaust system assembly schedule to generate muffler demand. This allowed the MSS model schedules to be compared to Walker Manufacturing's decisions. Tables 6.4 and 6.5 summarize the results for the muffler assembly line evaluation.

The beginning inventory levels for mufflers was not available, so they were set to the minimum level possible based on Walker Manufacturing's production schedule. This created a problem for the MSS model solutions. Although Walker Manufacturing's nominal production rate was 2,000 units per day (2 shifts), on November 16, 1993 (the second day of the planning horizon) they produced 2,506 model 8286 mufflers. The MSS model was not able to replicate this feat since it scheduled production based on the nominal production rate and was not able to find a feasible schedule using the (minimum) inventory levels that were assumed based on Walker Manufacturing's production schedule. For the MSS model to find a feasible schedule, 500 units of muffler #8286 and 3 units of muffler #8329 were added to the initial inventory for the MSS model. The

TABLE 6.4 SOLUTIONS FOR MUFFLER ASSEMBLY**IP Solutions¹**

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	16,366	30,416	47,933	61,968	83,175
4	15,138		45,931		83,712
2	14,289		46,734		83,671

SPFL Solutions¹

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	16,345	32,327	49,011	64,420	85,938
4	16,712	32,134	49,664	68,182	90,428
2	16,225	33,991	52,740	72,052	95,512

IP Solution % of Lower Bound on Optimal

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	35.55	23.27	24.79	16.93	17.59
4	27.31		19.64		18.19
2	20.22		21.51		17.91

¹ Figures do not include production costs for 500 units of #8286 and 3 units of #8329 required to find a feasible schedule.

TABLE 6.5 COMPARISON OF COSTS FOR MUFFLER ASSEMBLY**COMPARISON OF COSTS - 8 hr. Period²**

Solution	Planning Horizon (days)				
	10	20	30	40	50
Walker	17,800	32,884	50,791	69,434	92,599
IP	16,861	30,911	48,428	62,463	83,670
SPFL	16,840	32,822	49,506	64,915	86,433
ZSZI Bound	12,234	24,853	38,544	53,061	70,693

% OVER ZSZI BOUND - 8 hr. Period

Solution	Planning Horizon (days)				
	10	20	30	40	50
Walker	45.5%	32.3%	31.8%	30.9%	31.0%
IP	37.8%	24.4%	25.6%	17.7%	18.4%
SPFL	37.6%	32.1%	28.4%	22.3%	22.3%

COMPARISON OF COSTS - 4 hr. Period²

Solution	Planning Horizon (days)		
	10	30	50
Walker	17,800	50,791	92,599
IP	15,633	46,426	84,207
SPFL	17,207	50,139	90,923
ZSZI Bound	12,234	38,544	70,693

% OVER ZSZI BOUND - 4 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	45.5%	31.8%	31.0%
IP	27.8%	20.4%	19.1%
SPFL	40.6%	30.1%	28.6%

² Figures include \$495 direct cost for 500 units of #8286 and 3 unit of #8329 added to initial inventory for IP and SPFL models.

TABLE 6.5 (CONT'D)**COMPARISON OF COSTS - 2 hr. Period³**

Solution	Planning Horizon (days)		
	10	30	50
Walker	17,800	50,791	92,599
IP	14,784	47,229	84,166
SPFL	16,720	53,235	96,007
ZSZI Bound	12,234	38,544	70,693

% OVER ZSZI BOUND - 2 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	45.5%	31.8%	31.0%
IP	20.8%	22.5%	19.1%
SPFL	36.7%	38.1%	35.8%

³ Figures include \$495 direct cost for 500 units of #8286 and 3 unit of #8329 added to initial inventory for IP and SPFL models.

direct labor costs for these units is \$495, and the results are corrected for this cost where appropriate.

Table 6.4 shows the results for the integer programming and SPFL heuristic solutions for the muffler assembly problem. There is no clear pattern to the impact of period length on the integer programming solutions. For the SPFL heuristic, decreasing the period length dramatically increases total costs. Table 6.4 shows that the integer programming solution is superior to the SPFL heuristic in all cases except for a ten day planning horizon with an 8 hour period length. Both the SPFL and integer programming solution techniques can find solutions that are superior to the Walker Manufacturing production schedule, as shown in Table 6.5.

For exhaust system assembly, the GAMS/OSL software ran out of the 300 MB of memory allocated before an optimal solution was found. For the muffler line assembly problem, memory was not a problem. Some test problems ran for over 48 hours without finding an optimal solution or running out of memory. Since computer resources were not unlimited, a 24 hour CPU limit was imposed on all muffler assembly line problems. In the trial problems, little improvement was gained by running the problem longer (less than 0.5% reduction in costs).

The LP relaxation for the muffler assembly problem is less tight than for the exhaust system assembly problem. This can be seen in Table 6.4, where the best integer solution found could only be shown to be 17.91% from the lower bound on the optimal solution. In the muffler assembly problem, the LP relaxation of the variable δ_{ijt} effectively allows for solutions with no setup costs. Setup costs are formidable for this

problem, accounting for \$7,243 of the \$92,599 cost for the Walker Manufacturing schedule.

The SPFL solution degrades as the period length is decreased because of an increase in the number of setups. Since the heuristic does not consider grouping production runs to conserve setups, it tends to switch more frequently between products. This can be seen by comparing Figures 6.2 and 6.3. Figure 6.2 graphically illustrates the first 25 days of the production schedule for the integer programming solution with a two hour period length, while Figure 6.3 illustrates the first 25 days of the production schedule for the SPFL heuristic solution. These figures show that in the integer programming solution high volume mufflers are grouped into relatively long production runs compared to the SPFL heuristic solution. The SPFL heuristic solution for the 50 day planning horizon with two hour periods requires 165 setups, compared to 67 for the integer programming solution and 53 for Walker Manufacturing's schedule. The SPFL heuristic performs better for longer period lengths because it is forced to schedule longer production runs.

If there were no capacity constraints, the optimal production schedule likely would have even longer production runs. The economic order quantities for mufflers (expressed in terms of the equivalent number of two hour periods) is shown in Table 6.6.

The costs for the different muffler assembly line schedules are compared graphically in Figure 6.4. Note that the SPFL heuristic solution has the lowest inventory holding costs because it schedules shorter and more frequent production runs of each muffler. The integer programming solution has labor costs that are approximately the

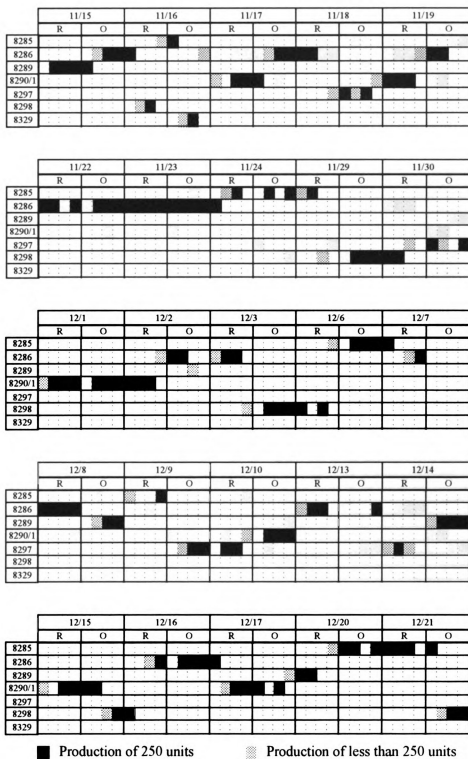


FIGURE 6.2 GRAPHICAL DISPLAY OF IP SOLUTION

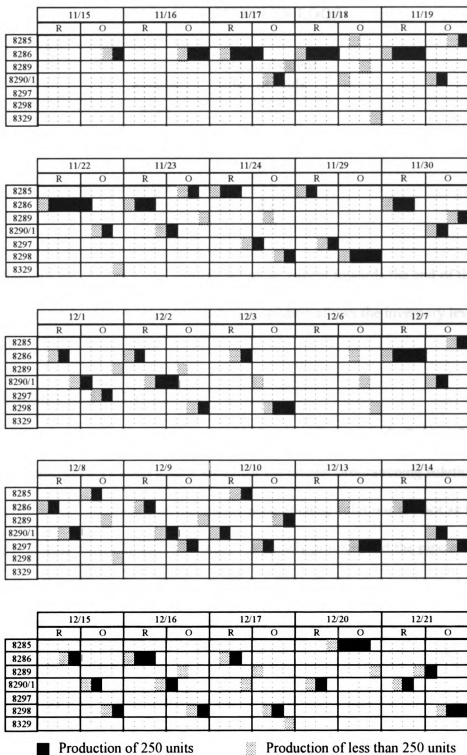


FIGURE 6.3 GRAPHICAL DISPLAY OF SPFL HEURISTIC SOLUTION

TABLE 6.6 MUFFLER EOQS

Muffler	EOQ equivalent 2 hr. periods
8285	9.6
8286	11.4
8289	5.6
8290/91	8.8
8297	5.5
8298	8.8
8329	2.0

same as those of the Walker manufacturing schedule, except towards the end of the planning horizon where the integer programming solution allows the inventory levels to fall to zero.

6.5 PIPE AREA RESULTS

Results for the pipe area are presented in Tables 6.7 and 6.8. In Table 6.7, no clear pattern emerges for period length, either for the integer programming solutions or the SPFL heuristic. The bounds on the integer programming solutions are not as tight as those of the muffler assembly line. The muffler assembly problem and the pipe area problem have the same number of binary variables--1800 for the 50 period, two hour period problem--but the pipe area problem is more complex. While the muffler line has only one workcenter, the pipe area has four. With the number of workers available in the pipe area either two or three workcenters can be operated during any period. Also, two workcenters in the pipe area can produce the same four parts. Thus, in the pipe area more complicated production "strategies" can be developed, and the branch and bound

procedure does not appear to be able to find as good a solution in this more complicated environment.

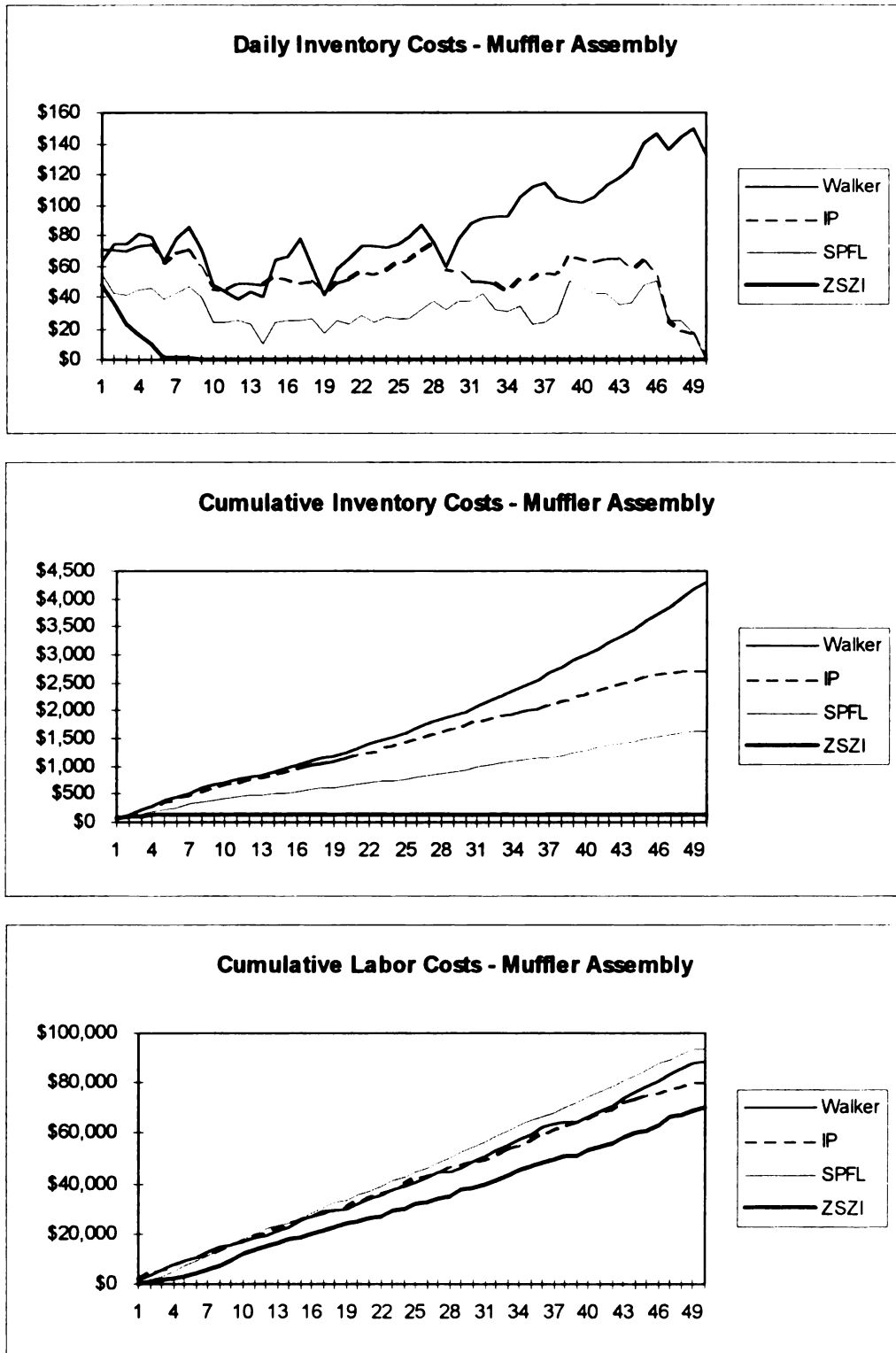


FIGURE 6.4 COMPARISON OF MUFFLER ASSEMBLY SCHEDULE COSTS

TABLE 6.7 SOLUTIONS FOR PIPE AREA**IP Solutions**

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	1,226	2,976	4,973	7,269	9,152
4	999		4,636		9,219
2	821		4,671		9,054

SPFL Solutions

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	1,225	3,105	4,750	7,337	9,519
4	998	3,049	5,164	7,068	9,888
2	1,022	2,963	5,118	7,420	10,108

IP Solution % of Lower Bound on Optimal

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	52.16	44.01	36.61	35.97	23.91
4	62.39		28.52		25.13
2	35.78		29.57		22.95

TABLE 6.8 COMPARISON OF COSTS FOR PIPE AREA**COMPARISON OF COSTS - 8 hr. Period**

Solution	Planning Horizon (days)				
	10	20	30	40	50
Walker	2,207	4,042	5,630	7,762	9,922
IP	1,226	2,976	4,973	7,269	9,152
SPFL	1,225	3,105	4,750	7,337	9,519
ZSZI Bound	604	2,030	3,604	5,311	7,363

% OVER ZSZI BOUND - 8 hr. Period

Solution	Planning Horizon (days)				
	10	20	30	40	50
Walker	265.4%	99.1%	56.2%	46.1%	34.8%
IP	103.0%	46.6%	38.0%	36.9%	24.3%
SPFL	102.8%	53.0%	31.8%	38.1%	29.3%

COMPARISON OF COSTS - 4 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	2,207	5,630	9,922
IP	999	4,636	9,219
SPFL	998	5,164	9,888
ZSZI Bound	604	3,604	7,363

% OVER ZSZI BOUND - 4 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	265.4%	56.2%	34.8%
IP	65.4%	28.6%	25.2%
SPFL	65.2%	43.3%	34.3%

TABLE 6.8 (CONT'D)**COMPARISON OF COSTS - 2 hr. Period**

Solution	Planning Horizon (days)		
	10	30	50
Walker	2,207	5,630	9,922
IP	821	4,671	9,054
SPFL	1,022	5,118	10,108
ZSZI Bound	604	3,604	7,363

% OVER ZSZI BOUND - 2 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	265.4%	56.2%	34.8%
IP	35.9%	29.6%	23.0%
SPFL	69.2%	42.0%	37.3%

6.6 PRESS AREA RESULTS

Results for the press area are presented in Tables 6.9 and 6.10. These problems proved extremely difficult to solve. For all previous problems, the branch and bound preprocessor was used in finding integer programming solutions ($bbpreproc = 1$ in GAMS/OSL). For many of the press area problems, there was not enough memory to allow for preprocessing, so this solution option could not be used. Table 6.9 indicates where preprocessing could not be performed. Even without branch and bound preprocessing, no integer solution could be found for many problems after 24 CPU hours. The press area problem is much more complicated than the other problems attempted. Table 6.11 compares the problem complexity for the muffler assembly and pipe area problems.

For the 10 day problems, the integer programming solution was superior to the SPFL heuristic, but the integer programming solutions degraded rapidly as the planning horizon increased. For problems with eight hour period lengths, the integer programming solution was worse than the SPFL heuristic solution for all planning horizons greater than 10 days, and the integer programming solution had significantly higher costs than Walker Manufacturing's schedule for planning horizons greater than 20 days. In all cases the SPFL heuristic solutions had lower costs than the Walker Manufacturing schedule.

6.7 ENTIRE MODEL RESULTS

Since the press area is a subset of the entire model, it is not surprising that the total model was very difficult to solve. The results of the entire model problems are given in

TABLE 6.9 SOLUTIONS FOR PRESS AREA

IP Solutions					
Planning Horizon (days)					
Period Length	10	20	30	40	50
8	1,296	5,059	9,342	12,396*	-*
4	1,007		6,365*		-*
2	938*		-*		-*

SPFL Solutions					
Planning Horizon (days)					
Period Length	10	20	30	40	50
8	1,297	3,585	6,603	9,367	12,539
4	1,056	3,157	5,796	8,858	12,351
2	1,031	3,117	5,837	8,917	-

IP Solution % of Lower Bound on Optimal					
Planning Horizon (days)					
Period Length	10	20	30	40	50
8	55.56	146.59	145.05	112.55	-
4	29.17		65.5		-
2	19.77		-		-

* Problem had to be solved without branch and bound preprocessing.

TABLE 6.10 COMPARISON OF COSTS FOR PRESS AREA**COMPARISON OF COSTS - 8 hr. Period**

Solution	Planning Horizon (days)				
	10	20	30	40	50
Walker	3,115	5,838	8,450	11,766	14,402
IP	1,296	5,059	9,342	12,396	-
SPFL	1,297	3,585	6,603	9,367	12,539
ZSZI Bound	517	1,245	3,550	5,757	8,294

% OVER ZSZI BOUND - 8 hr. Period

Solution	Planning Horizon (days)				
	10	20	30	40	50
Walker	502.5%	368.9%	138.0%	104.4%	73.6%
IP	150.7%	306.3%	163.2%	115.3%	-
SPFL	150.9%	188.0%	86.0%	62.7%	51.2%

COMPARISON OF COSTS - 4 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	3,115	8,450	14,402
IP	1,007	6,365	-
SPFL	1,056	5,796	12,351
ZSZI Bound	517	3,550	8,294

% OVER ZSZI BOUND - 4 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	502.5%	138.0%	73.6%
IP	94.8%	79.3%	-
SPFL	104.3%	63.3%	48.9%

TABLE 6.10 (CONT'D)**COMPARISON OF COSTS - 2 hr. Period**

Solution	Planning Horizon (days)		
	10	30	50
Walker	3,115	8,450	14,402
IP	938	-	-
SPFL	1,031	5,837	-
ZSZI Bound	517	3,550	8,294

% OVER ZSZI BOUND - 2 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	502.5%	138.0%	73.6%
IP	81.4%	-	-
SPFL	99.4%	64.4%	-

TABLE 6.11 MODEL COMPLEXITY FOR MUFFLER AND PIPE PROBLEMS

	Muffler Assembly 2 hour period length 50 periods	Pipe Area 8 hour period length 50 periods
Number of Binary Variables	2800	3900
Total Variables	14,400	23,000
Number of Equations	15,200	22,400

Tables 6.12 and 6.13. A number of the problems were too large to find integer programming solutions for within the 24 hour CPU limit. The SPFL heuristic found solutions for more of the problems, however, it had difficulty as well, especially when the period length decreased. Capacity becomes a problem for the SPFL heuristic for short period lengths because it schedules too many setup changes, which significantly reduces capacity. Except for the 10 day, four hour period model, the SPFL heuristic solutions are better than the integer programming solutions, and they are always significantly lower in cost than the Walker Manufacturing schedules.

6.8 EFFECT OF CAPACITY UTILIZATION ON SOLUTION PROCEDURES

The methods used to generate the high and low capacity demand schedules was discussed in Section 5.3. Capacity utilization estimates for the three demand schedules are presented in Table 6.14. The machine capacity estimates for the muffler, pipe and press areas were made ignoring setups.

The results of the capacity utilization experiments is shown in Tables 6.15 and 6.16. The exhaust assembly problems were run for 48 hours or until they ran out of the

TABLE 6.12 SOLUTIONS FOR TOTAL SYSTEM**IP Solutions**

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	14,358	41,626	80,084	-	-
4	12,481		-*		-
2	16,608*		-		-

SPFL Solutions

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	13,744	41,388	77,169	106,313	137,699
4	12,811	39,434	-	-	-
2	15,298	45,509	-	-	-

IP Solution % of Lower Bound on Optimal

Period Length	Planning Horizon (days)				
	10	20	30	40	50
8	50.65	35.28	31.43	-	-
4	33.24		-*		-
2	40.87*		-		-

* Problem had to be solved without branch and bound preprocessing.

TABLE 6.13 COMPARISON OF COSTS FOR TOTAL SYSTEM**COMPARISON OF COSTS - 8 hr. Period**

Solution	Planning Horizon (days)				
	10	20	30	40	50
Walker	35,601	66,612	99,457	134,371	174,783
IP	14,358	41,626	80,084		
SPFL	13,744	41,388	77,169	106,313	137,699
ZSZI Bound	9,423	30,909	61,934	86,811	112,465

% OVER ZSZI BOUND - 8 hr. Period

Solution	Planning Horizon (days)				
	10	20	30	40	50
Walker	277.8%	115.5%	60.6%	54.8%	55.4%
IP	52.4%	34.7%	29.3%	-	-
SPFL	45.9%	33.9%	24.6%	22.5%	22.4%

COMPARISON OF COSTS - 4 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	35,601	99,457	174,783
IP	12,481	-	-
SPFL	12,811	-	-
ZSZI Bound	9,423	61,934	112,465

% OVER ZSZI BOUND - 4 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	277.8%	60.6%	55.4%
IP	32.5%	-	-
SPFL	36.0%	-	-

TABLE 6.13 (CONT'D)**COMPARISON OF COSTS - 2 hr. Period**

Solution	Planning Horizon (days)		
	10	30	50
Walker	35,601	99,457	174,783
IP	16,608	-	-
SPFL	15,298	-	-
ZSZI Bound	9,423	61,934	112,465

% OVER ZSZI BOUND - 2 hr. Period

Solution	Planning Horizon (days)		
	10	30	50
Walker	277.8%	60.6%	55.4%
IP	76.2%	-	-
SPFL	62.3%	-	-

TABLE 6.14 MACHINE AND LABOR CAPACITY**Machine Capacity**

Production Area	Low Capacity	Walker Demand	High Capacity
Welding	16.7	37.7	41.9
Muffler	22.2	55.9	62.9
Bushing	5.2	20.0	23.0
Press	1.6	9.2	11.0

Labor Capacity

Classification	Low Capacity	Walker Demand	High Capacity
Welders	30.8	69.0	76.6
B Operators	16.8	44.0	49.7
C Operators	3.3	19.6	23.4

Note: Capacity figures calculated ignoring setups.

TABLE 6.15 CAPACITY EXPERIMENT WITH 30 DAY PLANNING HORIZON**Comparison of Solutions**

Model	Solution Type	Low Capacity	Walker Schedule	High Capacity
Exhaust Assy	IP	12,611	27,845	33,065
	SPFL	12,701	27,042	33,373
Muffler Assy	IP	17,280	40,315	50,217
	SPFL	17,306	40,652	51,793
Pipe Area	IP	1,131	3,702	4,057
	SPFL	1,133	3,378	4,520
Press Area	IP	3,211*	4,453*	6,068*
	SPFL	2,833*	4,618*	5,762*
Total System	IP	39,609	80,084	-
	SPFL	34,790	77,169	92,721

* Additional inventory had to be added to the problem to find a feasible solution using the SPFL heuristic.

IP Solution % of Lower Bound on Optimal

Model	Low Capacity	Walker Schedule	High Capacity
Exhaust Assy	11.52	10.21	4.46
Muffler Assy	54.54	22.42	17.52
Pipe Area	44.85	59.46	23.55
Press Area	36.42*	71.02	98.51
Total System	61.48	31.43	-

TABLE 6.16 CAPACITY EXPERIMENT WITH 50 DAY PLANNING HORIZON**Comparison of Solutions**

Model	Solution Type	Low Capacity	Walker Schedule	High Capacity
Exhaust Assy	IP	22,313	47,481	54,785
	SPFL	22,364	46,541	54,377
Muffler Assy	IP	35,131	72,822	85,501
	SPFL	31,790	73,826	87,144
Pipe Area	IP	2,668	7,282	7,634
	SPFL	2,603	6,864	8,271
Press Area	IP	5,328*	-	-
	SPFL	4,652*	8,792*	11,067*-
Total System	IP	-	-	-
	SPFL	62,874	137,699	151,605

*Additional inventory had to be added to the problem to find a feasible solution using the SPFL heuristic.

IP Solution % of Lower Bound on Optimal

Model	Low Capacity	Walker Schedule	High Capacity
Exhaust Assy	9.92	9.39	6.93
Muffler Assy	41.25	20.52	17.64
Pipe Area	60.02	40.55	18.50
Press Area	53.28		
Total System			

300 MB of memory available. For the low capacity models, running out of memory occurred quickly and the first solutions found for the low capacity exhaust assembly problems were the best found. For the Walker demand schedule, the solution procedure also stopped after running out of memory, but for both the 30 and 50 day problems, a number of better integer solutions were found as the problem ran. The high capacity models ran until the 48 CPU hour limit. It appears that for the high capacity problems the enumeration tree was smaller because branches could be “pruned” due to infeasibility. Integer programming found better solutions for the low capacity problems, but the SPFL heuristic solutions were better for high capacity problems. The bounds on the integer programming solutions were tighter for the high capacity problems, but that does not mean that the solutions found were necessarily closer to the optimal.

For the muffler assembly problems, demand was taken from the integer programming solutions from the exhaust system assembly problems. The integer programming solutions were in general better than the SPFL heuristic solutions. In only one case (low capacity model, 30 day planning horizon) was the SPFL solution was better than the integer programming solution. Low demand levels should favor shorter production runs, which would explain why the SPFL heuristic performed well in the low capacity models. For the muffler assembly problem, the bounds again are tighter when demand is high.

For the pipe area problem, the integer programming solutions were better for the high capacity problems but not for the Walker schedule or the low capacity problem. The

bounds on the integer programming solutions are in general tighter as demand increases, but this does not always hold true.

In the press area, demand was generated from the integer programming solutions for the muffler assembly problem. These demand schedules resulted in infeasible solutions to the SPFL heuristic, so additional inventory needed to be added to the problems. The labor cost for this additional inventory was small (less than \$20), but this points out a problem with hierarchical decomposition--it may be possible to find a solution to the entire problem, but decomposing the problem may result in a set of solutions at one level of the problem that creates feasibility problems at lower levels.

For the press area, integer programming solutions could not be found for all problems. The 50 day Walker demand schedule problem was run for 48 hours with no integer solution found. Where solutions could be found, the SPFL heuristic solutions were better in all but one case, where it was only 3.7% higher in cost.

Solutions for the total system could be found for the 30 day planning horizon problems with low capacity and Walker schedules. In both cases, the SPFL heuristic solution was significantly better than the integer programming solution. These solutions can also be compared to solving the problem using hierarchical decomposition. Adding the integer programming solutions for the exhaust system assembly and muffler assembly problems to the best solutions for the pipe and press area results in costs of 33,857 and \$77,991 for the low capacity and Walker demand schedules, respectively. Thus, hierarchical decomposition can result in lower cost solutions, but as mentioned above, feasibility can be a problem.

7.0 DISCUSSION

7.1 SOLUTION OF THE MODEL

The MSS model provides a framework to convert a master production schedule into a set of shop floor run schedules. These run schedules consider machine capacity, labor capacity and setups, not as aggregate quantities but in detail. The advantage of the MSS model over other scheduling methods is that the shop floor run schedules, if executed correctly, will meet the master production schedule within given capacity constraints. With techniques like Kanban and MRP, using the method does not guarantee that the master production schedule will be met.

In this study, two techniques were evaluated for solving the MSS model: integer programming via the branch-and-bound method and the SPFL heuristic. Integer programming did not prove to be a practical technique for most environments. When the problem was complex (many components, many workcenters or dependent demand) the solutions were not particularly good.

Further, many firms in repetitive manufacturing environments are of small to medium size and would not have computer resources similar to those used in this study. Even if these resources were available, the time required to find a good solution (most likely 24 hours or more) could result in many difficulties in actual implementation. In practice, many firms have dynamic environments where frequent rescheduling would be necessary. First tier automotive suppliers are frequently confronted with schedule changes from the big three automotive manufacturers, and this is often the case when the customer holds most of the power in the buyer-supplier relationship. Even if the master production

schedule is frozen for a reasonable planning horizon (as is typically done by Japanese auto manufacturers), other factors may require frequent replanning, such as employee absenteeism or machine breakdowns (although the MSS model could lead to reduced machine breakdowns, which is discussed in Section 7.3.5). Some firms in repetitive environments operate in an order-promising mode and would need quick solutions of the model to provide customers with firm delivery dates. Finally, the cost of computer resources to obtain good solutions via integer programming could very easily exceed the potential cost savings.

The SPFL heuristic can quickly find solutions to the MSS model. Based solely on the time to find a solution, it would be ideal for order promising, although it does not consider how best to schedule setup changes. When setups are non-existent, as in the exhaust system assembly problem at Walker Manufacturing, the SPFL heuristic works quite well. When setups are significant, as in the muffler assembly problem, the SPFL heuristic can produce solutions with significantly more setups than are ideal. In addition to increasing costs, scheduling too many setups can result in a significant loss of capacity.

Capacity management is a challenge in environments with setups. If setups are made too frequently, too much productive capacity is lost. As the number of setups is decreased, inventory levels must be increased as it takes longer to cycle through all of the components produced at a workcenter. When setups are significant, capacity problems can arise because setups are changed too frequently or not frequently enough. Modifying the SPFL heuristic to perform better when setups are significant will greatly increase its complexity, but a couple of approaches could prove useful.

One simple change to the procedure would be to change the choice of which components are scheduled first at a workcenter. The SPFL heuristic scheduled components based on low level code, then in order of highest unit cost. For the muffler assembly line, the highest cost components are not the highest volume components. Scheduling high volume rather than high cost components first may result in a schedule requiring fewer setups. Another approach would be to schedule larger production runs. For example, economic order quantities could be calculated from the master production schedule and converted into the equivalent number of periods of production (period order quantity, POQ). When production of a component is scheduled, the machine could be scheduled for a number of consecutive periods equal to its POQ. For high demand situations, the decision to schedule a group of periods may have to be evaluated in light of other components that need to be produced. Scheduling longer production runs would likely be a management decision that could be adapted to individual cases.

In some environments the SPFL heuristic may handle setups better than it did for the muffler assembly line. Demand for the muffler assembly line was driven by the exhaust system assembly workcenters. This resulted in a demand pattern with frequent, small quantities. In many production environments, the primary setup problem occurs in final assembly. If end-item demand results from relatively large customer orders, the SPFL heuristic may end up scheduling larger, and perhaps more ideal, production quantities.

Further research is clearly needed for MSS model solution procedures. While integer programming did work well for the muffler assembly line problem, it failed to do as well when the environment was more complex and had great difficulty finding solutions for larger problems. Since the branch-and-bound procedure tries to find integer solutions

in the “region” where the LP relaxation is optimal, it may fail to do well with more complex problems because it does not explore the “search space” well. A genetic search algorithm applied to the MSS model may find better solutions by evaluating more of the “search space.” The SPFL heuristic and variations on it might provide good starting “genetic material” in a genetic search algorithm.

7.2 THE COMPARISON TO WALKER MANUFACTURING

While the quality of solution procedures for the MSS model is important, the true test of the model is how good it is compared to other scheduling techniques. Comparing the MSS model to MRP or Kanban would provide the ideal evaluation. Unfortunately, it is difficult to compare the MSS model to these systems because they require numerous decisions to be made by schedulers and shop floor personnel, and it would be difficult to determine how these decisions are made in practice, much less how they should be made. The approach used in this dissertation was to compare the model to the decisions made by a firm (Walker Manufacturing) in a repetitive manufacturing environment. While this allowed for the model to be evaluated on an industrial sized problem, it produced only one comparison. Further, there is no objective way to evaluate how well Walker Manufacturing was handling its production scheduling compared to other firms, except to say that it was in business and profitable for a reasonably long period of time.

The value of the comparison to Walker Manufacturing was strengthened by assuming ideal labor productivity for the Walker Manufacturing schedule. Even assuming ideal efficiency, the MSS model provided clearly superior schedules. It is reasonable to expect that the MSS model, especially with improved solution heuristics, could improve the scheduling capabilities of many manufacturers in repetitive environments. The MSS

model structure can provide other benefits to manufacturing firms beyond good production schedules. While these benefits are difficult to quantify, they could prove to be significant. Section 7.3 describes these benefits

7.3 OTHER BENEFITS OF THE MSS MODEL

7.3.1 Simplified shop floor management

A principal benefit of the MSS approach is that the management of labor and machines is coordinated. The product of the MSS model is a detailed shop floor schedule that, if executed as planned, will allow orders to be shipped on time. Further, the shop floor schedules **can** be executed as planned because they were developed considering all of the facility's constraints in detail. In comparison, if MRP is used with capacity planning, what it produces is shop orders with due dates, and it is up to the shop floor supervisor to determine which order to process next, which workcenters to operate and where to assign workers. This is a formidable task which can consume much of the supervisor's time. With MSS run schedules, these decisions have been made--the supervisor has a schedule of what each workcenter will be producing at any given time. The supervisor must assign workers to each operating workcenter, but this is not a difficult task since the schedule was developed considering the available labor. With MSS run schedules, the shop floor supervisor is free to manage the production task, not the scheduling.

7.3.2 Reduced lead times compared to MRP

For an MRP system to function properly, lead times must be set so that a high percentage of shop orders can be completed on time. Long lead times reduce the responsiveness of the production system and increase WIP inventory. Many firms in repetitive environments have developed their own scheduling systems because of long lead times and other problems related to MRP systems. Frequently, these systems take the form of an “expert” system, where an individual becomes the scheduling expert and develops schedules through various means, including intuition. This, in fact, was the way in which Walker Manufacturing developed schedules. The MSS model converts the master production schedule into detailed shop floor schedules **without** using inflated lead times and, therefore, is a more responsive scheduling technique.

7.3.3 Proactive response to changing demand

Kanban systems have proven effective in Japan, but the disadvantage of a “pull” system like Kanban is that it cannot anticipate changes in demand patterns. One of the frequently misunderstood (and perhaps most important) factors in a JIT system is the use of level production schedules. Kanban systems have worked well for Japanese manufacturers that are willing to set level master production schedules. Japanese auto manufacturers typically provide suppliers with a demand schedule that is frozen for a number of weeks. When applied to an environment where demand patterns shift dramatically, Kanban systems suffer. The MSS model can provide a means to proactively respond to changes in demand pattern. The model can be modified easily to allow for the scheduling of overtime as well, so that overtime can be a planned response to demand

changes, rather than a short term reaction to a late order as in MRP or an empty Kanban in a JIT system.

7.3.4 One shop floor performance measure

With the MSS model, evaluating shop floor performance is simplified because performance objectives are built into the model. If management is convinced that the model correctly considers and weighs all relevant factors in determining a production schedule, all that shop floor personnel need to do is carry out the schedule developed by the MSS model. One of the most difficult tasks may in fact be convincing management that it is not likely that schedules developed using the model can be improved upon through trial and error and that other performance measures should not be analyzed.

In an MRP system where the shop floor supervisor makes numerous scheduling decisions, a number of performance measures (sometimes contradictory) are used to evaluate the supervisor. In trying to optimize performance measures, production schedulers and shop floor supervisors can end up making decisions that boost performance measures but degrade the performance of the system as a whole.

For example, at Walker Manufacturing an important performance measure was daily labor efficiency, which was defined as the dollar value of finished goods produced divided by the dollar value of the labor used that day. Labor efficiency measured in a more aggregate fashion (e.g. weekly or monthly) is probably a good measure of the efficiency of a production facility, but on a daily basis this measure is too volatile. An optimal production schedule could require relatively few finished products to be produced on a particular day, and while the production facility may be very efficient in producing

what it should be on that day, the daily labor efficiency measure would indicate poor performance. A manager who is evaluated by daily labor efficiency will face pressure to push finished goods out the door each day, with the result that the formal planning and scheduling system will be replaced with “hot lists” or other manifestations of an informal system.

Performance measures can also lead to poor decisions when measured too infrequently. Raw material inventory was used as a performance measure at Walker Manufacturing, but it was measured only at the end of each month. To achieve a good score on this performance measure, management of the Walker facility would let raw steel inventories drop to low levels at the end of the month, only to be replenished quickly at the beginning of the next month. Not only did this measure provide an inaccurate picture of raw materials inventory, it had an impact on production decisions. Because of low steel levels at the end of the month, the supervisor for the pipe and press areas could not consider grouping production batches to conserve setups because there would not be sufficient steel for other required components.

The MSS model can be used to avoid performance measure problems because only one performance measure is important--how well was the schedule met. Since the MSS model schedules are feasible and optimized (to the extent that the model and the solution procedures allow), there is no practical way to improve on the solution. To evaluate the performance of the production facility with an MSS schedule, there is only one performance measure: how well did the shop floor do in producing to schedule. With the MSS model managers, shop floor supervisors and shop floor workers would all be clear as to what is required for good performance. They would not be evaluated by a set of

measures that may be in conflict and driven to achieve good performance measures by making decisions that in the long run are bad for the firm. And with one performance measure, less effort would be spent measuring and evaluating performance.

7.3.5 Better management of labor and maintenance

Managing a labor force in light of changes in demand is one of the more challenging tasks of the operations manager. This is particularly true when the labor force is skilled and layoffs would result in the permanent loss of employees that would be needed in the near future. It is not uncommon for firms to operate with more labor than required to keep skilled workers in the company. During low demand periods, workers tend to work at a slower, more leisurely pace. For example, if a worker can produce 200 units a day but only 100 units are needed, the worker may produce the 100 units by working more slowly and inserting more coffee breaks and conversations into the workday. With the MSS model, the worker could be scheduled to produce 100 units during the first half of the day and the second half of the day could be used for other purposes such as training, maintenance or repair/rework. While excess labor capacity could be similarly employed with other scheduling approaches, the MSS model is particularly adept at allowing idle labor to be applied to other useful functions because it schedules labor in detail.

By producing detailed run schedules, the MSS model can lead to improved preventative maintenance scheduling. It is generally accepted that preventative maintenance can result in better facility performance because unexpected breakdowns are minimized. The trouble with implementing preventative maintenance programs is that

traditional scheduling systems do not have the ability to determine when equipment will be idle for maintenance. The MSS model defines what each machine will be doing in each production period. Maintenance can then be scheduled during idle periods or, if longer periods are required, the production schedule can be developed with maintenance periods blocked out.

7.3.6 Potential for increased discipline

All of the items described above can lead to a more disciplined production facility. First, the MSS model schedules provide a common “script” for the production facility. All people involved in production can determine what needs to be done from the run schedules. When the shop floor is not scheduled in detail, it is not unusual for supervisors and material managers to develop their own planning systems. These systems are frequently incompatible with each other even though they may be keeping track of similar information. With the MSS model, the run schedules provide a single detailed production plan that provides the information needed by all involved parties.

Successful implementation of the MSS model should lead to more stable production facility performance. With performance to schedule as the only performance measure, decisions that work at cross purposes to the efficient operation of the facility will likely be avoided. Managers will not be compelled to press shop floor supervisors to make bad decisions that make the “numbers” look good. The emphasis will be to meet the plan, which will make planning that much easier. The MSS model can facilitate preventative maintenance programs, which will result in more consistent production because there will be fewer unexpected breakdowns. A comprehensive scheduling system

like the MSS model can lead to production facility consistency, which improves the ability to schedule the production system.

7.4 MODIFICATION OF THE MODEL TO ALLOW SETUP CHANGES AT THE END OF A PERIOD

After completion of the experimental portion of this study, a modification to the model was suggested by Paul Rubin of the dissertation committee that would allow for setup changes to be started at the end of a period if idle time was available. To do this, the MSS model presented in Section 3.2 is modified by adding the continuous variable S_{jt} which is the idle production time in period $t-1$ that can be used to change the setup for production of a new component in period t . This variable is defined by adding the following constraint to the model:

$$S_{j,t+1} + \frac{1}{p_{ij}} \sum_i (X_{ijt} + Y_{ijt} + Z_{ijt}) \leq \sum_i \delta_{ijt}$$

This idle production time reduces (and, perhaps, eliminates) the time required to change the setup in period t . This is done in the model by modifying constraint (7). The new constraint is then:

$$Z_{ijt} + p_{ij}S_{jt} \geq U_{ij}\delta_{ijt} - \sum_{i'} v_{i'ij} \gamma_{i'j,t-1}$$

Allowing setup changes at the beginning and the end of a production period increases the flexibility of the model. The impact should be most pronounced when the period length is larger than the economic production quantity.

8.0 CONCLUSIONS

The MSS approach to production scheduling presented in this dissertation provides a framework that can be used to develop detailed production schedules in a repetitive manufacturing environment considering the three major production factors: labor capacity, machine capacity and machine setups. In this dissertation, the model was evaluated using a real production facility and the schedules produced by the model were compared to actual production decisions. This evaluation produced two significant results: the model provided schedules that were superior to those used by Walker Manufacturing, and improved solution techniques are needed. The SPFL heuristic provided quick solutions that were good except in the face of significant setups. Integer programming can be used to find solutions to the model, and it proved to work well for smaller problems, but when the problem got more complicated, the ability to find solutions degraded significantly and in all cases the cost of obtaining solutions via integer programming were significant.

Based on the favorable comparison of the model's schedules with Walker Manufacturing's decisions and the numerous advantages described in the previous section, further research on this model is warranted. First, improved solution heuristics need to be developed. Two areas appear promising. First, the SPFL heuristic can be improved. The primary area for improvement is in how setups are handled. What might develop from research in this area is a set of easily solved heuristics producing a number of solutions from which the best solution can be selected. A second approach that might work well is a genetic search algorithm.

With an improved set of solution techniques, the next step in the development of this approach would be to evaluate its performance further. One method of evaluating the model would be to construct a detailed simulation to compare the MSS model to MRP and Kanban systems. The major difficulty with this evaluation is the question of how to properly model the numerous human judgments used in these systems. The second means of evaluating the model would be to apply it in an actual production setting. The difficulty here is that a number of implementations would have to be evaluated to be confident that in general the model is an effective production scheduling technique.

Production scheduling has been an area of significant research, and much work still needs to be done. While the MSS model is not yet a fully functional production scheduling system, it does promise to provide a comprehensive system for scheduling production in a repetitive manufacturing environment.

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LIST OF REFERENCES

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APPENDIX

APPENDIX

COMPUTER PROGRAM DEVELOPED FOR THE MSS MODEL

Since a computer program was required to calculate production schedules using the SPFL heuristic, a program was written to both solve the problem using the SPFL heuristic and create data files for integer programming codes. The computer program, **MSS Plan**, was written in VisualBasic™ Professional version 3.0, an object-oriented programming language, to demonstrate that the MSS model and SPFL heuristic can be implemented so that a production planner would find it easy to use.

THE MSS PLAN COMPUTER PROGRAM

Figure A1 shows the main screen for the MSS Plan computer program. The options grouped under **Input Component and Process Data** allow the user to input data that primarily describe the production process. The options grouped under **Input Schedule Data**, allow the user to input data related to a particular planning problem. The options grouped under **Solution Options** allow the user to solve the model using the SPFL solution heuristic or create an input data file for either the GAMS/OSL™ or CPLEX™ integer programming software.

Selecting the **Components** option under **Input Component and Process Data** calls up the component data screen shown in Figure A2. This screen allows the user to define a component by entering the component name in the first text box. Along with

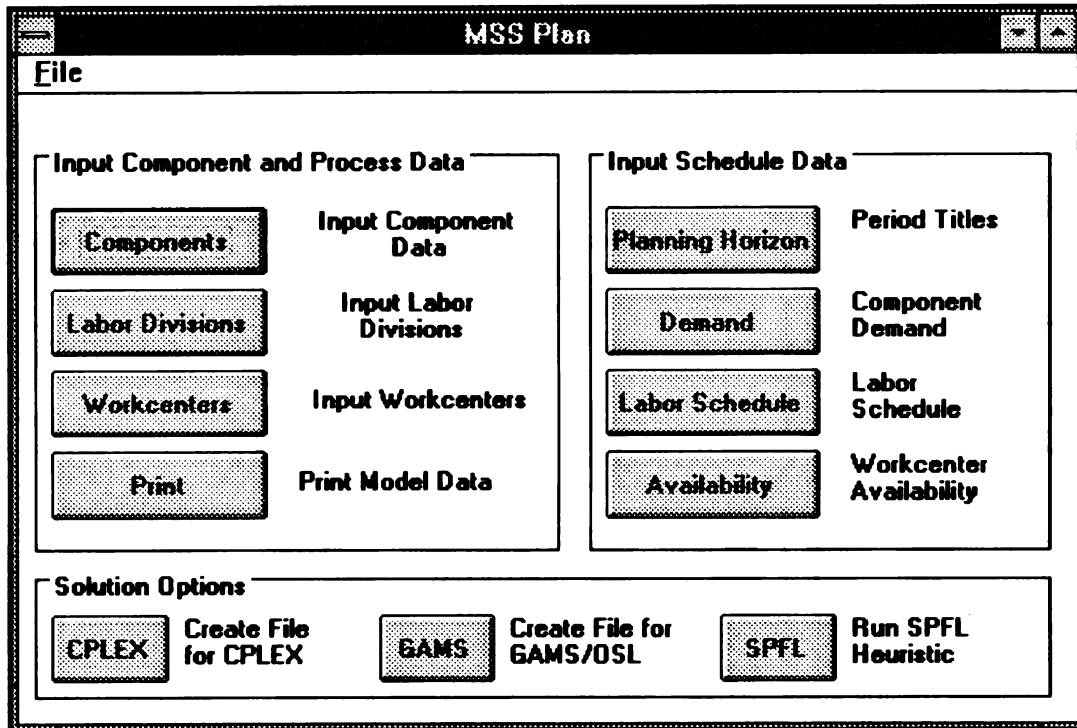


FIGURE A1 MSS PLAN MAIN SCREEN

The screenshot shows a software window titled "Component Data". At the top left is a "Return" button. The main area is divided into two columns. The left column contains an "Enter Component ID" section with a text box (labeled "Name Text Box" with an arrow), "Add" and "Delete" buttons, a list of component IDs (M 8286, M 8289, M 8290/91, M 8297, M 8298), a "Unit Cost" field with the value 17.31, an "Initial Inventory" field with the value 2048, and an "Inventory Carrying %" field with the value .2 (labeled "Inventory carrying charge for all components" with an arrow). The right column is titled "Constituent Components" and contains a "Child Components" list (324182, H 324202, H 324462, L 324142, L 324152, L 324162) with a "Quantity" field set to 1 and a "Delete" button. Below this is a "Components" list (324102, 324182, 324282, 324292, 324782, 324862) and an "ADD" button. Annotations on the right explain that the BOM is defined by child components and quantities, and that child components are selected by clicking on the component in the list and clicking ADD.

Component Data

Return

Enter Component ID

Name Text Box

Add Delete

M 8286
M 8289
M 8290/91
M 8297
M 8298

Unit Cost
17.31

Initial Inventory
2048

Inventory Carrying % .2
Inventory carrying charge for all components

Constituent Components

Child Components

324182
H 324202
H 324462
L 324142
L 324152
L 324162

Quantity 1

Delete

Components

324102
324182
324282
324292
324782
324862

ADD

BOM defined by child components and quantities

Child components are selected by clicking on the component in the list and clicking ADD

FIGURE A2 COMPONENT DATA INPUT SCREEN

the component name, the unit cost and initial inventory are also entered in this screen. On the right side of this screen, the BOM is entered by defining the child components for the component highlighted in the left-hand list of components. The inventory holding cost (% of unit value per year) is also entered in this screen. This figure is used for all components.

Selecting the **Labor Divisions** option under **Input Process and Component Data** calls up the screen shown in Figure A3. This screen allows the labor divisions to be defined along with the hourly wage rate.

Selecting **Workcenters** calls up the screen shown in Figure A4. On this screen, the facility workcenters are defined by naming the workcenters, defining the components that are produced at the workcenter and entering production data and labor requirements. Components that can be produced at a workcenter are defined by highlighting the workcenter in the list and selecting components from the list of components and clicking the **ADD** button. For each component that can be produced at a workcenter, additional data must be defined. When the active component is selected from the upper list of components the hourly production rate can be defined along with the nature of the material transfer delay. If **Periods** is selected, the entry shows how many periods must elapse before the components will be available for use at a downstream workcenter (in Figure A4, one period of delay is indicated, meaning that component M8285 will be available in the next period after it is produced). If **Parts** is selected, then the value represents the maximum number of parts that can be transferred to a downstream workcenter during the production period. This is the parameter f_{ij} defined in Section 3.

The screenshot shows a software window titled "Labor Divisions". At the top left of the window is a "Return" button. Below the title bar is a section titled "Enter Labor Division" which contains a form. The form has a text input field at the top. Below it are two buttons: "Add" and "Delete". Under these buttons is a list box containing the text "C Operator" and "Welder". At the bottom of the form is a label "Wage Rate (\$/hr)" followed by a text input field containing the value "12.00".

Labor Divisions

Return

Enter Labor Division

Add **Delete**

C Operator
Welder

Wage Rate (\$/hr)
12.00

FIGURE A3 LABOR DIVISION SCREEN

Workcenters

Return

Workcenter Data

Workcenter Name

Add Delete

Partition Press
SS 2-3/8
SS 2-5/8
SS 5

Setups

☐ No Setups

☒ Seq. Independent

125

☐ Seq. Dependent

Show Losses

Define Components and Labor Requirements

Component

M 8286
M 8289
M 8290/91
M 8297
M 8298
M 8329

Prod. per hour

125

Delete

8285
8286
8289
8290
8291
8297

Add

Delays

☒ Periods

1

☐ Parts

Workcenter Setup to Produce

M 8329

In First Period

Setups Allowed

☐ Yes

☒ No

Labor

Number of Workers

13

Delete

B Operator
C Operator
Welder

Add

Components that can be produced at the workcenter are added from this list

Selecting this entry adds constraint (6) to the IP model file

The labor required at the workcenter for the highlighted component is entered here

Text box for defining a workcenter

Data shown in the rest of the screen is for the workcenter highlighted in this list

FIGURE A4 WORKCENTER DEFINITION SCREEN

The labor requirements are defined by adding the labor divisions required from the list at the bottom-right of the screen. Selecting the labor division from the top-right-hand list allows the user to enter the number of workers in the text box.

When all components that can be produced at a workcenter are defined, the nature of the setups can be identified. Three options are grouped under **Setups** at the lower-left side of the screen. If setups are required, they are defined as sequence-independent or sequence-dependent. For sequence-independent setups, a single figure is entered which defines the setup loss in terms of the number of components of production lost while the workcenter setup is being changed. If the setups are defined as sequence-dependent, then by selecting **Show Losses** the screen shown in Figure 6.5 appears and allows the scheduler to define the sequence-dependent setup losses in terms of the units of production lost in switching from the component listed in the row to the component listed in the column. In addition to the nature of the setup losses, the scheduler can define whether production losses are allowed during idle periods. Selecting **YES** adds constraint (6) to the CPLEX and GAMS/OSL model files, but has no impact on the SPFL heuristic since the heuristic does not schedule setups during idle periods, even if they are allowed.

Completing the **Components, Labor Divisions and Workcenters** screens defines the production environment. Schedule data is entered by first selecting **Planning Horizon** under the **Input Schedule Data** group, which calls up the screen in Figure A6. The user can enter the number of periods in the planning horizon, the length of each period in hours, the number of periods in each inventory counting cycle (**Periods per Cycle**) and the number of inventory cycles per year.

Sequence Dependent Setup Losses							
Return							
Grid Commands							
Copy Paste Delete							
	P 324122	P 324132	P 324172	P 324322	P 324332	P 324342	P 324352
P 324122	X	750	750	750	750	750	750
P 324132	750	X	750	750	563	563	750
P 324172	750	750	X	750	750	750	750
P 324322	750	750	750	X	750	750	750
P 324332	750	750	750	750	X	750	750
P 324342	750	750	750	750	750	X	750
P 324352	750	750	750	750	750	750	X
P 324752	750	750	750	750	750	750	750
P 324762	375	750	750	750	750	750	750
P 324922	750	750	750	750	750	750	750
P 324972	750	750	750	750	750	750	750
P 324982	750	750	750	750	750	750	750
P 325812	375	750	750	750	750	750	750
P 325822	750	750	750	750	750	750	750
P 325832	750	750	750	750	750	750	750

FIGURE A5 SEQUENCE-DEPENDENT SETUP LOSS SCREEN

These 4 entries define the planning horizon

Return

Planning Horizon

Number of Periods: 100

Hours per Period: 8

Periods per Cycle: 2

Cycles per Year: 250

Grid Commands: Copy Paste Delete

1	2	3	4	5	6	7	8	9	10	11	12
11/15	11/15	11/16	11/16	11/17	11/17	11/18	11/18	11/19	11/19	11/22	11/22
1	2	1	2	1	2	1	2	1	2	1	2

This grid allows each period to be given 2 identifiers

FIGURE A6 PLANNING HORIZON SCREEN

Figure A6 shows a planning horizon screen for a model of the muffler assembly line using a 4-hour period length. Since the muffler line runs for two 8-hour shifts each day and there are four 4-hour periods in each day, **Periods per Cycle** is set at 4 and inventory costs are assessed on inventory levels at the end of each second shift. Assuming that there are 50 work weeks in the year, there would be 250 inventory cycles per year. Given the 4-hour period length and the two shift work day, the 200 period model covers 50 working days. Once the planning horizon has been defined, two text entries can be entered in the grid to uniquely identify each period.

With the planning horizon defined, a demand schedule can be entered by selecting **Demand** from the **Input Schedule Data** group, which calls up the screen in Figure A7. The user can enter the demand for any component in this screen (both end items and subcomponents). The convention is that the demand must be met by the end of the period in which it is entered.

The labor schedule can be entered in a similar manner using the screen shown in Figure A8. This screen defines the number of workers in each labor division that are available in each period of the planning horizon.

By choosing **Availability** from the **Input Schedule Data** group, the planner can define which workcenters are to be operated each period using the screen of Figure A9. This entry is required for those facilities where some workcenters are not operated every period. For example, at Walker Manufacturing the muffler assembly line worked

Demand Schedule											
File											
Grid Commands											
Copy Paste Delete											
	11/15		11/16		11/17		11/18		11/19		1
	1	2	1	2	1	2	1	2	1	2	1
8285	0	180	0	300	0	180	0	270	0	0	0
8286	0	390	0	270	0	390	0	300	0	0	0
8289	0	0	0	175	0	0	0	175	0	0	0
8290	0	0	0	270	0	0	0	270	0	0	0
8291	0	25	0	120	0	30	0	120	0	0	0
8297	0	120	0	120	0	121	0	120	0	160	0
8298	0	300	0	300	0	300	0	300	0	300	0
8329	0	0	0	25	0	0	0	25	0	0	0
H 117417	0	0	0	0	0	0	0	0	0	0	0
H 324202	0	0	0	0	0	0	0	0	0	0	0
H 324302	0	0	0	0	0	0	0	0	0	0	0
H 324462	0	0	0	0	0	0	0	0	0	0	0
H 324702	0	0	0	0	0	0	0	0	0	0	0
H 325782	0	0	0	0	0	0	0	0	0	0	0
L 324142	0	0	0	0	0	0	0	0	0	0	0

FIGURE A7 DEMAND SCHEDULE SCREEN

Labor Schedule											
Return											
Grid Commands											
Copy Paste Delete											
	11/15	11/15	11/16	11/16	11/17	11/17	11/18	11/18	11/19	11/19	1
	1	2	3	2	1	2	1	2	1	2	1
B Operator	9	2	3	2	3	3	3	3	3	2	3
C Operator	20	14	20	14	20	14	20	14	20	14	2
Welder	12	0	12	0	12	0	12	0	12	0	1

FIGURE A8 LABOR SCHEDULE SCREEN

Workcenter Availability											
Return											
Grid Commands											
Operating Unavailable											
	11/15		11/16		11/17		11/18		11/19		
	1	2	1	2	1	2	1	2	1	2	+
8205 Assy		X		X		X		X		X	
8206 Assy		X		X		X		X		X	
8289 Assy		X		X		X		X		X	
8290/91		X		X		X		X		X	
8297 Assy		X		X		X		X		X	
8298 Assy		X		X		X		X		X	
8329 Assy		X		X		X		X		X	
Head		X				X		X		X	
Louver											
Louver 2											
Louver											
Muffler											
Partition											
SS 2-3/8		X		X		X		X		X	
SS 2-3/8		X		X		X		X		X	

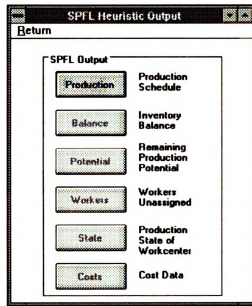
FIGURE A9 WORKCENTER AVAILABILITY SCREEN

two shifts, but most other workcenters did not. By entering an **X** in the appropriate periods, the program will not include the variables and constraints associated with the workcenter for those periods in the integer programming models and will not allow the SPFL heuristic to schedule production in those periods.

With the component, process and schedule data entered, the program will allow the user to create integer programming models or run the SPFL heuristic. If the SPFL heuristic is successful in finding a solution to the problem, a number of output options are available for the results as shown in the Figure 6.10. The production schedule screen shows the production schedule data (which can be printed) that can be used to run the shop floor. The screen displays a run schedule--a schedule that shows how many of each component should be produced at each workcenter in each period. This schedule is simple to interpret and use to run a shop floor, yet it was developed considering all of the constraints in the manufacturing facility: labor, setups, machine capacities, etc.

If the user selects the **GAMS** option, the file name and directory are defined by the top screen of Figure 6.11, while the GAMS solution parameters can be defined in the screen shown at the bottom of Figure 6.11. The program currently does not have the capability to read the solutions from the GAMS output files to create output screens similar to those in Figure 6.10, but this capability is easily added.

The MSS Plan program, besides providing the capability to quickly enter data to build integer programming models and generate SPFL heuristic solutions, demonstrates that the MSS model is easy to use by a production scheduler in an actual repetitive manufacturing environment.

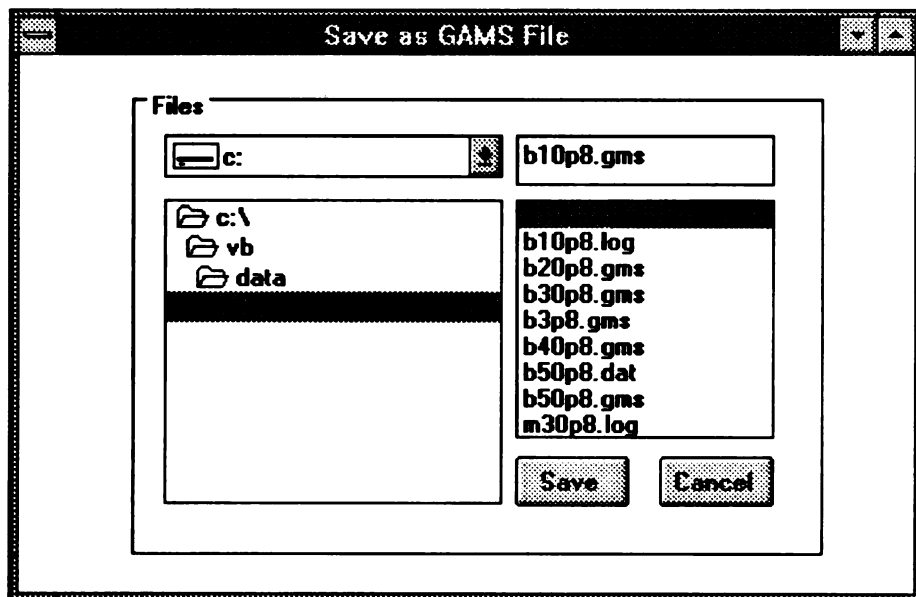


SPFL output options

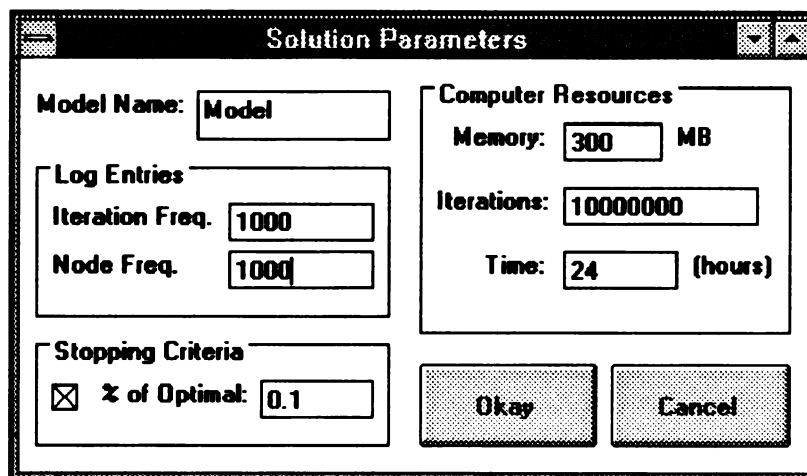
		Production Schedule							
Files									
Component	Workcenter	11/15	11/15	11/16	11/16	11/17	11/17	11/18	11/18
		1	2	1	2	1	2	1	2
8285	8285 assy								
8286	8286 assy								
8289	8289 assy								
8290	8290/91	324						324	
8291	8290/91			324					
8297	8297 assy								
8298	8298 assy					432		432	
8329	8329 assy			200					
H 117417	Head Press	325							
H 324202	Head Press								
H 324302	Head Press								
H 324462	Head Press								
H 324702	Head Press								
Labor Cost: \$129,526.08		Inventory Cost: \$8,173.36		Total Cost: \$137,699.44					

Production schedule screen

FIGURE A10 SPFL HEURISTIC RESULTS SCREENS



Screen for defining file name



Screen to specify GAMS solution parameters

FIGURE A11 GAMS MODEL SCREENS