LOT-SIZING IN THE WOOD FURNITURE INDUSTRY

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(ABSTRACT)

We consider the problem of scheduling production in a wood furniture plant. In particular, we consider the problem of selecting orders from various types of furniture products and determining their lot-sizes for production when there are sequence dependent setup times involved in the production of these items. This is termed the aggregate scheduling problem. In addition, we consider the problem of scheduling work at various production facilities in the presence of capacity constraints once the items for production and their quantities are selected. This is termed the detailed scheduling problem. The aggregate scheduling problem is formulated as a mixed integer program and solved using a dynamic programming procedure. The detailed scheduling program is a linear program and is solved using a canned linear programming package.

In order to understand the state-of-the-art in the furniture industry, various furniture plants in Southwest Virginia were visited and a national survey was conducted. The results are summarized. The survey emphasized the problem addressed in this research. In order to understand the decision points better in the furniture manufacturing process, the IDEF (ICAM definition) procedure is used to describe the furniture manufacturing process. The methodology developed is applied to a real-life problem and the results are summarized.

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CHAPTER ONE
INTRODUCTION

1.1 Overview

The American wood furniture industry is one of the oldest industries in the country. Ever since colonial days when furniture was hand-crafted for homes and businesses, there has been a demand for wood furniture. As the demand increased and automation became more available, the craftsman was, in large part, replaced by larger furniture plants which employed many of the production line techniques introduced in the automobile industry by Henry Ford. After this initial renaissance, many furniture mills remained family-owned businesses with very few changes made since the 1920's. Many of the techniques used today are the same as when the business was first opened and often key decisions are made based on the experience of a foreman who has been with the company for an extended period of time.

With the increased availability of computers and computer numerically controlled (CNC) machinery, many other industries have become highly automated. However, this has not been the case with the wood furniture industry. Furniture mills have been slow to jump on the bandwagon of CNC machinery, and are just now starting to reevaluate their production techniques. In 1989, it was estimated that only twenty-one percent of those plants involved in the woodworking industry owned at least one CNC router while it is expected that fifty percent of all woodworking shops will own at least one CNC router by the year 1994. Similar reports involve other types of CNC woodworking machinery [Wood & Wood Products, 1990].

In addition to the traditional management style of the family-owned or family-run business, there are several other factors which have restricted attempts at automating the wood furniture industry including:

1. Style orientation of the product
2. Diversity and short life cycles of parts
3. Aesthetic requirements of parts
4. Non-homogeneity of raw materials
5. Small scale of the typical manufacturing unit [Culbreth et al., 1989]

Due to the marketing strategy of the furniture industry, manufacturers are encouraged to produce a highly diverse product line. This seems to imply that small lot sizes should be used. Yet, most furniture manufacturers resist the smaller lot sizes based on claims of losing too much time in the setups of the production lines. Therefore, the finished goods inventory level tends to be rather high.

In addition to the traditional high level of finished goods, furniture manufacturers produce excess pieces to buff against losses due to material problems. Since the aesthetic characteristics of wood furniture are nearly as important as the overall design, scratched, marred, or dented pieces are considered waste and become scrap material. Most wood is relatively soft making it easy to incur such flaws. In addition, the non-homogeneity of wood, even within a species, causes differences in the weight and density in a given part. Because wood is a hygroscopic material, it is subject to shrinking, swelling, cracking and warping with respect to the moisture content of the surrounding atmosphere [Culbreth et al., 1989].

All of these factors contribute to a batch size which is larger than would be necessary if the raw material possessed more homogeneous characteristics. This leads to a congested production line with excessive work-in-process. In the furniture industry, there is a tendancy among managers to ignore inventory carrying costs and to assume that the storage of finished goods costs nothing. However, since partially completed pieces are not readily marketable, these same managers realize that the storage of work-in-process inventory is a cost, although they do little to minimize such storage.

1.2 Problem Areas

From the current status of furniture production, it is clear that furniture manufacturers can increase their competitiveness by creating smaller lot sizes in order to reduce finished goods inventory and to reduce manufacturing lead times. Therefore, it is necessary to look for ways in which the production line can be changed to be more accommodating to smaller lot sizes.

All research presented in this paper was based on current trends in the wood furniture industry. These trends were determined by on-site observations as well as by survey responses. The facilities which were visited mainly consisted of plants located within seventy miles of Blacksburg, Virginia. The survey responses, however, covered a wide range of locations in the United States as shown in table 1.1.

Table 1.1–Responses by State

State	Number of Responses
Alabama	1
Arkansas	1
California	1
Illinois	1
Indiana	2
Kentucky	2
Massachusetts	1
Maryland	1
Maine	1
Michigan	2
Minnesota	1
Mississippi	2
North Carolina	21
New Hampshire	1
New York	3
Ohio	1
Pennsylvania	3
South Carolina	1
Tennessee	6
Virginia	8
Vermont	1
Wisconsin	2

The survey was designed to discover what furniture manufacturers view as problem areas within the industry. The respondents were asked to prioritize improvement areas within a manufacturing framework using one as the most important area and nine as the least important area. The average priority assigned to each area was calculated and the areas were then ranked according to these average priorities. From these results, as shown in table 1.2, it was determined that manufacturers are most concerned with training programs for employees, scheduling work, machine loading and the determination of the product mix; while the areas that they were least concerned about included purchasing new and automated equipment. A copy of the survey as well as additional results may be found in Appendix A.

By investigating current practices in the furniture industry, it has become apparent that one area in which improvements can be made is that of production scheduling. When production is scheduled in such a manner as to reduce the amount of time required for setups between runs, smaller lots can be run without an inordinate amount of idle time. This would make a demand-driven production cycle practical for wood furniture.

In order to understand why these areas present particularly difficult problems for furniture manufacturers, it is necessary to clearly understand the processes involved in the production of wood furniture.

Table 1.2–Ranking of Problem Areas

Problem Area	Average Priority
Employee Training Programs	3.96
Scheduling of Work	4.13
Machine Loading	4.30
Determination of Mix	4.37
Better Flow of Information	4.71
Standardization of Items	4.74
Coordinating Purchasing with Manufacturing	5.21
Purchasing Automated Equipment	6.23
Purchasing New Equipment	6.50

1.3 Process Definition

Manufacturing wood furniture can be divided into six stages: preparing the order, preparing the lumber, dimensioning the pieces, shaping the pieces into parts, assembling the parts into finished goods, and packaging and shipping the finished goods.

The order preparation stage is the first step in wood furniture production. There are two parts to the order preparation stage. The first part is preparing the cutting order. This consists of taking the order from the customer, determining where on the master production schedule it should be placed, determining the bill of materials and establishing the work center schedules. When the order is placed on the master schedule, its primary attribute is its due date - the date by which it is to be finished in the cabinet room (the assembly operation for furniture plants). Currently, work center schedules are usually determined by backloading from these due dates. Work center schedules are constrained by the processing times for different parts, including changes in speed due to the tenacity of the wood involved. These processing times are usually developed through in-house studies or are established based on the expertise of some foreman or shop-floor supervisor. At this point, the order usually goes to the shop foreman to make sure that there is no problem with using that particular production sequence. It is obvious that the efficiency of the production sequence is dependent on the experience and judgement of the shop foreman and, therefore, the sequence of jobs is not an objective decision. The process of determining the bill of materials is usually a simple matter of retrieving those data from the initial design requirements.

The second part of this stage is procuring supplies. Supplies in the wood furniture industry include the lumber (boards), fasteners, pulls, slides, glass (for mirrors, etc.), glue, finishes, and packing materials. Once the bill of materials is received, the procurement agent checks the on-hand inventory and deducts that from the materials requirement list, providing the data upon which the purchase orders are based. The purchase orders are cut and sent to the appropriate vendors. The vendors return an order confirmation notice which includes a delivery date. If the delivery date is not prior to the date on the work center schedule for the work center which needs those materials to do their work, procurement notifies production control. Production control then, in turn, revises the work center schedule(s).

The next stage in manufacturing furniture is the lumber preparation stage. As soon as green lumber arrives in the lumberyard, it is stacked in a crisscross fashion to allow for maximum air drying. Dried lumber is sent directly to the shop floor. When the lumberyard workers receive their work center schedule, they retrieve the desired type of lumber from the yard and place it in a drying kiln where it is dried to the desired moisture content (if there was green lumber available). The amount of time the lumber is dried and the temperature inside the kiln is determined by the current moisture content of the boards and the desired moisture content of the boards as well as the type of lumber being used. The wood in the kiln is tested after the original estimate of time has passed. If the lumber is dry enough, it is sent on to the next stage. However, if the lumber is not dry enough production control must be notified with an estimated date for all the lumber to be dried, so they may reissue the cutting order and work center schedules with a revised delivery date. The wood that is not at the desired moisture content is left in the kiln and the testing and notification procedure repeated.

At this point, the cutting order has been issued, the supplies have been procured, the lumber has been prepared, and now the process moves to the plant floor. The first section of a furniture mill is called the rough mill. This is where the boards are cut to the rough dimensions the design requires.

The boards are first crosscut to the desired length. This is a common practice in the furniture industry even though research has shown that yield is usually increased if the boards are gang-ripped first, especially in the lower grades of lumber [Gatchell et al., 1983]. When the boards are crosscut, the board is scanned for defects. Then, the crosscut is placed along the edge of the last defect before a large clear area. The second crosscut (if necessary) is placed at the edge of the first defect after the large clear area. Any pieces of lumber which are too small to be used are placed in waste bins.

After the boards are crosscut to the desired length, they are ripped to acquire the desired widths. The blades on a gang-rip saw are set up for the desired widths and the boards are fed through. The edgings (long, narrow pieces which come off the top or bottom of the board) are placed in waste bins. Both the crosscut and rip operations produce sawdust which must be gathered up and removed.

Because wood has defects in a non-standard pattern on its surface, it is difficult to get lumber pieces that are wide enough and long enough to accommodate the dimensions of the design. This necessitates gluing pieces together with smaller width but longer length to create wide, long boards which have a clear surface. Once the boards have been cut to these "pre-glue" sizes, they are separated according to length. Boards of the same length are then sent to a glue-up procedure. In the glue-up procedure, the selector (man or machine) scans the pieces, and selects those pieces which when glued together produce a piece whose width is the closest to the desired width (compared to combinations of other available pieces) without falling short of the required width. These pieces are then glued together and placed in a dryer. After the glue has dried, the boards are trimmed to ensure smooth surfaces at the ends. These boards are called the core pieces. Throughout this process, the number of boards of certain sizes have been counted, and at the end of the shift these counts are returned to production control, so they may adjust the schedule for any delays the rough mill may have encountered.

The fourth stage in the manufacturing of wood furniture is sometimes called the finish machining stage. For the purposes of this research, the machines, workers, and processes which occur between the rough mill and the cabinet room are called the shaping phase. In this stage, the basic shapes are cut out of the glued-up boards. This refers to the external shape as well as any internal pattern which may be engraved in the wood. For these operations, routers, lathes, tenoners, planers, shapers, profiling machines, drills, carving machines, and boring machines among others are used. Since wood is hygroscopic in nature, it is very likely that some pieces may have cracked during the cutting operations. These are placed in waste bins or, if large enough, placed in a scrap lumber pile.

Once the pieces have their basic shapes, the edges are shaped. This may include use of moulders, dovetailers, or mitering machines. Again, sawdust and flawed pieces are disposed of properly. The edged pieces are sanded and inspected. Sanding involves both machine sanding and hand sanding; sanding small notches and intricate detail work is often done by hand even though the less complicated surfaces are sanded by machine. If the piece does not pass a visual inspection, the flaw is marked and, if minor, filled and sent back to a sanding operation. If the flaw is major, the piece is placed in the scrap lumber pile. If any of this group of pieces will be visible during utilization of the final product, but not easily accessible to the staining equipment, then that piece must be stained now. If staining is required, the piece is dried and joins the unstained pieces for entry into the cabinet room.

At this point, all pieces should be ready for assembly (or cabinet room, as the assembly operation is known in the furniture industry). The cabinet room can be broken down into two general areas consisting of the actual assembly and the stain/finish areas. Since this study deals with casegood pieces (bedroom and dining room furniture), the assembly processes described reflect those processes involved in the assembly of the most complicated design in the suite, that of the dresser. In addition, these same processes are used to assemble hutches, chests of drawers and nightstands, while bed headboards and footboards require little assembly other than attaching a few pieces of hardware.

The first step in the cabinet room is the assembly of the furniture's frame. The side pieces are attached to the top piece, creating a U-shape. The shelves are then attached to the sides. The fasteners used thus far depend on the quality level of the furniture. Higher end furniture uses screws, while lower end furniture is assembled with industrial staples. The runners for the drawers are attached to the interior sides of the shelves.

At this point, the piece is set upright on a wooden pallet to facilitate transporting the piece through the remainder of the cabinet room. The frame is attached to the pallet with industrial staples and the pallet is placed on a conveyor system.

The drawers of the dresser (nightstand, chest of drawers) are assembled on another line. The manner in which the sides are joined to the back varies with the company. For example, sometimes the edges of the back and one edge of each of the sides are dovetailed so they will fit together without the use of additional hardware; other times the sides and back are attached using L-shaped brackets inserted into grooves along the bottom edges of the pieceparts. The bottom of the drawer is stapled into place. The drawer fronts are generally attached with a dowel configuration. The slides are attached to the sides of the drawers so they will match the runners on the interior sides of the shelves. The drawer line also uses conveyors to accomplish the transportation through the cabinet room.

The drawers and frames are then incorporated into one line as the drawers are inserted into the frame and stops are affixed to the shelves to prevent the drawers from coming out completely when pulled open. The furniture is inspected and any flaws are marked. If there are flaws, the piece is literally pulled off the assembly line, at which point it is stored in a buffer area until that suite is run again. The flawed pieces are usually not reworked at this point because it may require a single additional piece from the rough mill for the correction, and manufacturers generally do not break down a current setup just to set up and run a single piece; instead they produce more than they actually anticipate selling in order to make sure that the anticipated amount *is* produced even with having to pull some pieces from the assembly line.

Now the pieces of furniture are ready for the staining/finishing operation. Any special effects that the manufacturer wishes to incorporate into the particular suite such as antiquing are usually done at this point. The amount of time the staining operation requires is dependent on the texture of the wood being used. The furniture passes through a stain station where the initial coat is applied. As the piece comes out of the staining station, any runs that may have appeared due to excess stain are rubbed out. The pieces then pass through a dryer and another coat of stain or finish is applied at another stain station. Again the runs are wiped away before they have a chance to dry. The furniture goes through another dryer and is given a high gloss rub-down as it exits the dryer.

The hardware for each piece of furniture such as knobs, pulls, or handles and the accompanying screws, nuts, washers are kitted and placed either within or on top of the piece. These are affixed by hand with any glass parts such as mirrors being the last to be inserted to minimize the possibility of breakage. The furniture is given one final rubdown or wipe-off before it goes through the final inspection station. At this inspection station, a thorough visual inspection of all sides is performed, usually with the aid of mirrors, and problems are again marked. If the piece does not pass inspection, it is pulled off the production line. The piece goes into another buffer storage area where it sits until the suite is run again, at which point, the flawed parts are replaced with newly manufactured parts.

If the piece passes this final inspection it progresses to the packaging and shipping area. The piece is wrapped in packing material and a box is fitted around it. The top of the box is sealed. As the furniture is removed from the pallet it is turned over making the bottom of the box accessible. The bottom of the box is sealed and the packaged piece is then transported to a warehouse or a waiting truck. This process is graphically described using the IDEF[1] [IDEF Manual, 1981] modeling procedure in Appendix B.

1.4 IDEF Representation of Processes

In order to establish the key decision points in the production of wood furniture, it was necessary to represent the production process in such a manner as to make the main decision points obvious. The IDEF modeling procedure provided such a representation. By decomposing functions into six or fewer sub-functions, decision points became evident. In addition, due to the forced limitations imposed on each chart, only related information is shown on any single graph, making the charts easy to understand.

In developing the graphical model of a furniture plant using the IDEF method, each box represents a function. In figure 1.1, it can be seen that each box represents each of the major six stages involved in the production of wood furniture as described above. All arrows entering a box from the left represent inputs and all arrows exiting a box from the right represents an output of the function. As described above, the order preparation stage ultimately produces the supplies, the due date, and the work center schedule. However, to see all the intermittent steps, it is necessary to explode this single

[1] ICAM (Integrated Computer-Aided Manufacturing) Definition

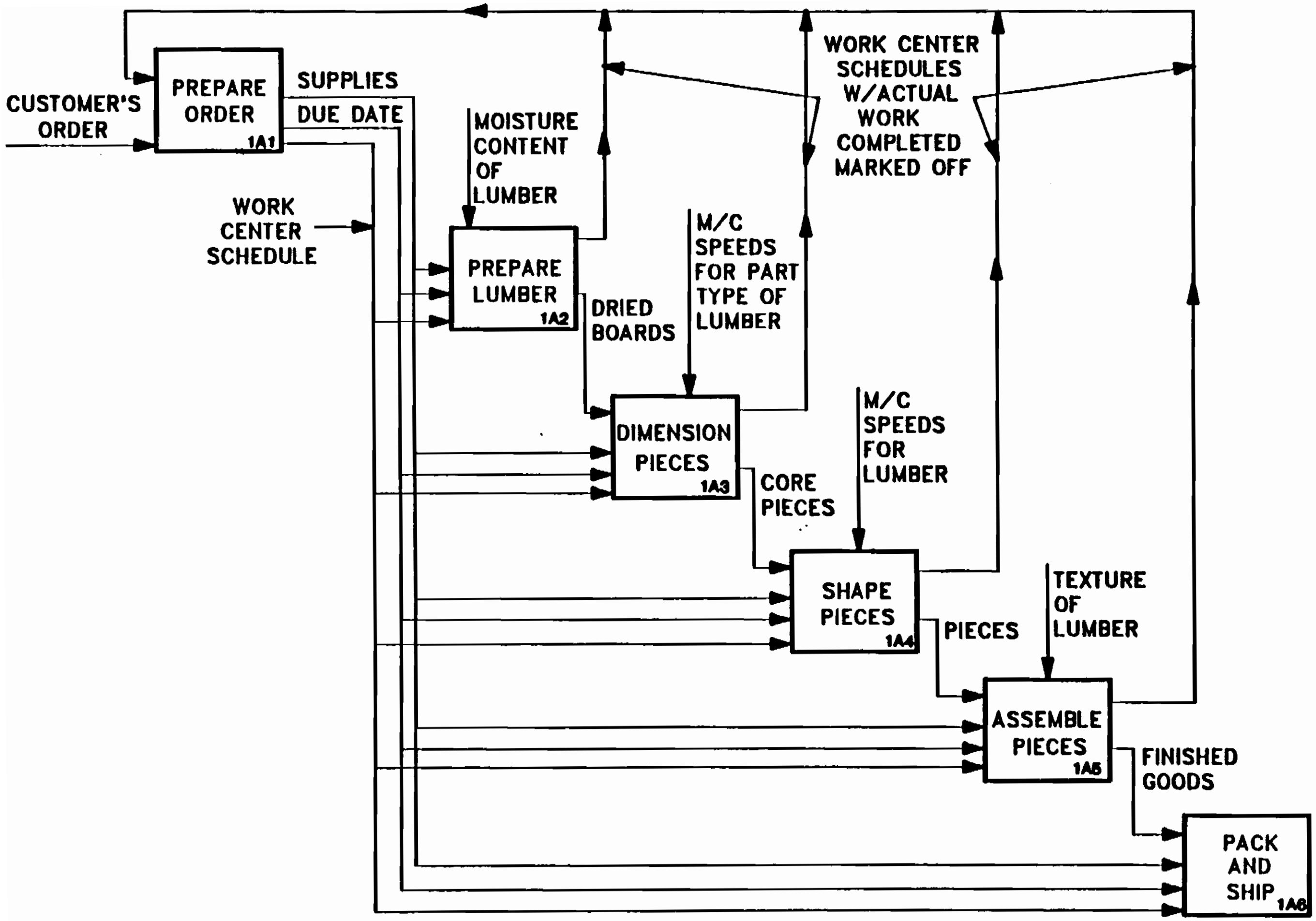


Figure 1.1--Node 1A

box into several smaller boxes. This decompostion is shown in figure 1.2. Each of these boxes in turn, can be decomposed further, hence figures 1.3 and 1.4.

All arrows entering a box from the top represent constraints. For example, in figure 1.1, the moisture content of the lumber is considered a constraint since this will affect how long it will take to prepare the lumber, but it is not a product of some other process. Arrows entering a box from the bottom represent mechanisms or devices needed in the execution of the function which that box represents.

In addition, the IDEF method associates a node index with the entire set of charts by assigning a number to each box within a single chart. For example, figure 1.1 is the overview of the entire process and it is assigned the number 1A. Each box is then numerically ordered and the number assigned to each box is then appended to that of the single chart. Table 1.3 provides the node index for Figures 1.1 - 1.4; the complete node index for the entire process can be found in Appendix C.

It is apparent, when analyzing the IDEF model, that many of the important decisions are made during the order preparation stage. Without this phase, there would be no coordination between customer orders and production. However, the assembly function essentially drives the entire process. As stated before, orders are scheduled by the date they are expected to leave the cabinet room. The order preparation phase needs to know the optimum lot size per furniture group, the processing and setup times associated with a given process, and the best sequence given a set of orders to make an intelligent decision regarding how to schedule orders. With this information, the

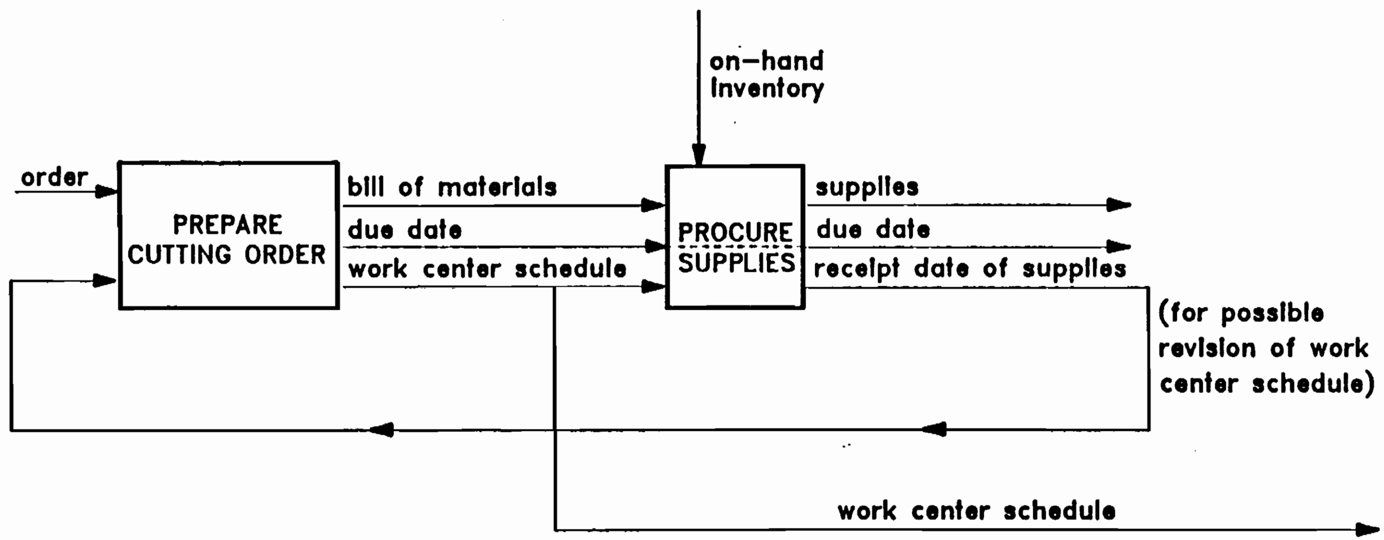


Figure 1.2--Node 1A1

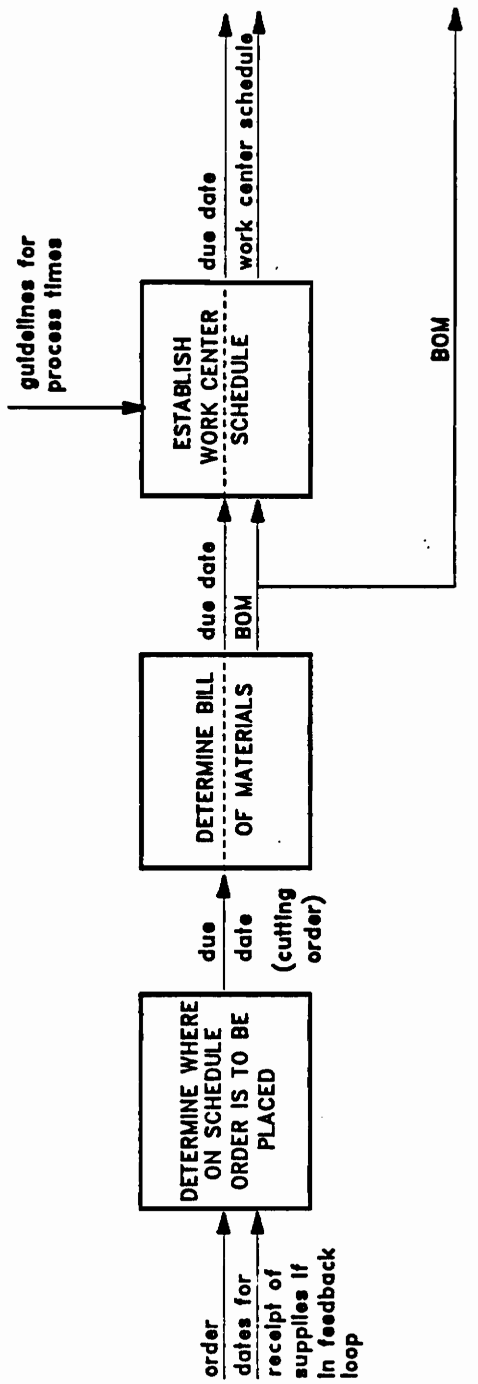


Figure 1.3--Node 1A11

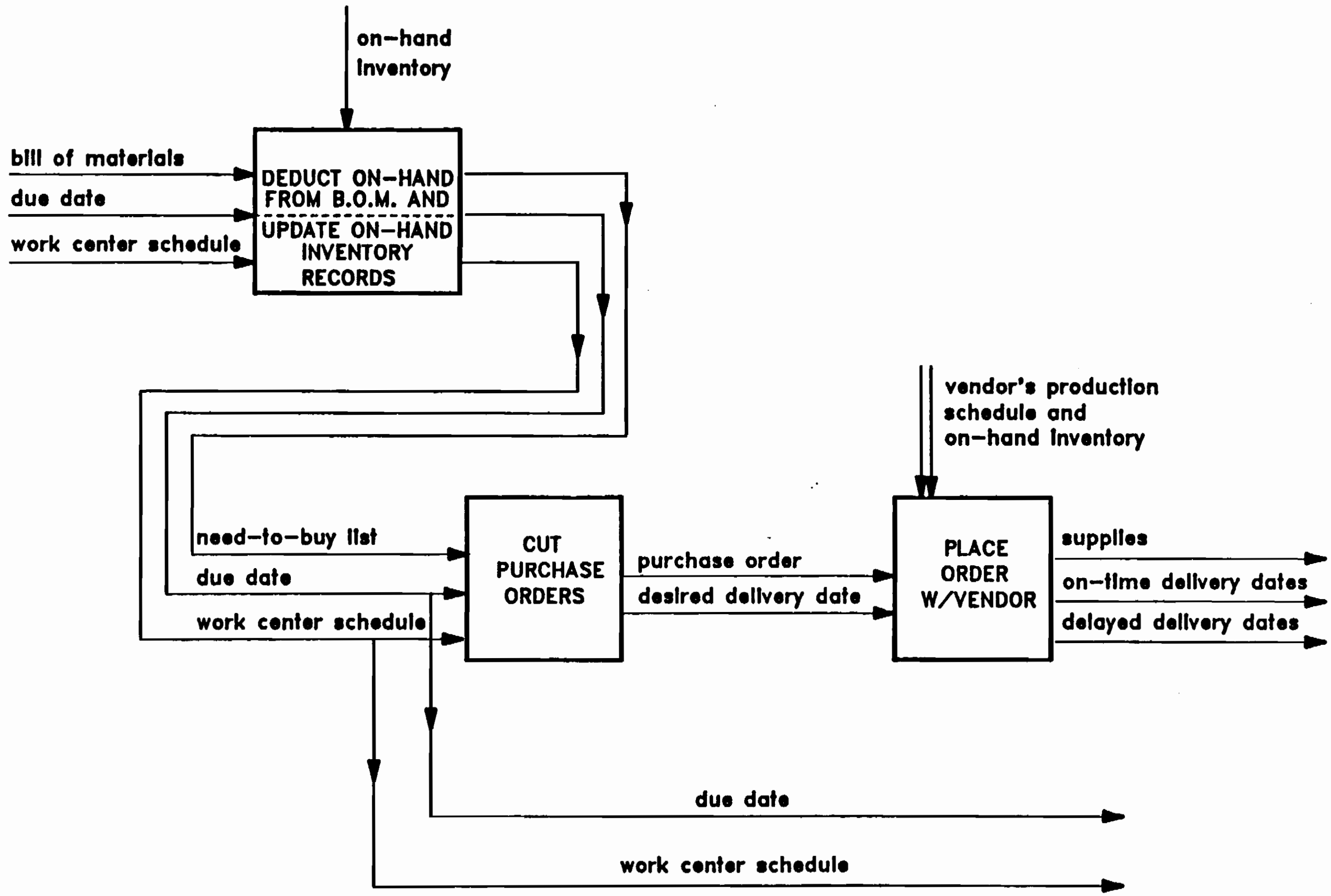


Figure 1.4--Node 1A12

Table 1.3–Node Index for Figures 1.1 thru 1.4

Label	Description
1A.	Overview
1A1.	Prepare order
1A11.	Prepare cutting order
1A111.	Determine where on (master) schedule order is to be placed
1A112.	Determine bill of materials
1A113.	Establish work center schedules
1A12.	Procure supplies
1A121.	Deduct on-hand inventory from bill of materials *and* update on-hand inventory records
1A122.	Cut purchase orders
1A123.	Place order with vendor
1A2.	Prepare lumber
1A3.	Dimension pieces
1A4.	Shape pieces
1A5.	Assemble parts
1A6.	Pack and ship

schedulers can produce a realistic production schedule which minimizes setup time, work-in-process, and finished goods inventory.

1.5 Problem Statement

The problem addressed here is to determine lot-sizes of the products to be manufactured in a multi-stage production facility, and to schedule them on work stations at different stages so as to minimize total cost of production. This problem is approached in two steps. The step one problem concerns determination of lot-sizes while considering sequence dependent setup costs at the critical stages. This is called the aggregate scheduling problem. Step two schedules work at various stages while considering dependent demand, inventory cost and capacity constraints. This is called the detailed scheduling problem.

1.6 Objectives of Research

The purpose of this research is to provide the wood furniture industry with a method for determining optimal lot sizes and optimal scheduling sequences. This involves three major objectives.

The first objective is to formulate a mathematical model for minimizing total cost in a furniture production environment while imposing a scheduling structure upon it. This will be done at an aggregate level as well as a more detailed level.

The second objective is to provide a method for determining the optimal lot size for a production run of casegood furniture. This will reduce work-in-process inventory as well as finished goods inventory thereby contributing to the overall objective of minimizing total cost.

The third objective is to derive a means by which furniture manufacturers may consider common setups when establishing a cutting schedule. This will lead to reduced changeover time and therefore assist in minimizing total cost.

CHAPTER TWO
LITERATURE REVIEW

2.1 Overview

In researching current literature, topics concerning the three objectives of this thesis were reviewed. Information regarding lot-sizing and scheduling in a multi-level facility was available and is presented here. However, a search through the current literature produced no research which had as its primary concern, the utilization of common setup considerations when establishing a production schedule. In addition, each of these topics was further researched to identify prior work in these areas as they pertain to the wood furniture industry. Although several industries have conducted research in this general area, no published work regarding lot-sizing, work sequencing (or scheduling), or considering common setups in the wood furniture industry could be found.

2.2 Lot-Sizing Problems

A review of the literature regarding lot-sizing problems is presented here. These problems have been divided into two categories: multi-level lot-sizing and dynamic lot-sizing. In addition to this review, a summary of a review conducted by Bahl, Ritzman, and Gupta in 1986 is presented.

2.21 Multi-Level Lot-Sizing

R. Kuik and M. Salomon (1990) reviewed a simulated-annealing heuristic for generating a reasonable solution to the multi-level lot-sizing problem such that the sum of set-up and holding costs is minimized. This technique was based upon a stochastic search which allows for disimprovements at some iterations. The quality of the final solution is dependent on the specification of the set of neighboring points, and the effectiveness of the entire technique is determined by the amount of effort required for computing the function value at a given point. From the experiments Kuik and Salomon performed, the method worked rather well and rather quickly for small problems (up to 20 items and 20 planning periods) only. However, larger problems required substantially longer CPU time. Another shortcoming of this technique is the inability to determine how far away from the true optimum is the heuristic's solution. Therefore, despite the similar problem structure in the aggregate model, a different solution methodology is desirable.

E. Steinberg and H. A. Napier (1980) modeled a dependent demand inventory management system as a constrained generalized network with fixed charge arcs and side constraints. This structure attempted to capture the complexity of the interactions of lot-sizing decisions for all components of the system. It also yields optimal decisions for purchasing, inventory, assembly and/or production activities at all levels over a finite planning horizon. The computational effort is completed through a standard mathematical programming package, and the computational time is fairly large, even for those problems considered small in a manufacturing environment. However, the method provides a means by which large problems may be decomposed into smaller problems which the model will handle.

R. Karni and Y. Roll (1982) proposed another heuristic for the multi-item lot-sizing problem under capacity constraints. The method considers setup costs and carrying costs (if the item was produced in a period prior to that in which it was demanded). This method also assumes that all demand must be met and that capacity may not be exceeded. The algorithm presented is comprised of three separate stages. The first stage is an application of the Wagner-Whitin algorithm in which a lower bound feasible solution is derived. The second stage combines adjacent lots in varying proportions to attain any improvements possible on the current incumbent lower-bound. The third stage looks for further improvements by "forcing changes in the structure of the current best solution" (p. 250).

The objective function is the minimization of total cost in this method. By implementing the second stage, in which adjacent lots are combined, the method tries to either eliminate or reduce infeasibility at a minimum cost or reduce the total setup and carrying cost by changing the solution structure. The computer run times for this heuristic are dependent on the size of the problem. However, it appears that for "practical problems of considerable size, run time would not be an obstacle" (p. 254). In addition, the heuristic was compared to an integer programming algorithm. Twenty-eight problems for which the integer programming algorithm had found at least one optimal point were selected for a test group. The heuristic found solutions which gave the same optimal value for the objective function slightly more than fifty percent of the time. Yet, the average deviation from the integer optimal was one percent for the twenty-eight problems.

P. Afentakis and B. Gavish (1986) proposed a method for finding the optimal lot-size for multi-level products by transforming the general product structure into an equivalent, larger assembly system, and reformulating the problem using additional constraints while minimizing total costs. The structure is then subjected to a branch and bound algorithm which uses Lagrangean relaxation and subgradient optimization procedures to attain lower bounds on the solutions. This algorithm is adaptable to a multiple end item system, but the computational results are not as favorable. The largest problem to run to optimality involved 3 end items, 15 stages and 12 periods. This algorithm was based on a more restricted method developed by Afentakis, Gavish and Karmarkar [Afentakis et al., 1984].

2.22 Dynamic Lot-Sizing

P. S. Eisenhut (1975) presented an approach to determining lot sizes for situations where the forecasted requirements fluctuate from period to period and the combined production of several products is limited. The algorithm is based on the rate of change of total cost per period and its objective function is to minimize total costs including setup costs, production costs, and inventory costs while considering those same costs between products as well as within a product. After satisfying the period's required orders, the schedule is then loaded as close to capacity as possible by selecting products by decreasing rates of change of per period cost. Once capacity is filled, or cannot be filled anymore without overflowing, the schedule is updated with new forecasted requirements. One of Eisenhut's concerns was to obtain a solution as nearly optimal as possible without the computations becoming too costly. The increased availability and acceptance of computers has eliminated (to a large extent) this particular restriction.

W. Crowston and M. Wagner (1973) developed two algorithms for computing optimal lot sizes in multi-stage assembly systems (systems in which each facility may have any number of predecessors but at most one successor) with known time-varying demand. The first algorithm employs dynamic programming techniques to uncover solutions where the solution time increases linearly if the number of stages is increased, but exponentially if the number of periods is increased. The second algorithm is based as a branch and bound approach where there are a large number of time periods but the system has a nearly serial structure. The models developed here assumed linear inventory holding costs and concave production costs. The objective of these algorithms is the minimization of all production and inventory holding costs.

2.23 Review Results

The objective of most lot-sizing algorithms is to reduce inventory carrying costs.

These costs are the costs associated with the storage of finished goods as well as the costs associated with work-in-process.

H. Bahl, L. Ritzman and J. Gupta (1986) reviewed current work in the lot-sizing area. Their review focused on medium range decisions with planning horizons of six to eighteen months dividing these problems into four different categories.

1. single-level, unconstrained resources (SLUR)
2. single-level, constrained resources (SLCR)
3. multiple-level, unconstrained resources (MLUR)
4. multiple-level, constrained resources (MLCR)

Due to the fact that the production of wood furniture is a multi-level process and it deals with constrained resources (available lumber, machines, workforce, etc.), the fourth category is the most relevant to the problem investigated here. The results of the review of algorithms dealing with this type of problem are represented in table 2.1. This review covers much of the previous work on which the appproaches discussed in sections 2.21 and 2.22 were based. Upon inspection, it can be seen that no single approach developed thus far excels at each of the critical factors discussed. The interested reader is referred to Appendix D for a summary of their reviews on SLUR, SLCR, and MLUR solving algorithms.

Table 2.1--Selected Research on MLCR Problem

Description of Work	Classification Criteria[a]					Strength	Weakness
	C	G	O	S	T		
Haehling von Lanzenhaeur (1970): Formulates MLCR problem	Poor	Fair	Yes	Fair	N/A	One of first statments of problem	Computationally feasible solution procedure not available. Setups not considered.
Berry (1972); Biggs (1979); Biggs, Goodman and Hardy (1977); and Collier (1980): First simulation studies of SLUR heuristics, lead time and sequencing rules in MLCR environment	Good	Poor	No	Good	Poor	Identifies interactions between rules. Considers SLUR heuristics easily implemented in practice	Limited range of environmental settings
Lambrecht-Vandervecken and Gabbay (1978-1979): Formulation for serial production environment	Poor	Poor	Yes	Poor	N/A	Provides an alternative to current MRP practice	Limited to special product structures
Berry, Vollman and Whybark (1979): Summarizes current MPS practice	N/A	N/A	No	N/A	N/A	Provides richer understanding of real problems	Limted to MPS component of MRP
Billington, McClain and Thomas (1983): Proposes way to compress product structure	Fair	Good	Yes	Fair	N/A	Introduces lead time offsets as decision variables	Solving by mixed integer linear programming limits compressed problem to very small size
Harl and Ritzman (1985): Proposes capacity-sensitive SLUR heuristics to MLCR problem	Good	Good	No	Good	Fair	Easily implemented in current MRP systems	Priority rules remain capacity insensitive

Table 2.1--Selected Research on MLCR Problem (cont'd)

Description of Work	Classification Criteria[a]					Strength	Weakness
	C	G	O	S	T		
Bahl and Ritzman (1983, 1984b): Heuristic procedure for lot sizing and capacity choices with any product structure	Fair	Good	No	Fair	Fair	Identifies environments when coordination between MPS, lower-level lot-sizing, and capacity planning is most crucial	Assumes predetermined lead time offsets and lot-for-lot production at middle levels of BOM
Bitran, Haas and Hax (1983): Two-stage heuristic procedure for making MLCR decisions	Fair	Fair	No	Fair	Fair	Aggregation procedure for simplifying the problem	Limited testing and not generalized for all types of MLCR problems
Bott and Ritzman (1983): Identifies key factors combining with lot sizing to create capacity problems	N/A	Good	No	N/A	N/A	Brings out importance of capacity constraints when lot sizing	Does not propose new methods for making lot-sizing and capacity decisions simultaneously
Krajewski et al. (1982a, b, 1983); Ritzman, King and Krajewski (1984): Compares impact of environmental factors and system choice on performances	N/A	Good	No	N/A	N/A	Widest range of factors studied to date, with settings established by panel of managers	Cannot be generalized for all possible plant settings. Limited to current systems used in practice
Ritzman and Krajewski (1983): Compares MRP and ROP systems	N/A	Good	No	N/A	N/A	Finds MRP's advantage is strongest with more BOM levels and larger lot sizes	Limited testing and restricted to systems currently used in practice

[a]C = computational effort, compared to other MLUR procedures, G - generality to all MLUR problems, O = optimality, S = simplicity in understanding, T = thorough testing, if heuristic

2.3 Scheduling Problems in Multi-stage Production Facilities

C. Haehling von Lanzenauer (1970) developed a model for scheduling production and employment for multi-stage, multi-product production systems. This method involved using Zangwill's model [Zangwill, 1966] and changing some of the attributes. Demands requirements no longer had to be met. Stages were permitted to produce various different products. Workforce decisions were integrated. The cost structure imposed was slightly different from those in Zangwill's model. The model determines the amount of the demand per product that should be satisfied, how much should be backlogged and how much should remain unfilled. It also deals with how the workforce should be assigned to the different production stages. The objective function in this model is to maximize profit.

H. Gabbay (1979) takes a different approach to the scheduling question. He provides an analytic framework for a hierarchical procedure to analyze a multi-stage production planning problem. The paper specifically addresses a linear model with capacity constraints. The primary emphasis is showing when a multi-stage system can be treated as a sequence of single stage problems. In this manner, the author attempts to provide a means by which managers can utilize their aggregate resources effectively and, at the same time, optimize individual item runs on a daily basis.

P. Billington, J. McClain and L. Thomas (1983) developed Product Structure Compression to reduce the problem size of the MRP (Materials Requirement Planning) integer linear program used to model production planning. The method involves scheduling constrained resources first and then scheduling the unconstrained resources. Product Structure Compression appears to be most effective when there are many unconstrained resources. All variables are eliminated except those related to items which have significant setup costs and/or items produced on a constrained facility, as well as those items which share a common sub-assembly. Items with large setup costs must remain in the problem to allow batching. The items produced on a constrained facility are required because their lead times depend on how the limited capacity is allocated. Finally those items which share a common sub-assembly must remain in the problem in order to avoid extreme analytic difficulty.

2.4 Combined Lot-sizing and Sequencing Problem

D. Aras and L. Swanson (1982) proposed an algorithm for sequencing and determining lot sizes for a variety of manufacturing organizations while considering that finite capacities and holding costs for products during the period in which they are produced exist. The authors point out that "consideration of holding cost during the period of production requires the production sequence determination" (p. 178). The problem is constrained by requiring that demand is met and the capacity of the facility is not exceeded. The objective function is to minimize total inventory holding cost. The paper suggests a heuristic approach to this problem which involves back loading the schedule. Basically, the approach involves looking at a subset of the entire set of processes and checking the different sequences of the subset's processes. The sequence with the smallest inventory holding cost is selected and demand satisfaction is checked. If there is unmet demand, this excess demand's production is scheduled for the next earlier period.

CHAPTER THREE
PROBLEM FORMULATION and SOLUTION METHODOLOGY

3.1 Overview

The primary purpose of this research is to develop and validate a method for determining the optimal lot size and sequence for wood furniture production. This method will address the problem of sequence dependent setup times in a manufacturing environment.

In developing any integrated production planning and control system, an effective plan must address a complex network of interrelated systems. Das and Sarin have proposed a method for developing such a plan by disaggregating the problem into different subproblems and then reaggregating them into different levels [Das, Sarin 1989]. Figure 3.1 shows the different levels into which the master aggregate schedule should be disaggregated. In following this plan, it is possible to ignore certain constraints at higher levels because they are addressed in lower levels. The reaggregation automatically implies that these constraints have been adhered to.

The first objective of this research is to develop a mathematical formulation of the minimization of total cost in the production of wood furniture while imposing a scheduling structure upon it. This must be decomposed into two separate problems.

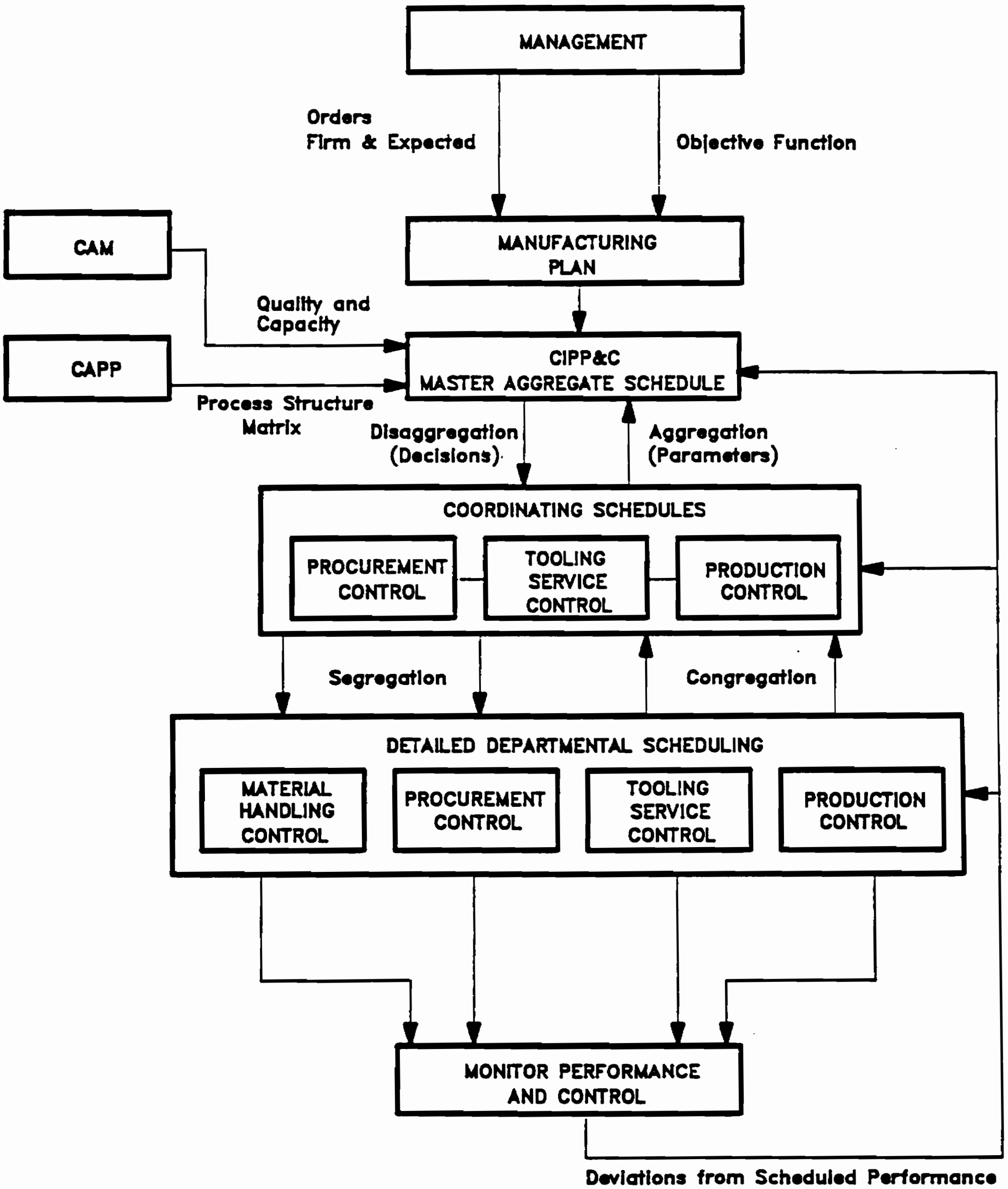


Figure 3.1--Plan for CIPP&C System

The first problem involves scheduling at an aggregate level and the second involves scheduling at a more detailed level. The first model selects the products to be produced and their lot-sizes taking into consideration the sequence dependent setup cost, inventory cost and production cost. These lot-sizes and the sequence in which they are to be produced gives the production sequence for the final stage (cabinet room) of the furniture manufacturing process. The scheduling of production at other stages is then accomplished by the detailed scheduling model using the dependent demand at various stages.

3.2 Aggregate Scheduling Model

In the aggregate sense, the scheduling procedure for the production of wood furniture involves setup costs, inventory costs and production costs as well as the demand for the various items produced. The objective function is to minimize total cost. This objective is constrained by satisfying demand and by imposing a sequencing structure upon the production processes. A mixed integer program was formulated to model this problem and follows:

Let: N = number of products

T = number of time periods in the planning horizon

$$y_{ijt} = \begin{cases} 1, & \text{if product } j \text{ follows product } i \text{ in period } t; \\ 0, & \text{otherwise.} \end{cases}$$

$i = 0,\ldots,N \quad j = 1,\ldots,N \quad t = 1,\ldots,T$

d_{jt} = demand of product j in period t

h_j = inventory cost/unit/period for product j

I_{jt} = amount of product j in inventory in period t

p_{jt} = production cost/unit for product j in period t

s_{ij} = setup requirements for j given that product j follows product i

x_{jt} = amount of product j produced in period t

objective function:

$$\min \sum_{t=1}^{T} \Big[\sum_{i=0}^{N} \sum_{\substack{j=1 \\ j \neq i}}^{N} s_{ij} y_{ijt} + \sum_{j=1}^{N} h_j I_{jt} + \sum_{j=1}^{N} p_{jt} x_{jt} \Big].$$

subject to:

$$I_{jt} + x_{jt} = I_{jt+1} + d_{jt}$$

$t = 1, \ldots, T$ (1)

$$x_{jt} \leq M \cdot \sum_{i=0}^{N} y_{ijt}$$

where M is some large positive number

$j = 1, \ldots, N \quad t = 1, \ldots, T$ (2)

$$\sum_{i=0}^{N} \sum_{t=1}^{T} y_{ijt} \geq 1$$

$j = 1, \ldots, N$ (3)

$$y_{0i1} = \sum_{j=1}^{N} y_{ij2} \qquad i = 1, \ldots, N \qquad (4)$$

$$\sum_{i=1}^{N} y_{ijt} \leq 1 \qquad t = 2, ..., T \quad j = 1, ..., N \qquad (5)$$

$$\sum_{j=1}^{N} y_{ijt} \leq 1 \qquad t = 2, ..., T \quad i = 1, ..., N \qquad (6)$$

$$\sum_{k=1}^{N} y_{kit-1} = \sum_{j=1}^{N} y_{ijt} \qquad t = 2, ..., T \quad i = 1, ..., N \qquad (7)$$

$$y_{ijt} \geq 0 \qquad i = 1, ..., N \quad j = 1, ..., N \quad t = 1, \ldots, T \qquad (8)$$

The first constraint (1) ensures that sufficient quantities are produced in order to meet demand. This is followed by (2) which guarantees that a product is not produced unless production for that item is scheduled. (3) allows multiple runs of a single product while (4) provides a means to start the production sequence. Each scheduled item is allowed a maximum of one immediate predecessor and a maximum of one immediate successor in the production schedule. This is enforced in constraints (5) and (6). The schedule's linking constraint, (7), maintains the order of the schedule.

3.3 Detailed Scheduling Model

The above model determines lot-sizes and sequences them at the last stage of production (the cabinet room). Next, detailed scheduling is done to produce the selected items and the quantities at various stages. The model now considers the different stages a product must go through during its production. Capacity constraints are added in terms of resource requirements and workforce requirements. In addition, costs are now expanded to include penalties incurred through backordering and shortages as well as workforce cost. This formulation is largely based on that presented by von Lanzenauer (1970). Lanzenauer's formulation was modified to provide improved constraints regarding the workforce requirement. An additional workforce cost was introduced in order to obtain the cost of idle employees as well as productive employees.

Let: N = number of products

T = number of time periods in the planning horizon

K = number of stages

x^r_{ijt} = amount of product i produced during regular time in stage j at time t

x^o_{ijt} = amount of product i produced during overtime in stage j at time t

g_{ikt} = Selling price of product i at stage k in period t

D_{iKt} = Demand for completed (at stage K) product i during period t.

This is obtained as a result of the aggregate scheduling model (d_{it}).

B_{iKt} = the backorders of item i in period t at stage K

S_{iKt} = the shortages of item i in period t at stage K

I_{ijt} = the amount of inventory of product i at stage j during period t

a_{ijlk} = number of units of stage j's product i required to produce one unit of stage k's ($k = j + 1, j + 2, \ldots, K$) product l

p_{ij} = time required to produce a unit of product i at stage j during period t

R_{jt} = available regular time at stage j in period t

O_{jt} = available overtime at stage j in period t

q_{ij} = maximum number of units of product i produced by a worker at stage j during a period t[1]

W_t = workforce in period t

w_{jt} = workforce at stage j in period t

H_t = number of workers hired in period t

F_t = number of workers fired in period t

c_{ijt} = material cost of product i at stage j in period t

h_{ij} = inventory cost/unit of product i at stage j

---

[1] Includes overtime production and $q_{ij} > 0$

b_{ij} = backorder cost per unit of product i at stage j

s_{ij} = shortage cost per unit of product i at stage j

z_{ij} = regular pay for producing one unit of product i at stage j

z = average pay for one worker per period

α = factor for overtime

u = hiring cost per person

v = firing cost per person

$i = 1, ..., N$

$j = 1, ..., K$

$t = 1, ..., T$

objective function:

max

$$\sum_{t=1}^{T} \sum_{i=1}^{N} g_{iKt}(D_{iKt} - S_{iKt}) \tag{9a}$$

$$-\sum_{t=1}^{T} \sum_{j=1}^{K} \sum_{i=1}^{N} c_{ijt}(x^{r}_{ijt} + x^{o}_{ijt}) \tag{9b}$$

$$-\sum_{t=1}^{T} \sum_{j=1}^{K} \sum_{i=1}^{N} h_{ij} \frac{1}{2}(I_{ijt} + I_{i,j,t-1}) \tag{9c}$$

$$-\sum_{t=1}^{T}\sum_{i=1}^{N}(b_{iK}B_{iKt}+s_{iK}S_{iKt})$$

(9d)

$$-\sum_{t=1}^{T}\sum_{j=1}^{K}\sum_{i=1}^{N}[\frac{1}{q_{ij}}(z_{ij}(x_{ijt}^{r})+z_{ij}(1+\alpha)(x_{ijt}^{o}))]-\sum_{t=1}^{T}(uH_t+vF_t)$$

(9e)

$$-\sum_{t=1}^{T}\sum_{j=1}^{K}z(w_{jt}-\sum_{i=1}^{N}\frac{1}{q_{ij}}[x_{ijt}^{r}+x_{ijt}^{o}])$$

(9f)

subject to:

$$I_{i,j,t-1}+x_{ijt}^{r}+x_{ijt}^{o}=I_{ijt}+\sum_{l=1}^{N}a_{ijlk}(x_{lkt}^{r}+x_{lkt}^{o})$$

$$i=1,...,N \quad t=1,...,T$$
$$j=1,...K\text{-}1 \quad k = j\text{+}1 \quad (10)$$

$$I_{i,K,t-1}+x_{iKt}^{r}+x_{iKt}^{o}=I_{iKt}+D_{iKt}$$
$$i=1,...,N \quad t=1,...,T \quad (11)$$

or

$$I_{i,K,t-1}-B_{i,K,t-1}+x_{iKt}^{r}+x_{iKt}^{o}=I_{iKt}-B_{iKt}+D_{iKt}-S_{iKt}$$
$$i=1,...,N \quad t=1,...,T \quad (12)$$

$$\sum_{i=1}^{N}p_{ij}x_{ijt}^{r}\le R_{jt}$$

$$j=1,...,K \quad t=1,...,T \quad (13)$$

$$\sum_{i=1}^{N} p_{ij} x_{ijt}^{o} \leq O_{jt}$$

$$j = 1, ..., K \quad t = 1, ..., T \quad (14)$$

$$w_{jt} \geq \sum_{i=1}^{N} \frac{1}{q_{ij}} (x_{ijt}^{r} + x_{ijt}^{o})$$

$$t = 1, ..., T \quad j = 1, ..., K \quad (15)$$

$$W_t = \sum_{j=1}^{K} w_{jt}$$

$$t = 1, \ldots, T \quad (16)$$

$$W_t - W_{t-1} = H_t - F_t$$

$$t = 1, \ldots, T \quad (17)$$

$$z = \frac{\sum_{j=1}^{K} \sum_{i=1}^{N} z_{ij} q_{ij}}{K * N}$$

$$(18)$$

$$S_{iKt} \geq 0$$

$$t = 1, ..., T \quad i = 1, ..., N \quad (19)$$

$$x^{r}_{ijt} \geq 0 \qquad i = 1,...,N \quad j = 1,...,K \quad t = 1,\ldots,T \tag{20}$$

$$x^{o}_{ijt} \geq 0 \qquad i = 1,...,N \quad j = 1,...,K \quad t = 1,\ldots,T \tag{21}$$

$$I_{ijt} \geq 0 \qquad i = 1,...,N \quad j = 1,...,K \quad t = 0,\ldots,T \tag{22}$$

$$B_{ikt} \geq 0 \qquad i = 1,...,N \quad t = 1,...,T \tag{23}$$

$$p_{ij} \geq 0 \qquad i = 1,...,N \quad j = 1,...,K \tag{24}$$

$$q_{ij} \geq 0 \qquad i = 1,...,N \quad j = 1,...,K \tag{25}$$

$$w_{jt} \geq 0 \qquad j = 1,...,K \quad t = 1,...,T \tag{26}$$

$$W_0 \geq 0 \tag{27}$$

The objective function represents maximizing the difference between revenue and cost. The first step of the objective function (9a) represents the revenue generated through sales. Since stage K is the final stage, g_{iKt} is the selling price of the assembled product. The subscript t may be dropped if the price is not going to change within the planning horizon.

(9b) represents the material costs due to additional material used at each stage. Again, the subscript t may be dropped if costs of materials remain constant throughout the planning horizon. Inventory costs are included in part (9c) of the objective function. These costs are based on the average inventory of period t. Backordering and shortage costs are described in (9d).

The workforce cost is divided into 2 separate costs-that of the productive workforce (9e) and that of the idle workforce (9f). Without a cost for the idle workforce, the model never fires any employees, it simply ignores paying them.

The first constraint (10) ensures that production at the next subsequent stage does not exceed that for which there are sufficient parts being supplied by the current stage either by production during the current period or from inventory at the current stage.Constraints (11) and (12) would not appear in the same program. If they do, (11) dominates (12). These are the constraints which ensure that demand is met in the case of (11), or determines how nearly demand can be met in the case of (12).

(13) and (14) enforce available time limits. Regular time cannot be exceeded by (13), and (14) restricts the use of overtime. (15) guarantees that production cannot exceed the current workforce's ultimate output, and (16) keeps track of the current workforce,

thereby ensuring that the penalties for hiring and firing employees are activated in the objective function when appropriate.

The remaining constraints were developed for ease of computations and to enforce "common sense" on the sign of certain variables.

3.4 Solution Methodology

3.41 Aggregate Scheduling Model

The aggregate scheduling model presented above is a mixed integer program. It can be solved using a branch and bound based method as well as a dynamic programming based method. Here, we develop a procedure based on the dynamic programming approach. The dynamic programming based approach uses the following well-known result from [Wagner and Whitin, 1958].

Result

If production is scheduled in period t_1 for the demand of period t_2 ($t_2 > t_1$), then the quantity produced in period t_1 covers the whole of demand of period t_2. In other words, it is not optimal to cover only a partial demand of a period (t_2) by scheduling production in period t_1 ($\leq t_2$). With this in mind, the dynamic programming model can be given as follows:

$$f_t(i, s_t) = min_{j \in (s_t \cup \phi)}[S_{ij} + I_i + f_{t-1}(j, s_t - \{j\})]$$

$$t = T\text{-}1, T\text{-}2, \ldots, 1$$

$$f_T(i, \phi) = 0$$

$$\forall \; i$$

where s_t = a subset of demands occurring from periods $t+1$ to T, and $s_{t-1} = s_t - \{j\}$. I_i includes the cost of production plus inventory for future demand. If product i is scheduled for production in period t then the amount produced covers all the demand until the product i is produced again in s_t. If a product does not appear in s_t then the amount to be produced in period t will cover all the demand of product i from periods t through T. The subscript t represents the period under consideration. The product i that is scheduled for production in period t can be the product demanded in period t or any product in set s_t. The minimization is over the set $(s_t \cup \phi)$ because an option of not scheduling any production in period t is also permitted. Similarly, i can also be ϕ. $f_t(i, s_t)$ represents the total cost of setup, inventory and production, if the product i is scheduled followed by product j in period t. Note that if for an $i \neq \phi, j = \phi$, then the setup cost is considered with respect to the first non-zero entry in s_t. Next we demonstrate an application of this recursive equation on an example problem.

3.411 Example of Dynamic Programming Formulation

A problem consisting of 3 products and 9 time periods was selected to demonstrate the dynamic programming methodology described above. Each time period consists of four weeks.

The products, Product 1, Product 2, and Product 3, have the following setup costs ($S_{0j}, j = 1, ..., 3$) if they are the initial item in the sequence:

Product 1: \$725.00

Product 2: \$695.00

Product 3: \$800.00

These costs are the setup costs incurred throughout the entire facility. The remaining setup costs ($S_{ij}, i = 1, ..., 3, j = 1, ..., 3$) are the costs associated with changing from one product, product i, to the next, product j. These costs are shown in Table 3.1.

For this example, production costs remain constant over the 36 weeks. This implies that the production costs will be the same for a specified number of units of a product whether the total is made in two batches or one. Therefore, the production costs may be ignored since shortages are not allowed, and setup and inventory costs are the only costs which need to be considered. Inventory carrying costs for the three products are:

Product 1: \$4.50/piece/period

Product 2: \$3.75/piece/period

Product 3: \$5.00/piece/period

The demand data is shown in Table 3.2. A quick look reveals that there is no demand for any of the products in periods 4 and 6. Product 1 is demanded in periods 1, 5, and 8. Product 2 is demanded in periods 2 and 7, and Product 3 is demanded in periods 3 and 9.

A FORTRAN computer program was developed to execute the dynamic program and a flow chart describing the logic of the program is included in Appendix E. At the first iteration, the problem begins with period 9. The first step is to check if this is the only period in the planning horizon. In this case, it is obviously not the only period. The Do-Nothing option is checked and determined to be feasible. At this point the two possible schedules are $\{3\}$ and $\{\phi\}$.

At the next iteration, the first schedule, $\{3\}$ is used to build a stream of possible sequences. The checks are perfomed, and it is determined that these options are posible: $\{\phi, 3\}, \{1, 3\}$. The second schedule from the first iteration, $\{\phi\}$, is also expanded to provide the alternate stream of $\{\phi, \phi\}, \{3, \phi\}, \{1, \phi\}$. These are feasible options since due dates will be met as long as production occurs before or during the period of demand. There is sufficient time prior to the current period in which production may take place. Now there are five distinct possibilities for the production schedule.

Table 3.1–Costs for setup if item j follows item i.
(in dollars)

i	j 1	2	3
1	0	895	575
2	695	0	700
3	800	650	0

Table 3.2–Product demand

Period	Product	Quantity Demanded
1	1	100
2	2	150
3	3	100
4	-	---
5	1	150
6	-	---
7	2	100
8	1	150
9	3	100

There are two schedules with the first non-zero element as a three, $\{\phi, 3\}$ and $\{3, \phi\}$. These two schedules are gathered for possible comparison. The quantity produced of each item in the two schedules is the same; therefore, the one with the lower cost will be retained since it will always be a more desirable option when this decision point is reached. The schedule $\{\phi, 3\}$ has no inventory cost and a setup cost of \$800.00. The schedule $\{3, \phi\}$ has an inventory cost of \$5.00/piece/period times 1 period times 100 pieces for a cost of \$500.00. The setup cost is \$800.00. The total cost for $\{\phi, 3\}$ is \$800.00 and the total cost for $\{3, \phi\}$ is \$1300.00. Therefore, $\{3, \phi\}$ is eliminated from the set of possible schedules.

Schedules $\{1, 3\}$ and $\{1, \phi\}$ are gathered as having the same first non-zero element. However, costs are not compared since the production of the two schedules is not the same.

Therefore, the following four schedules proceed to the next iteration: $\{\phi, 3\}$, $\{1, 3\}$, $\{\phi, \phi\}$, $\{1, \phi\}$.

At the third iteration, $\{\phi, 3\}$ is expanded to: $\{\phi, \phi, 3\}$, $\{1, \phi, 3\}$, and $\{2, \phi, 3\}$. $\{1, 3\}$ generates the possible schedules $\{\phi, 1, 3\}$ and $\{2, 1, 3\}$, while $\{\phi, \phi\}$ gives $\{1, \phi, \phi\}$, $\{2, \phi, \phi\}$, $\{3, \phi, \phi\}$ and $\{\phi, \phi, \phi\}$. The fourth 2-element schedule produces $\{\phi, 1, \phi\}$, $\{2, 1, \phi\}$ and $\{3, 1, \phi\}$.

The schedules were gathered according to the first non-zero elements:

Group 1 $\{1, \phi, 3\}$

$\{1, \phi \phi\}$

$\{\phi, 1, \phi\}$

$\{\phi, 1, 3\}$

Group 2 $\{2, \phi, 3\}$

$\{2, 1, 3\}$

$\{2, \phi, \phi\}$

$\{2, 1, \phi\}$

Group 3 $\{\phi, \phi, 3\}$

$\{3, \phi, \phi\}$

$\{3, 1, \phi\}$

Group 4 $\{\phi, \phi, \phi\}$

Comparable sets are $\{1, \phi, 3\}$ and $\{\phi, 1, 3\}$; $\{1, \phi, \phi\}$ and $\{\phi, 1, \phi\}$; and $\{\phi, \phi, 3\}$ and $\{3, \phi, \phi\}$. Costs of those schedules with like production within each group are then calculated. From the complete set of twelve possible sequences, nine continue to the next iteration where the process is repeated. Those schedules which continue are $\{\phi, \phi, \phi\}, \{\phi, 1, \phi\}, \{\phi, 1, 3\}, \{2, \phi, \phi\}, \{2, 1, \phi\}, \{2, 1, 3\}, \{2, \phi, 3\}, \{\phi, \phi, 3\}$, and $\{3, 1, \phi\}$.

This procedure is recursively executed until the first period is reached. This is graphically depicted in Appendix F. At that point only the schedule with the lowest cost manages to survive. The solution to the example is:

Produce 100 units of product 1 in period 1.

Produce 150 units of product 2 in period 2.

Produce 100 units of product 3 in period 3.

Produce 150 units of product 1 in period 5.

Produce 100 units of product 2 in period 7.

Produce 150 units of product 1 in period 8.

Produce 100 units of product 3 in period 9.

3.42 Detailed Scheduling Model

The detailed scheduling model may be solved using a commercial linear programming software package. The package used in this research is LP87, which was developed by Eastern Software Products, Inc.

The program finds the values for the amounts produced during regular time and overtime, shortages, workforce size, number of employees hired and number of employees fired which optimize the objective function. The solution to the linear program also indicates the periods in which products should be produced and how the workforce should be divided among the different production stages during a given period.

CHAPTER FOUR
APPLICATION of the METHODOLOGY to a REAL LIFE PROBLEM

4.1 Overview

The three objectives of this research were to develop models for minimizing total cost, provide a way to determine lot-sizes and a way to consider common setups when establishing a cutting schedule.

The experimentation of the methodology developed was performed on survey generated data and on data provided by Pulaski Furniture Corporation. Information from the survey was used to generate the data required for testing the aggregate math model. Responses were weighted and averaged in order to create acceptable order sizes and setup/changeover costs. Inventory carrying costs were developed as the loss of interest on invested monies. This data was confirmed as being representative of small casegood furniture firms by researchers at the USDA Forest Service's Forestry Sciences Laboratory in Princeton, WV, and by plant managers currently employed in the wood furniture industry.

Detailed data was provided by Pulaski Furniture Corporation. The data included production costs, production time requirements, workforce size, materials required and material costs.

4.2 Minimizing Total Cost

As stated previously, the first objective of this research was to formulate a mathematical model for minimizing total cost in a wood furniture production environment while imposing a scheduling structure upon it. The dynamic programming model addresses this issue in an aggregate sense, and the linear programming model addresses this issue at a more detailed level.

4.21 Aggregate Model

4.211 Computer Software

A FORTRAN computer program was developed to implement the dynamic programming algorithm of the aggregate model. The program asks for the following inputs:

1. Number of products to schedule
2. Number of time periods in the planning horizon
3. Setup costs (initial and sequence dependent)
4. Inventory carrying costs for each product per unit per period
5. Length of time period
6. Product demanded at the end of each period and the quantity demanded

The program looks at the different combinations of possible schedules, and through comparisons, selects the single schedule with the lowest total cost. In this case, the costs are setup costs and inventory carrying costs. Since this is a dynamic programming application, the solution time grows proportionally to the number of stages.

The data used for testing this model was generated from survey responses and is given in Appendix G. Based on conversations with researchers and industry personnel, the average hourly wage rate, including benefits, was estimated to be seven dollars per hour. The main difference between the generated data and an actual production schedule is that during actual production, more than one order is processed during the span of one period. As the main objective of this model is to determine the best sequence in which to the orders, this is not a restriction actually. According to the survey responses, two to six weeks are usually required to process an order. Therefore, a four week time period was used. A single product was produced during the four weeks from start to finish in order to limit the amount of storage required for program execution. By concentrating on a few single products, it was easier to determine trends regarding the lot-size/demand-cycle/inventory carrying relationship. A sample data set is given in Tables 4.1 - 4.3.

4.212 Heuristic

A modified version of the program was developed as an heuristic in order to reduce solution time, and to increase the size of the problem the computer is able to handle. This heuristic eliminated possible combinations by discarding those schedules in which inventory is held for more than sixteen weeks.

Table 4.1 Sample demand schedule

Period	Product demanded	Quantity demanded
1	3	125
2	1	150
3	6	50
4	3	75
5	10	50
6	2	200
7	0	0
8	10	50
9	7	75
10	8	110
11	6	90
12	0	0
13	9	200
14	10	50
15	9	100
16	2	124
17	7	120

Table 4.2 Sample inventory carrying costs

Product	Inventory carrying cost (per unit/4 week)
1	5.00
2	4.25
3	7.20
4	5.50
5	7.10
6	4.20
7	2.50
8	3.20
9	4.10
10	8.90

Table 4.3 Sample setup costs (in dollars)

Preceding	Succeeding product										
product	0	1	2	3	4	5	6	7	8	9	10
0	0	795	620	1050	1100	895	925	500	575	690	1400
1	0	0	700	800	900	1000	1100	400	500	600	970
2	0	995	0	900	1000	925	850	1100	700	720	1200
3	0	720	600	0	650	700	650	625	600	550	800
4	0	845	800	820	0	840	780	760	900	700	1200
5	0	520	1050	500	970	0	1200	400	900	850	1040
6	0	600	200	1400	850	1200	0	500	975	1075	1000
7	0	700	725	800	725	600	725	0	1000	400	500
8	0	750	750	750	890	430	1000	1050	0	700	600
9	0	500	525	725	925	1000	800	700	870	0	1050
10	0	1040	1200	1000	500	800	600	1200	1050	970	0

Both the optimizing program and the heuristic utilized dynamic programming techniques to compare possible solutions at each iteration. For the original program, the number of possible schedules becomes very large very quickly. For example, in one instance involving ten products and thirty time periods, the number of possible schedules grew to over ten thousand for the original program. However, the heuristic had to deal with one hundred twenty-six possible sequences at the most congested iteration.

4.22 Detailed Scheduling Model

As mentioned earlier, a linear programming software package, LP87, developed by Eastern Software Products, Inc., was used to solve the detailed scheduling model. Data for this model was supplied by Pulaski Furniture Corporation.

The linear program's solution ensures that capacity is not exceeded, and that demand will be met as nearly as possible. The results from the aggregate model provide the target schedule for the detailed model, and the program provides information on workforce size as well as production scheduling.

4.221 Determining the Production Schedule

The linear program determines the quantity of a specific product to be made at a specific stage during a specific period, such that the objective function is optimized. The results provide managers with production quantities they can reasonably expect from their workforce if the data they input is correct. The program is designed to ensure that production will be adequate to meet due dates if economically feasible. The program also indicates the quantites which are produced during regular time as well as during overtime. The amount produced during overtime production directly affects total costs, thus making the integration of the production schedule with the workforce schedule imperative.

4.222 Determining Workforce Requirements

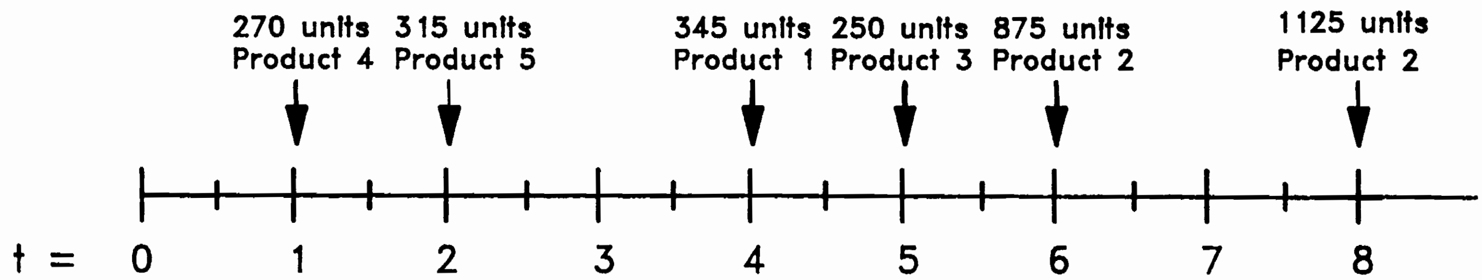
The linear program determines the optimum number of workers at each stage during a given period. Aside from the volume of business the plant does, the number of workers is affected by the increased wage rate that results when an employee works overtime. This must be weighed against the cost of hiring an additional employee and paying them regular wages in addition to the workforce cost already incurred. Conversely, the cost of firing an employee may be smaller than paying an employee to be idle over a period of time.

4.223 Data

Pulaski Furniture Corporation, a firm which produces occasional furniture (curios, hall trees, etc.), supplied data which was used to test the linear program for validity. Since occasional furniture requires fewer raw materials and less time to produce, the costs associated with this data were smaller than those seen in the aggregate casegood runs. Pulaski Furniture was unable to supply the information needed for the aggregate model, providing, instead, their own aggregate production schedule. This schedule was used in the same manner as the aggregate model's output would be used and is shown in Figure 4.1. Information regarding the manufacture of three different products was provided. The manufacturing process was decomposed into six different stages (Figures 4.2 - 4.4).

Due to the fact that there was such a limited amount of information, it was determined that the entire planning horizon would consist of a single work week (4 days). The time periods consisted of 4 hours each. The aggregate production schedule indicated 5 different items were to be produced during the 8 time periods. Three of these items were very similar to those described in Figures 4.2 - 4.4. Therefore, data for the three shown products was used and data for the remaining two products was estimated based on size descriptions.

Also, information was not available for the time requirements at various machines or machining centers. However, a total time was supplied for each stage. Therefore, it was not feasible to link machining centers in the dependent demand constraints, only stages.



Product 1 – 11608 Curio
Product 2 – 11945 Curio
Product 3 – 11944 Curio
Product 4 – 3420 Hall Tree
Product 5 – 4945 Console

Figure 4.1 Time line for aggregate schedule

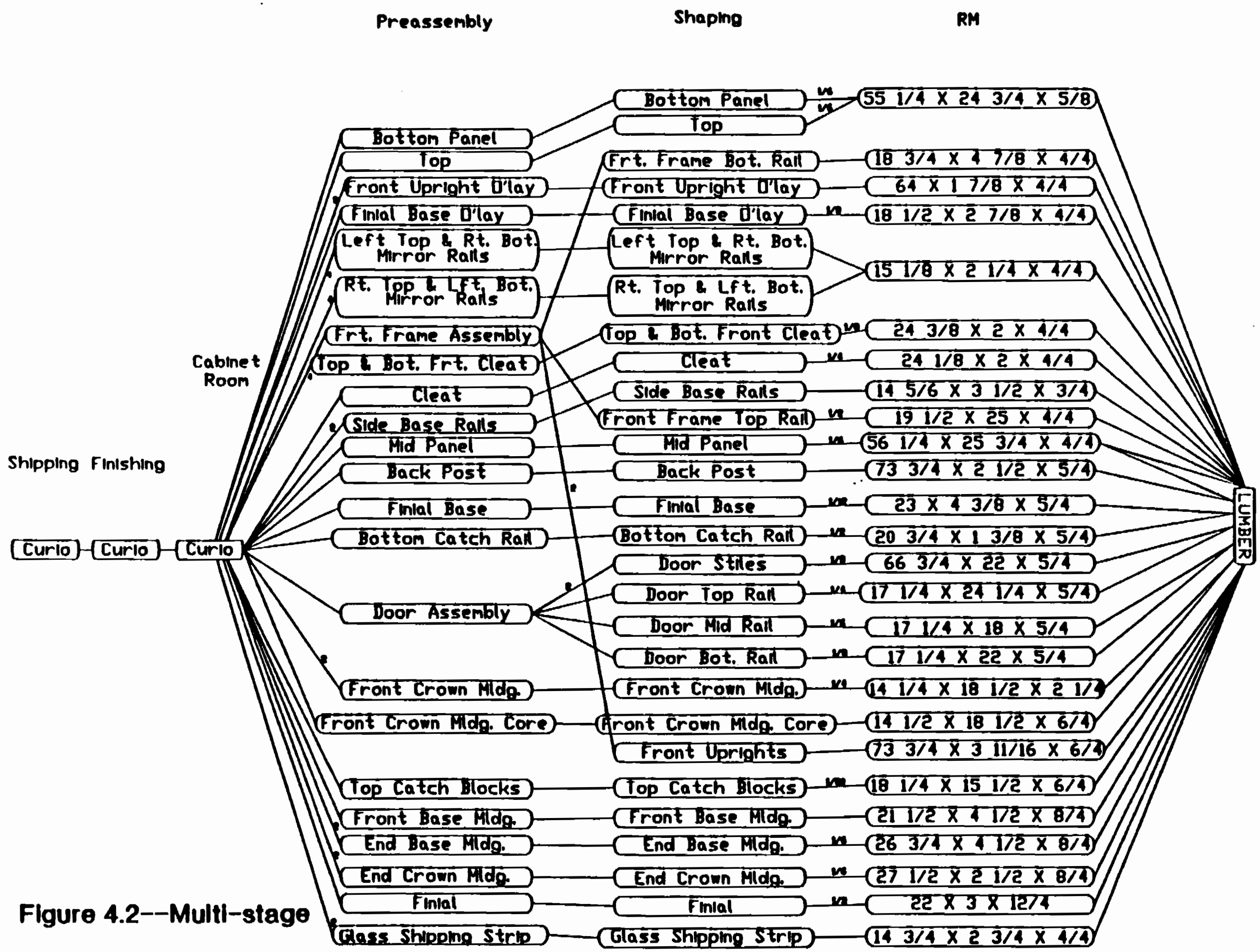


Figure 4.2--Multi-stage decomposition of curio 11608

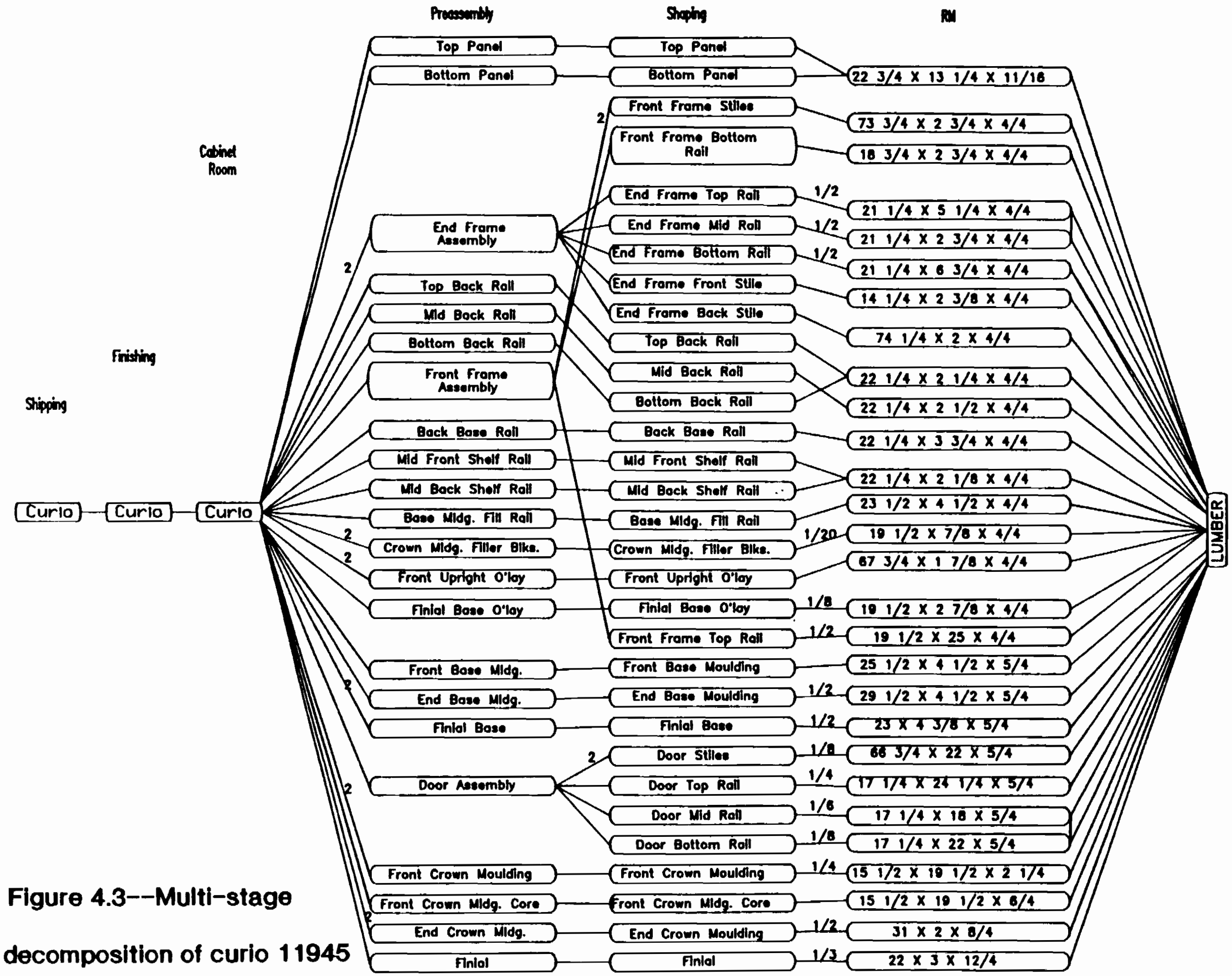


Figure 4.3--Multi-stage decomposition of curio 11945

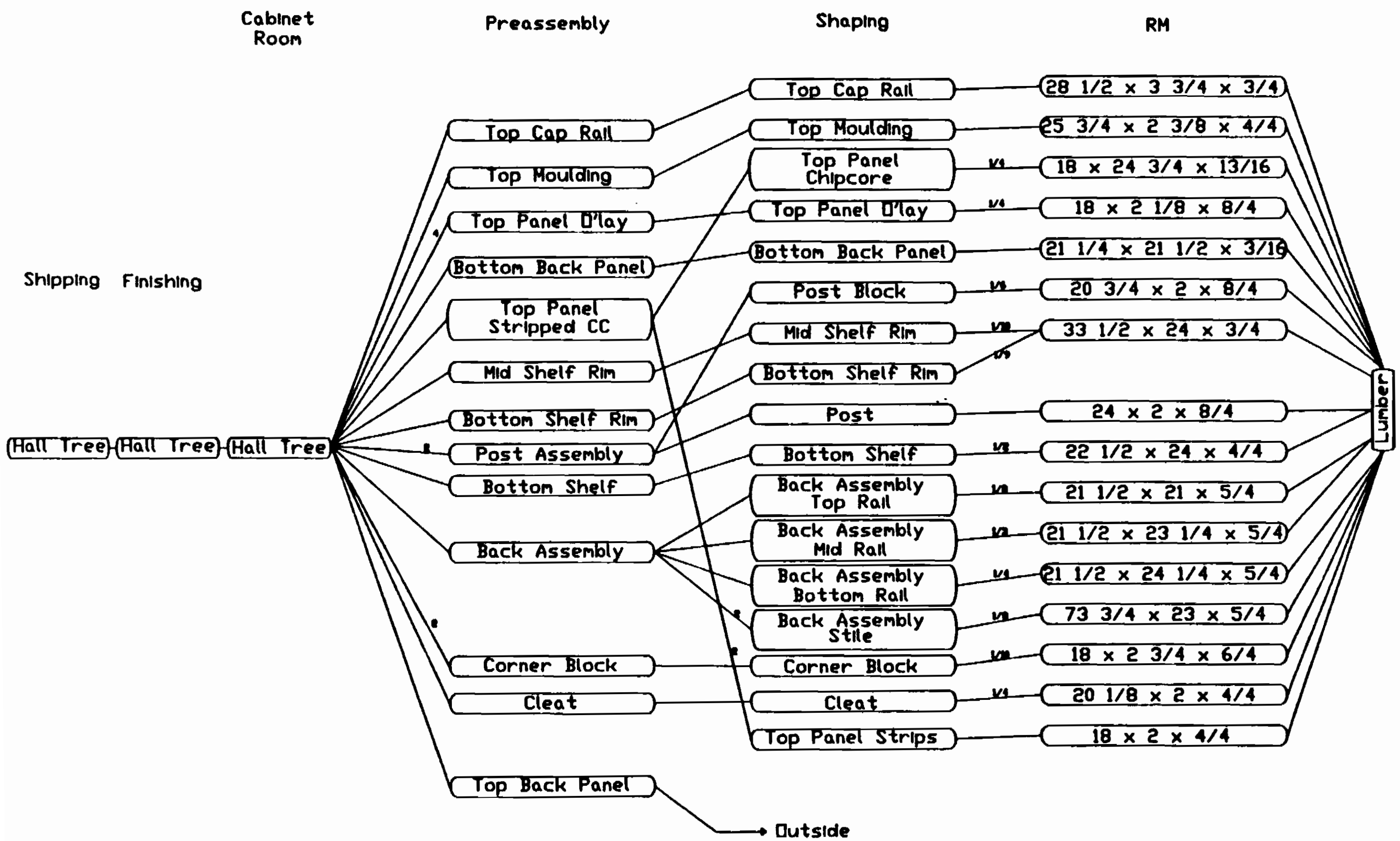


Figure 4.4--Multi-stage decomposition of hall tree 3420

The detailed scheduling model was applied to the following data:

Five products will be scheduled for eight 4-hour time periods. Each product must proceed through six stages, the rough mill, the shaping, preassembly, cabinet room, finishing and shipping. The initial workforce at each stage is 51 employees in the rough mill (stage 1), 122 employees in shaping (stage 2), 16 employees in preassembly (stage 3), 46 employees in the cabinet room (stage 4), 121 employees in finishing (stage 5) and 15 employees in shipping (stage 6). The penalty for hiring an employee is \$800.00 and the penalty for firing an employee is \$1500.00. The selling prices are \$219.84, \$231.15, \$256.63, \$174.69, and \$199.20 for products 1 - 5 respectively. Shortage penalties for the five products are \$440.00, \$463.00, \$515.00, \$350.00, and \$400.00.

Data for material costs are presented next. The notation is the same as that described in Chapter Three; c_{ij} is the cost of additional material used at stage j for product i(in dollars).

	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$
$j = 1$	27.67	30.44	36.53	21.00	27.50
$j = 2$	0.00	0.00	0.00	0.00	0.00
$j = 3$	1.56	1.57	2.06	1.67	1.25
$j = 4$	6.73	7.40	8.88	7.02	6.10
$j = 5$	31.54	34.69	41.63	25.82	30.89
$j = 6$	12.25	13.48	16.18	11.65	10.91

Data for time requirements for producing a single unit of product i at stage j (in hours)

	$i=1$	$i=2$	$i=3$	$i=4$	$i=5$
$j=1$	1.14	1.14	1.20	0.84	1.12
$j=2$	1.57	1.57	1.80	1.02	1.55
$j=3$	0.08	0.08	0.08	0.05	0.09
$j=4$	0.58	0.58	0.50	0.47	0.62
$j=5$	1.44	1.44	1.48	1.19	1.29
$j=6$	0.52	0.52	0.75	0.37	0.54

Data for maximum number of units of product i at stage j produced by a single worker during a period is given below.

	$i=1$	$i=2$	$i=3$	$i=4$	$i=5$
$j=1$	4.21	4.21	4.00	5.71	4.29
$j=2$	3.06	3.06	2.67	4.71	3.10
$j=3$	60.00	60.00	60.00	96.00	53.33
$j=4$	8.28	8.28	9.60	10.21	7.74
$j=5$	3.33	3.33	3.24	4.03	3.72
$j=6$	9.23	9.23	6.40	12.97	8.89

The matrix below shows the pay one worker receives for producing one unit of product i at stage j (in dollars)[1].

	$i=1$	$i=2$	$i=3$	$i=4$	$i=5$
$j=1$	5.64	5.64	5.94	4.16	5.54
$j=2$	8.29	8.29	9.51	5.39	8.18
$j=3$	0.40	0.40	0.40	0.25	0.46
$j=4$	2.95	2.95	2.54	2.39	3.15
$j=5$	7.51	7.51	7.73	6.21	6.73
$j=6$	2.66	2.66	3.83	1.89	2.76

[1] Data does not include a dollar amount for employee benefits

The amounts for holding a single unit of product i at stage j for one 4-hour period are shown below (given in dollars).

	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$
$j = 1$	.0065	.0065	.0080	.0040	.0050
$j = 2$	.0075	.0075	.0090	.0040	.0060
$j = 3$	.0075	.0080	.0100	.0050	.0060
$j = 4$	.0120	.0120	.0150	.0090	.0110
$j = 5$	.0200	.0210	.0230	.0160	.0180
$j = 6$	.0220	.0230	.0260	.0180	.0200

The linear program, in its entirety, is available upon request.

4.224 Results of Detailed Scheduling Model

The detailed model appeared to work very effectively with the data provided by Pulaski Furniture Corporation. The objective function value was $353,802.03. The program provided an optimal solution with no shortages. Therefore, the revenues were simply demand times the selling price or $699,091, and the total costs were $345,288.97. Implementation of the model resulted in the recommendation to increase the workforce by 63 employees in order to optimize the utilization of overtime production while ensuring no shortages. A summary of recommendations regarding the workforce after utilizing the model and the current employment situation is shown in Tables 4.4 and 4.5. For this example, a soft ceiling was imposed on workforce requirements at each stage. In other words, the upper limit on available time at a stage was 4 hours times the number of workers at that stage.

Table 4.4. Workforce schedule - by period
Soft Ceiling Imposed

	Currently				Periods				
Stage	used	1	2	3	4	5	6	7	8
1	51	137.8	287.1	0	95.7	71.9	36.7	111.4	0
2	122	159.2	0	412.6	140.3	104.3	50.4	153.1	0
3	16	5.4	3.4	21.4	7.1	5.0	2.6	8.0	0
4	46	43.9	23.3	0	50.0	107.1	16.5	46.4	89.7
5	121	67.0	84.7	0	103.5	98.8	240.9	115.1	222.4
6	15	20.8	35.4	0	37.4	46.9	87.0	0	121.9
Total	371	434.1	433.9	434.0	434.0	434.0	434.1	434.0	434.0

Table 4.5 Workforce schedule - by day
Soft Ceiling Imposed

Stage	Currently used	Days 1	2	3	4
1	51	212.5	47.9	54.3	55.7
2	122	79.6	276.5	77.4	76.6
3	16	4.4	14.3	3.8	4.0
4	46	33.6	25.0	61.8	68.1
5	121	75.9	51.8	169.9	168.8
6	15	28.1	18.7	67.0	61.0
Total	371	434.1	434.2	434.2	434.2

A more realistic situation is one in which a hard ceiling is imposed on the workforce size at a given stage. This is restricted by the number of machines at each stage. A second experiment was conducted which imposed such a hard ceiling at each stage (20 more workers than currently used at each stage). The objective function value was only $105,377.0 with several shortages. The production schedule allowed a shortage of 345 pieces of product 1 in period 4, 74 pieces of product 2 in period 8, and 315 pieces of product 5 in period 2. Workforce schedules are shown in Tables 4.6 and 4.7, and the ceiling used is shown in the final column of each.

A third experiment tested the situation in which some products were already partially completed. In this case, the same hard ceiling was imposed, and it was assumed that 270 units of product 4 had been completed through the third stage; 115 units of product 5 were completed through the second stage; and an additional 200 units of product 5 were completed through the first stage. This time, the objective function was slightly more than $230,000. Shortages occurred in period 5 (250 units of product 3) and in period 2 (269 units of product 5). The workforce schedules are presented in Tables 4.8 and 4.9.

Amounts produced during regular production for each of the three runs are shown in Tables 4.10, 4.11, and 4.12. In the first experiment, all products utilized some overtime production. Products 3 and 5 used few overtime hours, while product 2 incurred quite a bit of overtime expense. This concurred with information provided by Pulaski Furniture regarding the use of overtime when producing the 11945 curio. Similar results can be observed in the other two experiments.

Table 4.6. Workforce schedule - by period
Hard Ceiling Imposed

Stage	Currently used	Periods 1	2	3	4	5	6	7	8	Maximum allowed
1	51	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71
2	122	111.2	117.3	119.2	119.2	119.2	117.1	117.1	117.1	142
3	16	4.4	5.1	5.0	5.0	5.0	5.1	5.1	5.1	36
4	46	36.1	39.3	34.8	34.8	34.8	36.1	36.1	36.1	66
5	121	113.8	109.4	106.9	106.9	106.9	107.4	107.4	107.4	141
6	15	34.4	28.9	34.0	34.0	34.0	34.3	34.3	34.3	35
Total	371	370.9	371.0	370.9	370.9	370.9	371.0	371.0	371.0	491

Table 4.7 Workforce schedule - by day
Hard Ceiling Imposed

Stage	Currently used	Days 1	2	3	4	Maximum allowed
1	51	71.0	71.0	71.0	71.0	71
2	122	114.3	119.2	118.2	117.1	142
3	16	4.8	5.0	5.1	5.1	36
4	46	37.7	34.8	35.5	36.1	66
5	121	111.6	106.9	107.2	107.4	141
6	15	31.7	34.0	34.2	34.3	35
Total	371	371.1	370.9	371.2	371.0	491

Table 4.8. Workforce schedule - by period
Beginning Inventories

Stage	Currently used	Periods								Maximum allowed
		1	2	3	4	5	6	7	8	
1	51	60.9	71.0	71.0	71.0	71.0	71.0	71.0	71.0	71
2	122	85.8	142.0	142.0	124.9	123.9	123.9	123.9	123.9	142
3	16	3.7	6.6	5.1	5.1	5.1	5.1	5.1	5.1	36
4	46	52.9	34.1	33.9	38.8	39.1	39.1	39.1	39.1	66
5	121	132.6	82.3	84.0	96.2	96.9	96.9	96.9	96.9	141
6	15	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35
Total	371	370.9	371.0	371.0	371.0	371.0	371.0	371.0	371.0	491

Table 4.9 Workforce schedule - by day
Beginning Inventories

Stage	Currently used	Days				Maximum allowed
		1	2	3	4	
1	51	65.9	71.0	71.0	71.0	71
2	122	11339	133.5	123.9	123.9	142
3	16	5.2	5.1	5.1	5.1	36
4	46	43.5	36.4	39.1	39.1	66
5	121	107.5	90.1	96.9	96.9	141
6	15	35.0	35.0	35.0	35.0	35
Total	371	371.1	370.9	371.2	371.0	491

Table 4.10 Production during regular hours
Soft Ceiling Imposed

Stage	Products 1	2	3	4	5
1	345.0	1579.1	250.0	138.8	315.0
2	345.0	1561.5	250.0	145.2	315.0
3	203.6	1750.9	250.0	186.8	287.2
4	345.0	1790.9	250.0	195.3	285.2
5	287.5	1624.1	250.0	225.1	262.7
6	287.5	1606.6	250.0	225.0	262.5
Total demanded	345.0	2000.0	250.0	270.0	315.0

Table 4.11 Production during regular hours
Hard Ceiling Imposed

Stage	Products 1	2	3	4	5
1	0	1580.6	250.0	202.4	0
2	0	1925.9	250.0	270.0	0
3	0	1614.1	250.0	201.7	0
4	0	1748.7	79.1	208.6	0
5	0	1925.9	250.0	270.0	0
6	0	1565.9	250.0	195.5	0
Total demanded	345.0	2000.0	250.0	270.0	315.0

Shortages: 345 units Product 1

74 units Product 2

315 units Product 5

Table 4.12 Production during regular hours
Beginning Inventories

Stage	Products 1	2	3	4	5
1	345.0	1612.7	0	0	0.0
2	345.0	2000.0	0	0	0.0
3	253.7	1731.5	0	0	180.7
4	298.2	1686.0	0	180.5	45.7
5	340.3	1684.5	0	181.0	45.7
6	345.0	1623.1	0	194.0	45.7
Total demanded	345.0	2000.0	250.0	270.0	315.0

Note: I.410 = 270
I.510 = 200
I.520 = 115

Shortages: 250 units Product 3

269 units Product 5

Inventory build ups occurred most often in the production of Product 2. The largest amount of inventory held at any stage was 1254 units of Product 2, at stage 3 at the end of period 4.

4.3 Determining Lot Sizes

The aggregate model provides a suggested lot-size to the plant manager. As described above, once this lot-size has been determined, it is necessary to then input this information to the linear program in order to make sure the capacity of the plant is not exceeded.

A comparison of runs made on the heuristic which limits the inventory holding period and the optimizing program, showed that the heuristic produced the same results as the original program 92% of the time. The only instances in which the lot sizes were not the same had the following characteristics:

One product held for more than 4 four week periods had an inventory carrying cost of $3.00/unit/period, and the amoun t demanded was 50 units.

$$\frac{3 * 50}{4weeks} * 16weeks = 6000 \leq s_{4j} \quad \forall j \quad j \neq 10$$

The other product had an inventory carrying cost of $3.10/unit/period and the amount demanded was 50 units.

$$\frac{3.10 * 50}{4weeks} * 16weeks = 620 \leq s_{10j} \forall j \quad j \neq 4,6$$

The difference in total costs for these problems under the two algorithm was approximately 1.0112% of the optimum. The data is shown in Tables 4.13 - 4.15, and the results are shown in Table 4.16.

Orders were batched in 50% of the twenty runs and the largest amount carried in inventory was 125 units. This was considered economically feasible only when all orders were of uniform size (125 units). This occurred five times within the ten runs. Batching an order of size 75 units occurred 4 times and an order size of 50 was batched 7 times.

For theses instances in which orders were batched a comparison of costs incurred by 1)producing as demanded, 2)producing via optimizing algorithm and 3)producing via the heuristic method is provided in Table 4.17.

4.4 Consider Common Setups

The dynamic programming model provides an effective method for considering common setups when planning the production schedule. The production sequence was different from the demand sequence in 40% of the trial runs. A comparison of costs incurred by following the demand sequence and those incurred via the dynamic program is presented in Table 4.18.

Table 4.13 Inventory carrying costs
(Inventory held for more than 16 weeks)

Product	Inventory carrying cost Run 1	Run 2
	(per unit/4weeks)	
1	2.00	5.00
2	2.10	4.25
3	2.30	7.20
4	3.00	5.50
5	3.20	7.10
6	3.40	4.20
7	2.70	2.50
8	2.50	3.20
9	2.90	4.10
10	2.00	3.10

Table 4.14 Demand schedule - Run 1
(Inventory held for more than 16 weeks)

Period	Product demanded	Quantity demanded
1	7	125
2	5	150
3	1	50
4	7	50
5	3	50
6	10	200
7	9	80
8	3	50
9	0	0
10	4	110
11	5	90
12	3	120
13	5	75
14	2	250
15	7	100
16	10	124
17	6	50
18	7	50
19	4	50
20	2	100

Table 4.15 Demand schedule - Run 2
(Inventory held for more than 16 weeks)

Period	Product demanded	Quantity demanded
1	3	125
2	2	150
3	6	50
4	3	75
5	5	50
6	2	200
7	0	0
8	10	50
9	7	75
10	8	110
11	6	90
12	0	0
13	9	200
14	10	50
15	9	100
16	2	124
17	7	120
18	8	75
19	7	50
20	2	100

Table 4.16 Results of dynamic program
(Inventory held for more than 16 weeks)

																					Total cost*
Run 1																					
Demand sequence	7	5	1	7	3	10	9	3	0	4	5	3	5	2	7	10	6	7	4	2	$13,280
Dynamic program	7	5	1	7	3	10	9	0	0	4	5	3	0	2	7	10	6	0	0	2	12,435
Heuristic	7	5	1	7	3	10	9	0	0	4	5	3	0	2	7	10	6	2	4	0	12,505
Run 2																					
Demand sequence	3	1	6	3	5	2	0	10	7	8	6	0	9	10	9	2	7	8	7	2	17,915
Dynamic program	3	1	6	3	5	2	0	10	7	8	6	0	9	0	9	2	7	8	0	2	16,050
Heuristic	3	1	6	3	5	2	0	10	7	8	6	10	9	0	9	2	7	8	0	2	16,325

*Total cost = Setup cost + Inventory cost

Table 4.17. Comparison of costs - batch schedule vs demand schedule

Run	Schedule as Demand	Schedule using Optimizing Algorithm	Schedule using Heuristic Algorithm
1	$13,280	$12,435	$12,505
2	17,915	16,050	16,325
3	13,280	11,200	11,200
4	12,430	11,730	11,730
5	12,785	12,610	12,610
6	11,610	10,015	10,015
7	17,915	17,570	17,570
8	17,915	17,488	17,488
9	18,165	16,694	16,694
10	8,720	8,190	8,190

Table 4.18. Comparison of costs - common setups vs demand

Run	Demand	Optimizing algorithm
1	13,280	12,435
8	17,915	17,488
9	18,165	16,694
11	$15,155	$14,661
12	15,390	13,561
13	8,970	8,680
14	8,575	8,415
15	14,417	13,750

CHAPTER FIVE

CONCLUSIONS and REMARKS

5.1 Overview

The problem of determining optimal lot-sizes in order to minimize total cost in the wood furniture industry has been investigated. Dynamic and linear programming models were developed and implemented to provide managers with a way to determine lot-sizes, consider common setups and schedule production.

5.2 Assessment of Math Models

When used together, the two mathematical models presented in this thesis provide an effective means of scheduling production and determining lot-sizes. The models may be implemented using the methodology developed, and they determine solutions which have been confirmed by industry personnel as realistic and valid. The outputs include an aggregate production schedule, a detailed (by stage) production schedule with regular and overtime production specified, workforce requirements, and total costs, as well as optimal lot-sizes.

The detailed model assumes that workers in the firm are familiar with work performed throughout the plant. This would prove very accommodating if the wood furniture industry moves towards a just-in-time environment. However, in many cases, membership in local unions prevents employees from "floating" from department to department. If a hard ceiling on workforce size is imposed, the detailed scheduling model can provide recommendations which result in very consistent workforce requirements at each stage throughout the planning horizon.

In addition, it was observed that beginning inventory levels had a significant effect on the outcome of the detailed scheduling model. Other factors which affect the lot-sizing and scheduling problem are inventory costs, setup costs, length of the holding period, penalties for hiring and firing workers, and shortage costs.

The main impediment to implementing these models is that many wood furniture firms do not keep accurate records of many of the variables which impact production costs. In other cases, the data exists even though plant managers fail to realize it. This problem is especially noticeable in the dependent demand constraint of the detailed scheduling model. Without information regarding individual machining centers, it was necessary to assume that one "kit" was required from stage to stage. Otherwise, collective data would have been divided by the number of total parts, and then multiplied by the number of total parts, thus adding no additional information to the solution. Although this was quite sufficient to test the model, additional information may be obtained if data is collected at each machine center.

5.3 Assessment of Lot-Sizing Methodology

The aggregate model provides a lot-sizing mechanism. The batching of orders is determined by sequence dependent setup costs and inventory carrying costs. Capacity constraints must be checked by using the output of the dynamic program as input to the linear program. If capacity is exceeded, the workforce is increased (if the constraint prohibiting shortages is included) or shortages surface. At this point the aggregate solution must be reevaluated and the input sufficiently altered in order to produce a feasible solution if possible.

Some basic trends became apparent during the testing of the model. Due to the nature of the industry, it appeared that

$$h_i * x_{it} * 16 \text{ weeks} \geq s_{ij} \quad \forall j$$ [1]

In addition, there was a tendancy to batch a product's order with the preceding order of that product if the time span between the two orders' due dates was eight weeks or less providing some other product was scheduled in between the two.

In twenty trials, there were only two cases in which it was cost effective to set up the machines twice. While this may vary from company to company, given the generic nature of the data, it appears that in many companies it would be worthwhile to batch a product's runs if the time span between due dates is no more than eight weeks

[1] h_i = inventory carrying cost of one unit of product i; x_{it} = amount produced of product i at time t; s_{ij} = setup cost of product j given that product i immediately preceeds product j

($h_i * x_{it_2} * 8$ weeks $\leq s_{ij}$ if D_{it_1}>0 and D_{it_2}>0 and $t_2 - t_1 \leq 8$ weeks[2].) Nonetheless, this trend supports the decision to focus on one item per period production since runs on identical objects within a period would be batched regardless.

For the most part an item was not scheduled for production until the period in which it was first demanded. During the twenty trials of the computer program, there were ten instances where it was more cost effective to produce an item prior to its period of first demand. Even though this may seem like a large proportion of the runs, it must be understood that 10 - 13 products were introduced in each run, implying that it was more economic to schedule production prior to first demand only 5% of the time.

Therefore, for a casegood manufacturer, it seems advisable to batch orders of the same product if the time span between the two due dates is eight weeks or less. On the other hand, a casegood producer may find it advantageous to dispel batching as an option when the time span between orders is more than 16 weeks. By implementing these "rules of thumb," a plant manager's lot-sizing decisions are greatly simplified, leaving those orders having a repetition in 9 - 15 weeks as the area of main concern, which, incidentally, would remain within the limits of a computer program implementing the aggregate model.

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[2] D_{it_1} = amount of product i demanded at the end of period t_1; D_{it_2} = amount of product i demanded at the end of period t_2

5.4 Assessment of Common Setup Considerations

Planning a production schedule while taking into account a cost savings based upon common setups appears to be a worthwhile endeavor. As seen in the test runs, common setup configurations may affect the optimal lot-size if they are considered in the production schedule. In addition, it was seen that at some points, a change in the work sequence, without a change in the lot-size could also produce substantial savings. By running the dynamic aggregate model, plant managers have at their disposal a work sequence which minimizes inventory and setup costs.

Again, the main drawback to utilizing this tool is the industry's failure to track sequence dependent setup costs. Through interviews with various industry personnel, it became apparent that there is a wide range of opinions as to whether setup costs are dependent upon the preceding item produced. For the most part, casegood manufacturers seemed to advocate the importance of planning production while taking into account common setups much more than occasional furniture manufacturers. Once this attitudinal obstacle is overcome, consideration of common setups in planning a production schedule may be easily incorporated into the decision making process with the aggregate model.

5.5 Further Research

Prospective research should be conducted in which additional data is collected, and the models presented here applied. This will require working very closely with several furniture manufacturers in order to attain the required data. Once this data is collected and the methodologies applied, a statistical analysis should be conducted to determine if the cost savings are statistically significant, and to what degree if they are. From there, it would be possible to project realistic cost savings for individual firms.

One area which remains open for investigation is a study of the problem with uniform demand. It appears that some furniture manufacturers believe demand is nearly uniform over time; an investigation of this problem would result in recommendations specifically targeted at this group of manufacturers.

In order for the linear program to produce an even more detailed schedule, data needs to be collected and analyzed for time requirements at each machining center. An especially advantageous situation would be one in which the same furniture group is produced in several types of wood. In that case, the effects of different raw materials on machining times could be studied as well.

In addition, information regarding the number of pieces lost due to material problems must be collected. This figure could then be calculated into the optimal lot-size to provide plant managers with a tool to reduce costs. This data would necessarily be collected by specie since different species of wood have different properties.

Integration of all the preceding research areas will contribute to the general scope of improving the solution algorithm. Once the algorithm is improved, it can then be integrated into the CIPP&C plan described in Figure 3.1.

Further research appears warranted in the area of forecasting models for the wood furniture market. If forecasted sales are incorporated into the master schedule, the forecasting model should be integrated with the aggregate scheduling model.

Wood furniture manufacturers are also in need of a way to gather and record setup information. Because numerically controlled machinery is not widespread throughout furniture plants, there are differences in the amount of time alloted for a particular setup.

Another area for additional research is to develop an easily implemented method of determining the costs of hiring and firing employees. These penalties directly affect the workforce size which in turn controls the production capacity of the plant.

LITERATURE CITED

Afentakis, Penayotis and B. Gavish. 1986. Optimal Lot-Sizing Algorithms for Complex Product Structures. **Operations Research**. Vol. 34. No. 2. pp. 237-249.

Afentakis, Penayotis, B. Gavish, and U. Karmarkar. 1984. Computationally Efficient Optimal Solutions to the Lot-Sizing Problem in Multistage Assembly Systems. **Management Science**. Vol. 30. No. 2. pp. 222-239.

Aras, D. A. and L. A. Swanson. 1982. A Lot Sizing and Sequencing Algorithm for Dynamic Demands upon a Single Facility. **Journal of Operations Management**. Vol. 2. No. 3. pp. 177-185.

Bahl, H. C., L. P. Ritzman, and J. N. D. Gupta. 1986. Determining Lot Sizes and Resource Requirements: A Review. **Operations Research**. Vol. 35. No. 3. pp. 329-345.

Benders, J. F. 1962. Partitioning Procedures for Solving Mixed-Variables Programming Problems. **Numerische Mathematik**. Vol. 4. pp. 238-252.

Billington, P. J., J. O. McClain, and L. J. Thomas. 1983. Mathematical Programming Approaches to Capacity-Constrained MRP Systems: Review, Formulation and Problem Reduction. **Management Science**. Vol. 29. No. 10. pp. 1126-1141.

Crowston, Wallace B. and M. H. Wagner. 1973. Dynamic Lot Size Models for Multi-Stage Assembly Systems. **Management Science**. Vol. 20. No. 1. pp. 14-21.

Culbreth, C. Thomas, Russell E. King, and Ezat T. Sanii. "A Flexible Manufacturing System for Furniture Production." **Manufacturing Review**. Vol. 2. No. 4. Dec. 1989. p. 257.

Das, Sanchoy K. and S. C. Sarin. A "City Plan" for Design and Research of Computer Integrated Production Planning and Control Systems. **International Journal of Production Planning and Control**. May 1989. Submitted.

Eisenhut, P. S. 1975. A Dynamic Lot-Sizing Algorithm with Capacity Constraints. **AIIE Transactions**. Vol. 7. pp. 170-176.

Gabbay, Henry. 1979. Multi-Stage Production Planning. **Management Science**. Vol. 25. pp. 1138-1148.

Gatchell, Charles J., R. B. Anderson and P. A. Araman. "Effect of gang-ripping width on C1F yields from No. 2 Common oak lumber." **Forest Products Journal**. Vol. 33. No. 6. pp. 43-48.

Haehling von Lanzenauer, C. 1970. Production and Employment Scheduling in Multi-Stage Production Systems. **Naval Research Logistics Quarterly**. Vol. 17. pp. 193-198.

Integrated Computer-Aided Manufacturing (ICAM) Architecture Part II Volume IV - Function Modeling Manual (IDEF). AFWAL-TR-81-4023. Softech, Inc. 1981.

Karni, Reuven and Y. Roll. 1982. A Heuristic Algorithm for the Multi-Item Lot-Sizing Problem with Capacity Constraints. **IIE Transactions**. Vol. 14. No. 4. pp. 249-256.

Kuik, R. and M. Salmomn. 1990. Multi-Level Lot-Sizing problem: Evaluation of a Simulated-Annealing Heuristic. **European Journal of Operational Research**. Vol. 45. pp. 25-37.

Steinberg, E. and H. A. Napier. 1980. Optimal Multi-Level Lot Sizing for Requirement Planning Systems. **Management Science**. Vol. 26. No. 12. pp. 1258-1271.

Wagner, M. H. and T. M. Whitin. 1958. Dynamic Version of the Economic Lot-Sizing Model. **Management Science**. No. 5. pp. 89-96.

Wood & Wood Products. Jan. 1990. p. 3. "Project 1990: The U.S. woodworking industry now and five years from now."

Appendix A

Survey Responses

Total Number of Surveys Sent	179
Total Number of Surveys Returned as Undeliverable	10
Total Number of Surveys Delivered	169
Total Number of Responses Received	63
Percentage of Responses	37.3%

Many of the companies who responded produce more than one type of furniture. When asked what type of furniture they manufacture, the responses were:

40 out of 63 (63%)	Bedroom Suites
34 out of 63 (54%)	Dining Room Suites
35 out of 63 (56%)	Occassional Tables
29 out of 63 (46%)	Other

The Other category included such items as Entertainment Centers, Living Room Furniture, Desks, Family Room Furniture and Upholstered Furniture.

In describing the average number of orders they received, the responses were:

7 out of 63 (11.1%)	1 - 15 per day
14 out of 63 (22.2%)	16 - 30 per day
22 out of 63 (34.9%)	More than 30 per day
1 out of 63 (1.6%)	1 - 15 per week
18 out of 63 (28.6%)	More than 30 per week
1 out of 63 (1.6%)	No Answer

The average order size:

59 out of 63 (93.7%)	1 - 250 pieces
1 out of 63 (1.6%)	251 - 500 pieces
3 out of 63 (4.8%)	More than 750 pieces

Lead time for raw material procurement[1]:

16 out of 63 (25.4%)	0 - 4 weeks
13 out of 63 (20.6%)	4 - 8 weeks
15 out of 63 (23.8%)	8 - 12 weeks
14 out of 63 (22.2%)	More than 12 weeks
5 out of 63 (7.9%)	No Answer

[1] One respondent indicated that they use 8-12 weeks for some items and more than 12 weeks for others. This response was classified in the more than 12 weeks category.

Type of lumber:

23 out of 63 (36.5%)	Dried lumber only
9 out of 63 (14.3%)	Green lumber only
30 out of 63 (47.6%)	Both dried and green
1 out of 63 (1.6%)	No Answer

45 out of the 63 respondents (71.4%) indicated that they use printed forecasting reports to schedule anticipated production. 17 (27.0%) responded no and there was one with no answer indicated.

Amount of past sales history used to schedule anticipated production:

3 out of 63 (4.8%)	1 - 6 weeks
3 out of 63 (4.8%)	6 - 8 weeks
1 out of 63 (1.6%)	8 - 10 weeks
10 out of 63 (15.9%)	10 - 12 weeks
21 out of 63 (33.3%)	12 weeks - 6 months
14 out of 63 (22.2%)	More than 6 months
10 out of 63 (15.9%)	None
1 out of 63 (1.6%)	No Answer

Length of time from receipt of order to order release date[2]:

16 out of 63 (25.4%)	Less than 2 weeks
27 out of 63 (42.9%)	2 - 6 weeks
11 out of 63 (17.5%)	6 - 10 weeks
2 out of 63 (3.2%)	More than 10 weeks
8 out of 63 (12.7%)	No Answer

28 out of the 63 respondents (44.4%) indicated that they use a computer software package to do work center scheduling. 34 (54.0%) indicated no and 1 (1.6%) had no answer.

However, when asked if the program was developed in house or was a canned program, 2 of the no responses indicated that their program was developed in house. In addition to these 2, 18 others indicated that they also had in house computer programs. 8 indicated they were using canned programs, and 2 indicated that they were using a canned program which has been modified or supplemented by additional in house programming.

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2 One respondent indicated 2-10 weeks. This response is included in both pertinent categories, making the total response greater than 100%.

The software which was mentioned for work center scheduling was:

Mapics	Part of Ask Man-Man
Merlin	Cruze
AMAPS	Copics
Novell	Inflow by DataWorks
Production Software Ltd.	

The discrepancies continued when asked if the procurement procedure was integrated with the scheduling package. This time there were 32 responses. 20 indicated that the procurement and scheduling programs were integrated and 12 indicated that they were not.

When asked if the computer determines the work sequence, 10 respondents indicated yes. 14 respondents indicated the work sequence was an input to their program.

Common setups are considered by many of the companies responding:

16 out of 63 (25.4%)	Within a suite only
1 out of 63 (1.6%)	Among suites only
30 out of 63 (47.6%)	Within and among suites
12 out of 63 (19.0%)	No
4 out of 63 (6.3%)	No Answer

8 of the 63 respondents (12.7%) indicated they own an MRP package. 4 of the 63 respondents (6.3%) indicated they own an MRP II package. 51 of the 63 respondents (81.0%) indicated they do not own an MRP or MRP II package.

Of the 12 affirmative responses, 9 indicated they use the package for planning purposes, 2 indicated they do not, and 1 did not respond to this question.

13 respondents indicated they were seeing improvements as a result of an MRP or MRP II package. This would seem to indicate that one respondent overlooked the question concerning ownership of one of these packages, but continued on to answer this question.

The areas in which these 13 respondents saw improvements were:

Response Time	Timely Ordering
Inventory	Delivery
Raw Materials on Time	Reduced Raw Materials Inventory
Less Errors	Plant Efficiencies
Raw Materials Utilization	Inventory Turns
More Information Available	Lead Time Reductions
Controlled Inventories	Better Yield from Rough Mill
Level Loading on Shop Floor	Inventory Reductions

Less Fluctuation in volume of raw materials

Better control of overstock inventories

Minimum lot size[3]:

39 out of 63 (61.9%)	1 - 100 pieces
12 out of 63 (19.0%)	101 - 200 pieces
3 out of 63 (4.8%)	201 - 300 pieces
11 out of 63 (17.5%)	More than 300 pieces

[3] Two respondents indicated they use 2 different minimum lot sizes; both used 1-100 pieces. One marked 201-300 as their other minimum lot size and the other respondent marked more than 300 pieces.

These lot sizes were based on a combination of the experience of management and an economic evaluation in 7.9% of the companies. It was based on experience only in 50.8% of the companies, and on economic evaluation only in 38.1% of the companies. Two companies (3.2%) did not respond to this question.

Percentage extra for a buffer against material problems[4]:

25 out of 63 (39.7%)	0 - 3%
26 out of 63 (41.3%)	3.1 - 5%
3 out of 63 (4.8%)	5.1 - 7%
6 out of 63 (9.5%)	7.1 - 10%
4 out of 63 (6.3%)	More than 10%
2 out of 63 (3.2%)	No Answer

14 of the 63 (22.2%) respondents stated that they have a 100% immediate delivery policy regarding stock inventories. 11 (17.5%) stated that they have an 80% immediate delivery and 20% stock policy. 18 (28.6%) claimed 60% immediate delivery and 40% stock. 5 (7.9%) claimed 40% immediate delivery and 60% stock. 6 of the 63 (9.5%) said they have a 20% immediate delivery and 80% stock policy. 5 (7.9%) said they have a 100% stock policy. 2 (3.2%) gave no response; 1 (1.6%) indicated 0-20% immediate delivery and 80-100% stock; and 1 (1.6%) indicated 40-60% immediate delivery and 40-60% stock.

[4] One respondent answered both 0-3% and 3.1-5%. Another answered both of these and 5.1-7%, thus making the total response greater than 100%.

This inventory policy was based on the experience/intuition of management in 35 of the 63 companies (55.6%). It was based on an economic evaluation of the policy in 14 (22.2%) of the companies. 5 (7.9%)of the companies stated that they determined their policies through computer software package. 5 (7.9%) others used a combination of the experience of management and an economic evaluation. 1 (1.6%) company indicated that they use a combination of the experience of management and a computer software package, and 1 (1.6%) company claimed to base their policy on all three methods. 2 respondents (3.2%) did not answer this question.

The responses for the average length of time from the day the cutting order is released to the shop floor and the day the order is completed were:

1 of the 63 (1.6%)	Less than one week
19 of the 63 (30.2%)	1 - 3 weeks
23 of the 63 (36.5%)	3 - 6 weeks
20 of the 63 (31.7%)	More than 6 weeks

Average number of changeovers/day/machine in the rough mill[5]:

20 of the 63 (31.7%)	0 - 3
16 of the 63 (25.4%)	4 - 6
8 of the 63 (12.7%)	7 - 9
2 of the 63 (3.2%)	10 - 12
13 of the 63 (20.6%)	More than 12
5 of the 63 (7.9%)	No Answer

Average changeover time in the rough mill:

27 of the 63 (42.9%)	1 - 10 min.
18 of the 63 (28.6%)	11 - 20 min.
8 of the 63 (12.7%)	21 - 30 min.
2 of the 63 (3.2%)	31 - 40 min.
2 of the 63 (3.2%)	1 hour or more
6 of the 63 (9.5%)	No Answer

[5] One respondent indicated between 7 and 12. This was recorded in both pertinent categories.

Average number of changeovers/day/machine in the shaping phase:

18 of the 63 (28.6%)	0 - 3
22 of the 63 (34.9%)	4 - 6
4 of the 63 (6.3%)	7 - 9
10 of the 63 (15.9%)	10 - 12
4 of the 63 (6.3%)	More than 12
5 of the 63 (7.9%)	No Answer

Average changeover time in the shaping phase:

7 of the 63 (11.1%)	1 - 10 min.
20 of the 63 (31.7%)	11 - 20 min.
21 of the 63 (33.3%)	21 - 30 min.
7 of the 63 (11.1%)	31 - 40 min.
1 of the 63 (1.6%)	41 - 59 min.
2 of the 63 (3.2%)	1 hour or more
5 of the 63 (7.9%)	No Answer

Average number of changeovers/day/machine in the cabinet room:

32 of the 63 (50.8%)	0 - 3
14 of the 63 (22.2%)	4 - 6
2 of the 63 (3.2%)	7 - 9
3 of the 63 (4.8%)	10 - 12
2 of the 63 (3.2%)	More than 12
10 of the 63 (15.9%)	No Answer

Average changeover time in the cabinet room:

14 of the 63 (22.2%)	1 - 10 min.
21 of the 63 (33.3%)	11 - 20 min.
8 of the 63 (12.7%)	21 - 30 min.
8 of the 63 (12.7%)	31 - 40 min.
1 of the 63 (1.6%)	41 - 59 min.
1 of the 63 (1.6%)	1 hour or more
10 of the 63 (15.9%)	No Answer

Number of computer controlled machines:

11 of the 63 (17.5%)	0
31 of the 63 (49.2%)	1 - 3
12 of the 63 (19.0%)	4 - 6
3 of the 63 (4.8%)	7 - 9
1 of the 63 (1.6%)	More than 12
5 of the 63 (7.9%)	No Answer

Total number of machines[6]:

6 of the 63 (9.5%)	0
31 of the 63 (49.2%)	1 - 50
13 of the 63 (20.6%)	51 - 100
5 of the 63 (7.9%)	100 - 150
4 of the 63 (6.3%)	More than 150
4 of the 63 (6.3%)	No Answer

48 of the 63 respondents (76.2%) indicated that they do not use bar coding to track inventory and 15 (23.8%) indicated that they do, in fact, use bar coding to track inventory.

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[6] It has been concluded that 5 respondents misunderstood this question due to the fact that they responded with 0.

58 of the 63 respondents (92.1%) indicated that they do not have an automated materials handling system while 5 (7.9%) indicated that they do.

Appendix B

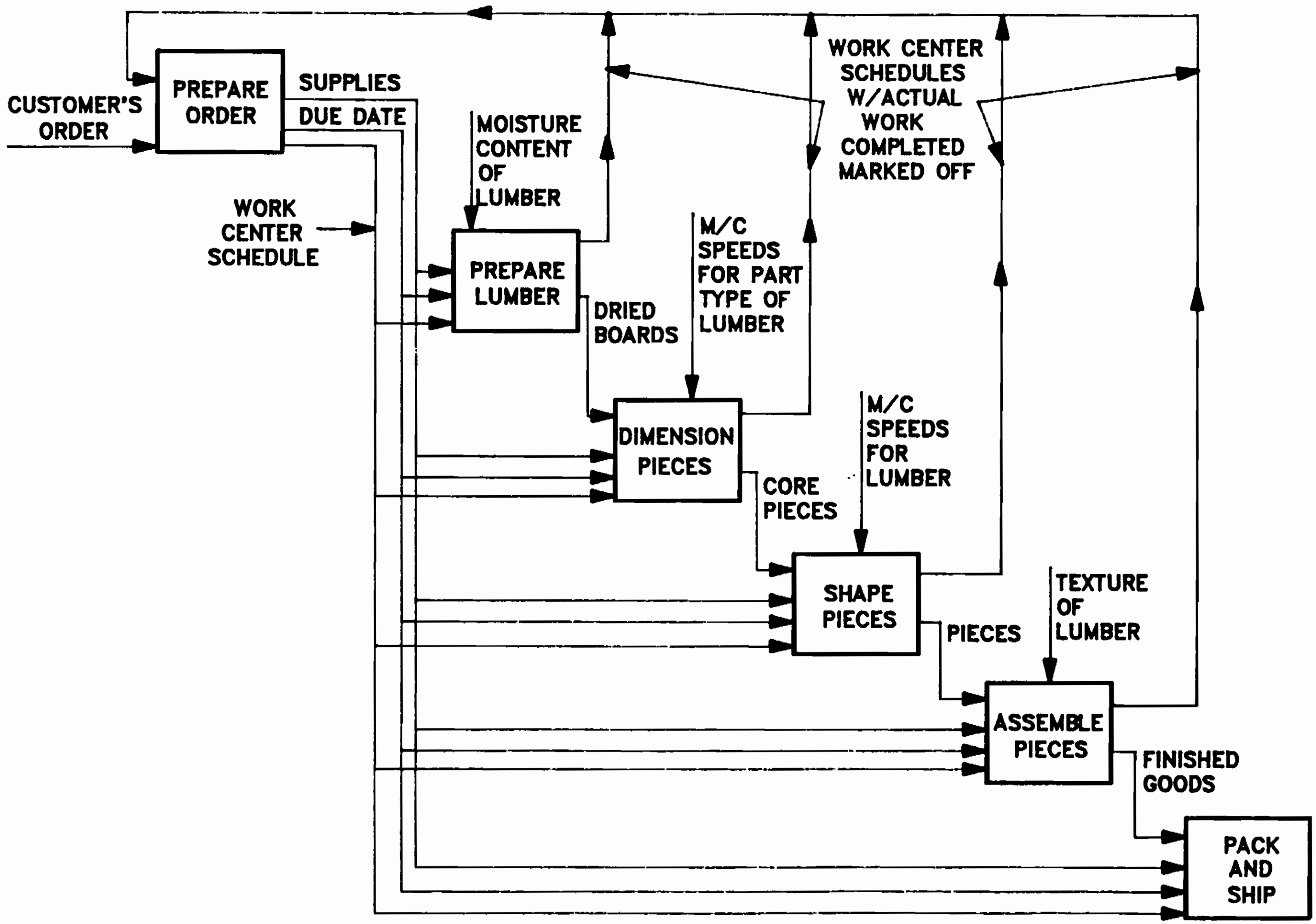


Figure B.1 1A Overview

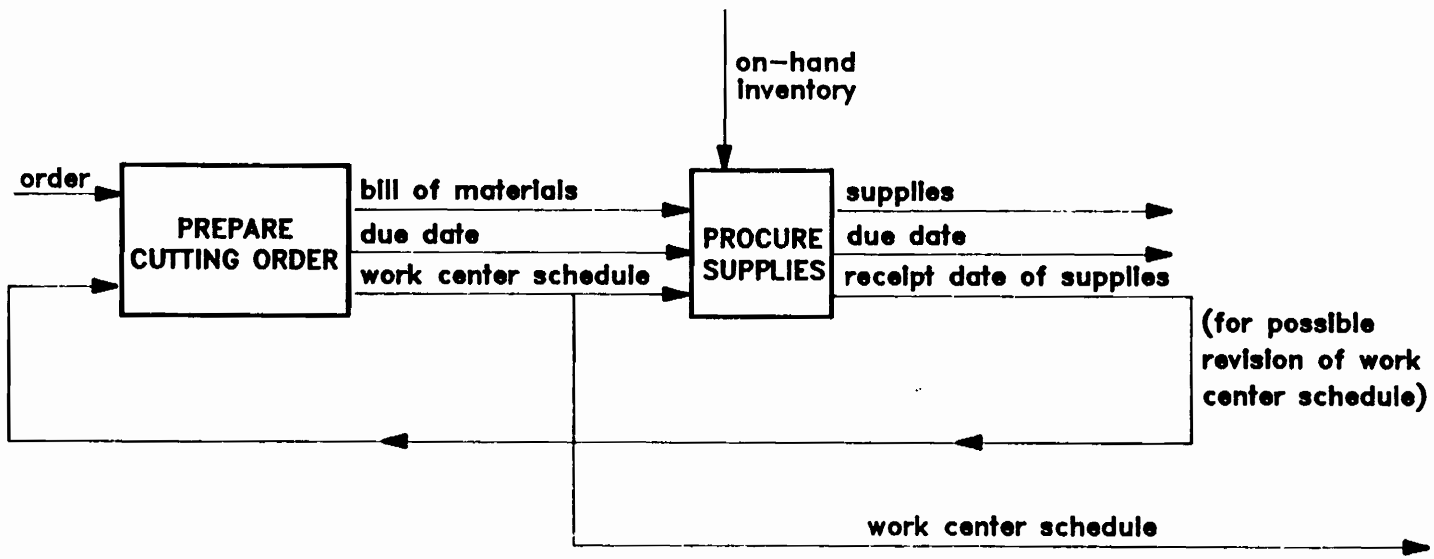


Figure B.2 1A1 Prepare Order

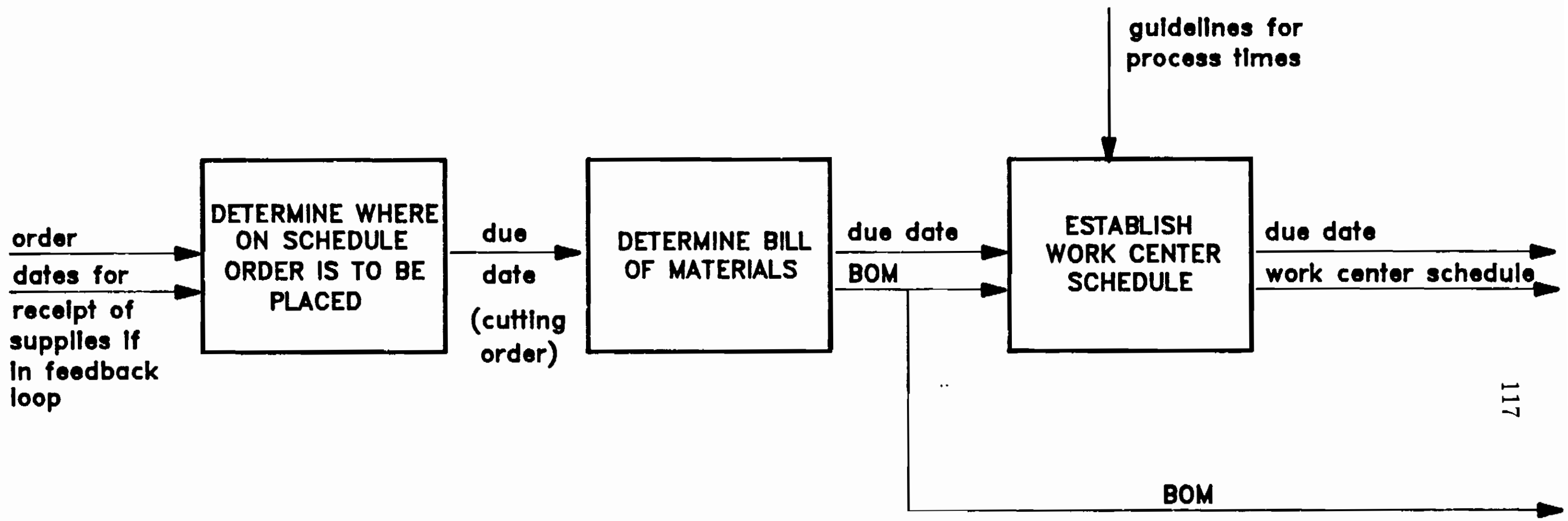


Figure B.3--1A11 Prepare Cutting Order

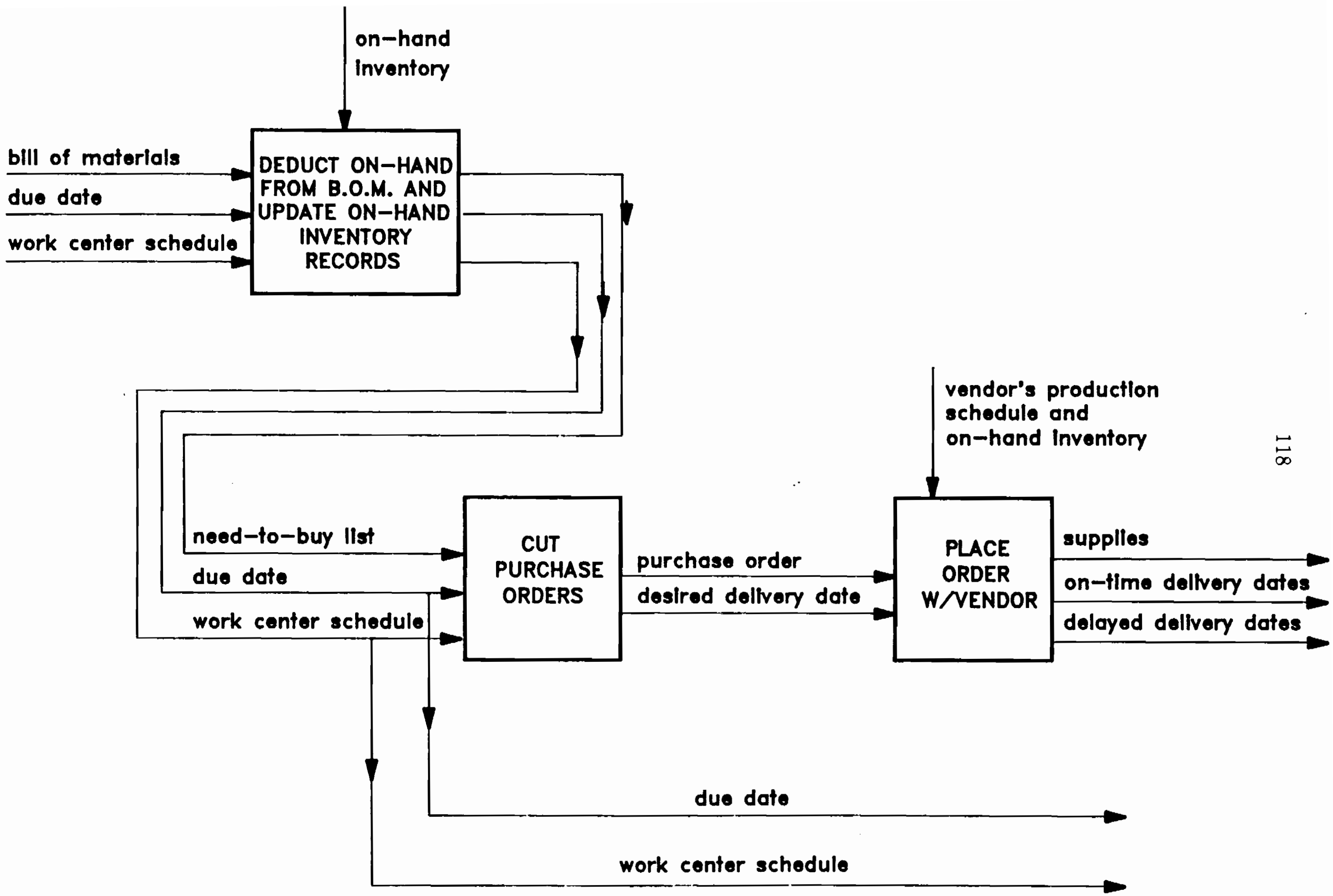


Figure B.4--1A12 Procure Supplies

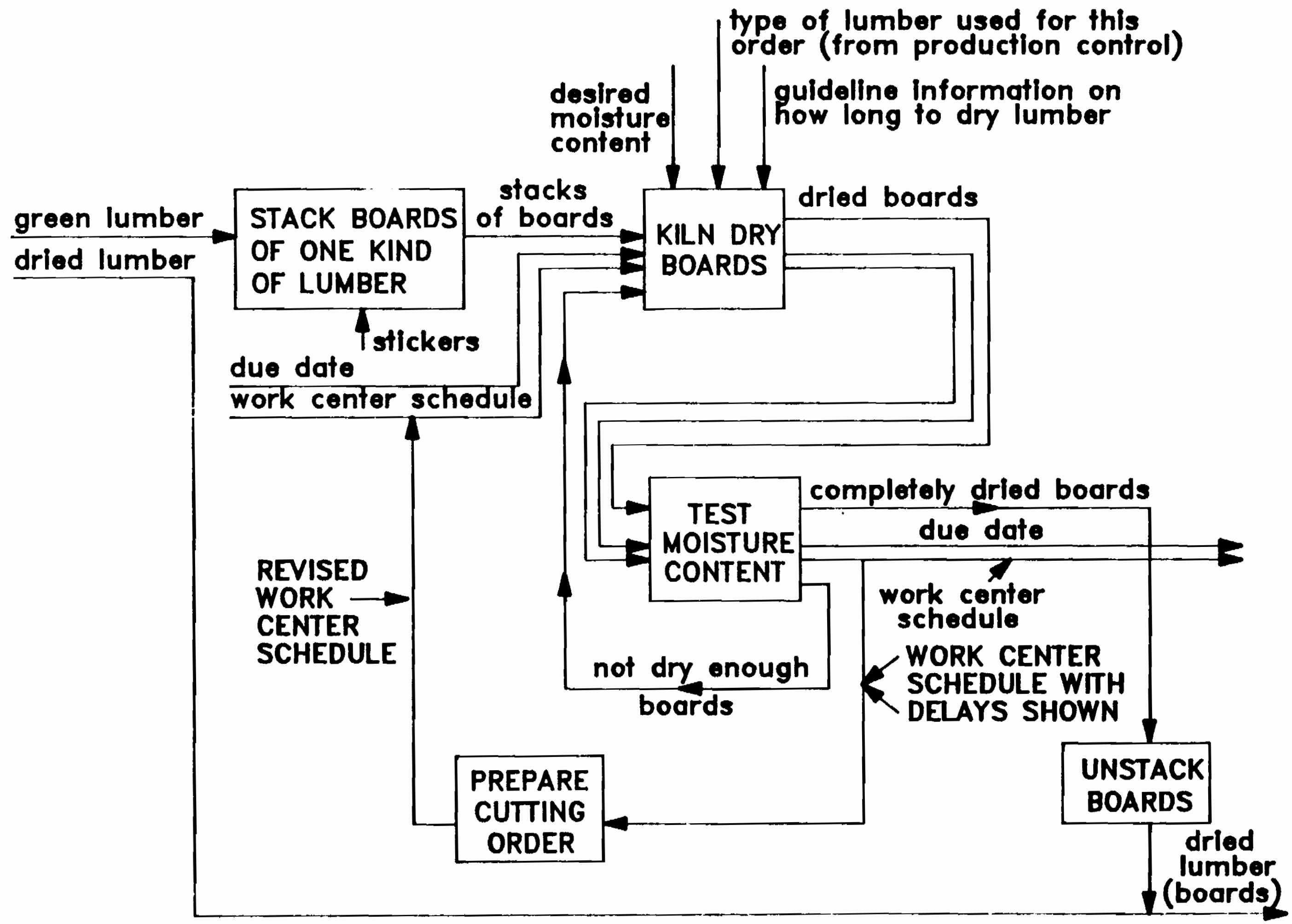


Figure B.5--1A2 Prepare Lumber

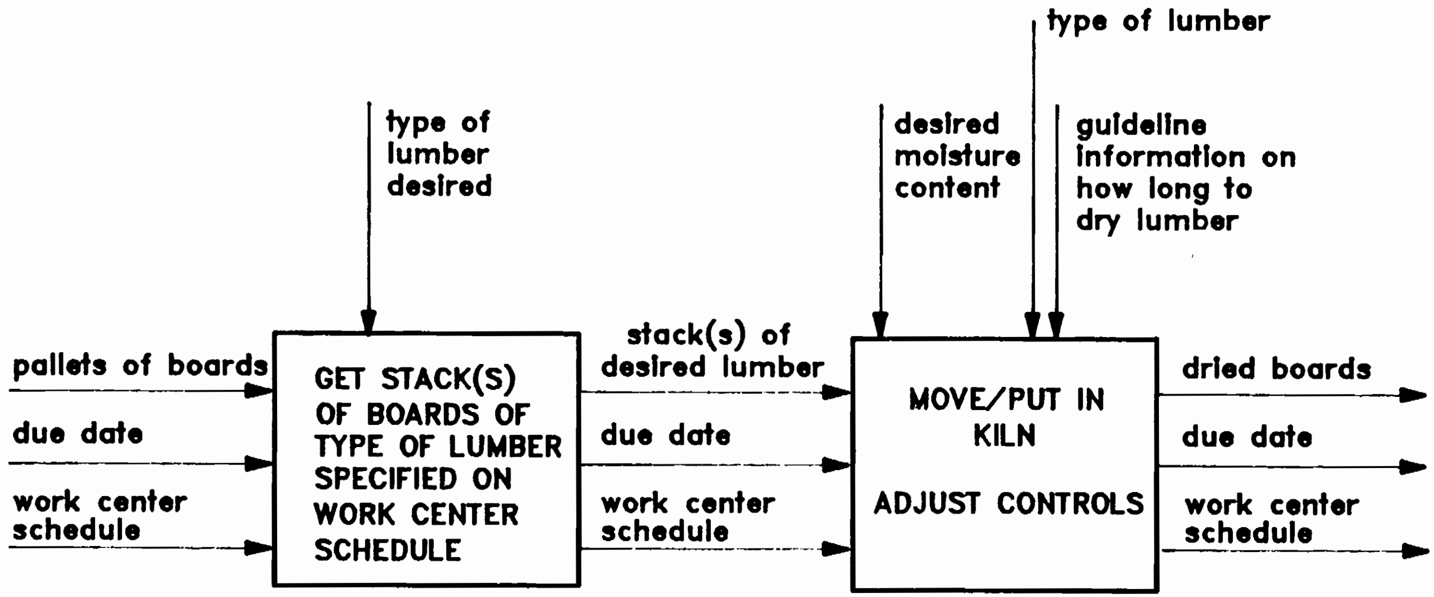


Figure B.6--1A22 Kiln Dry Boards

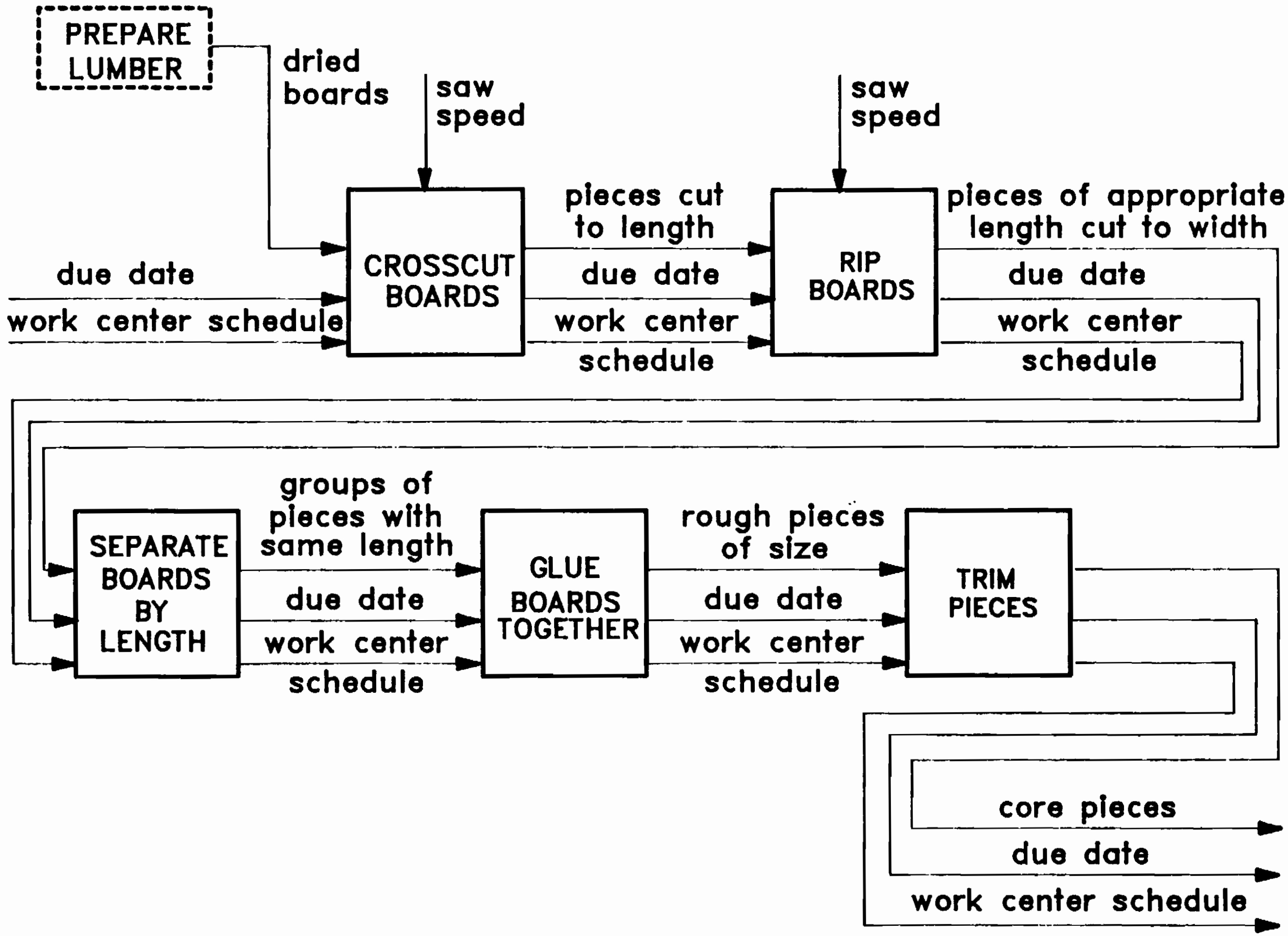


Figure B.7 1A3 Dimension Pieces

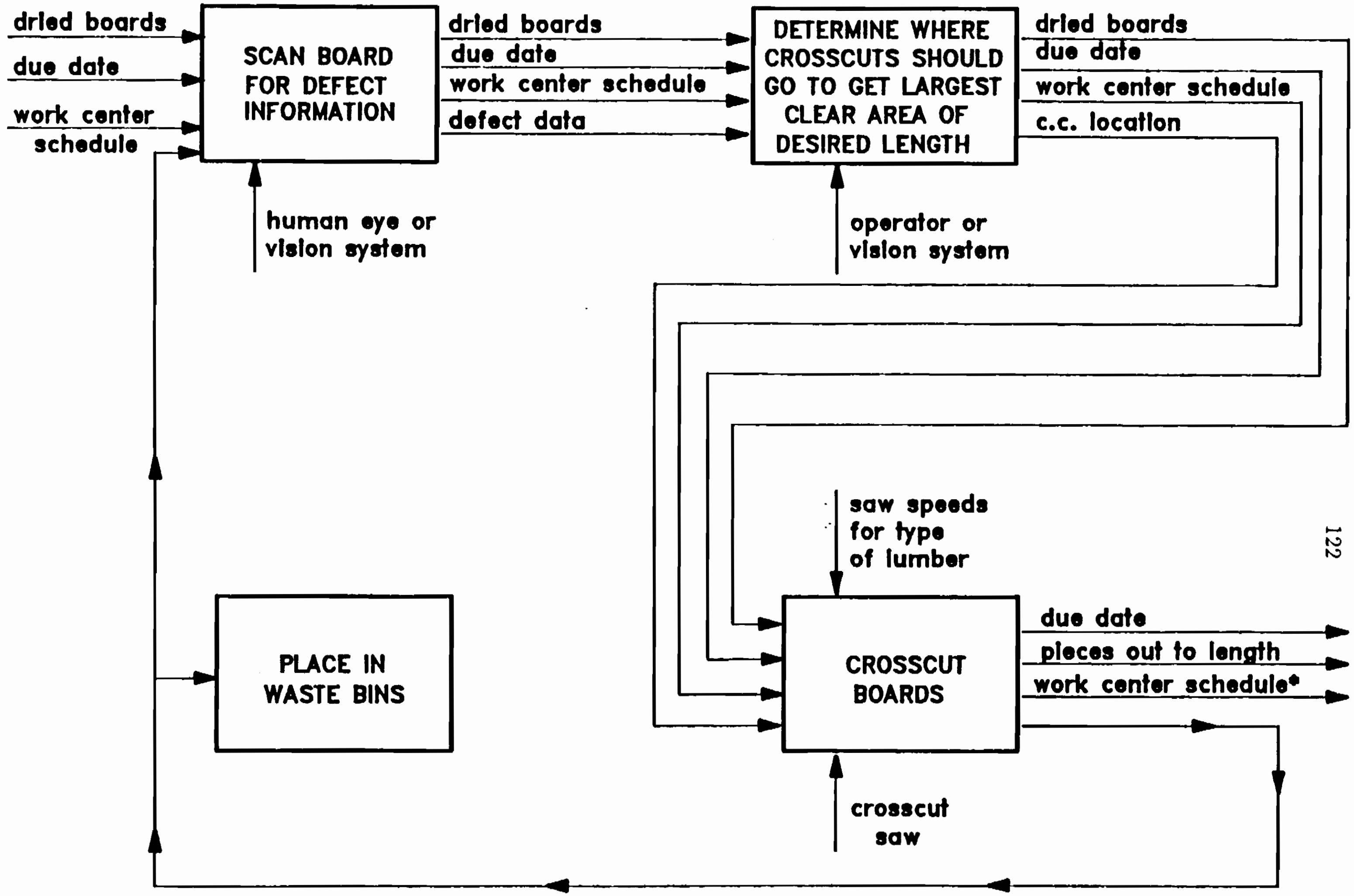


Figure B.8--1A31 Crosscut Boards

* work center schedule with attached work completed marked off.

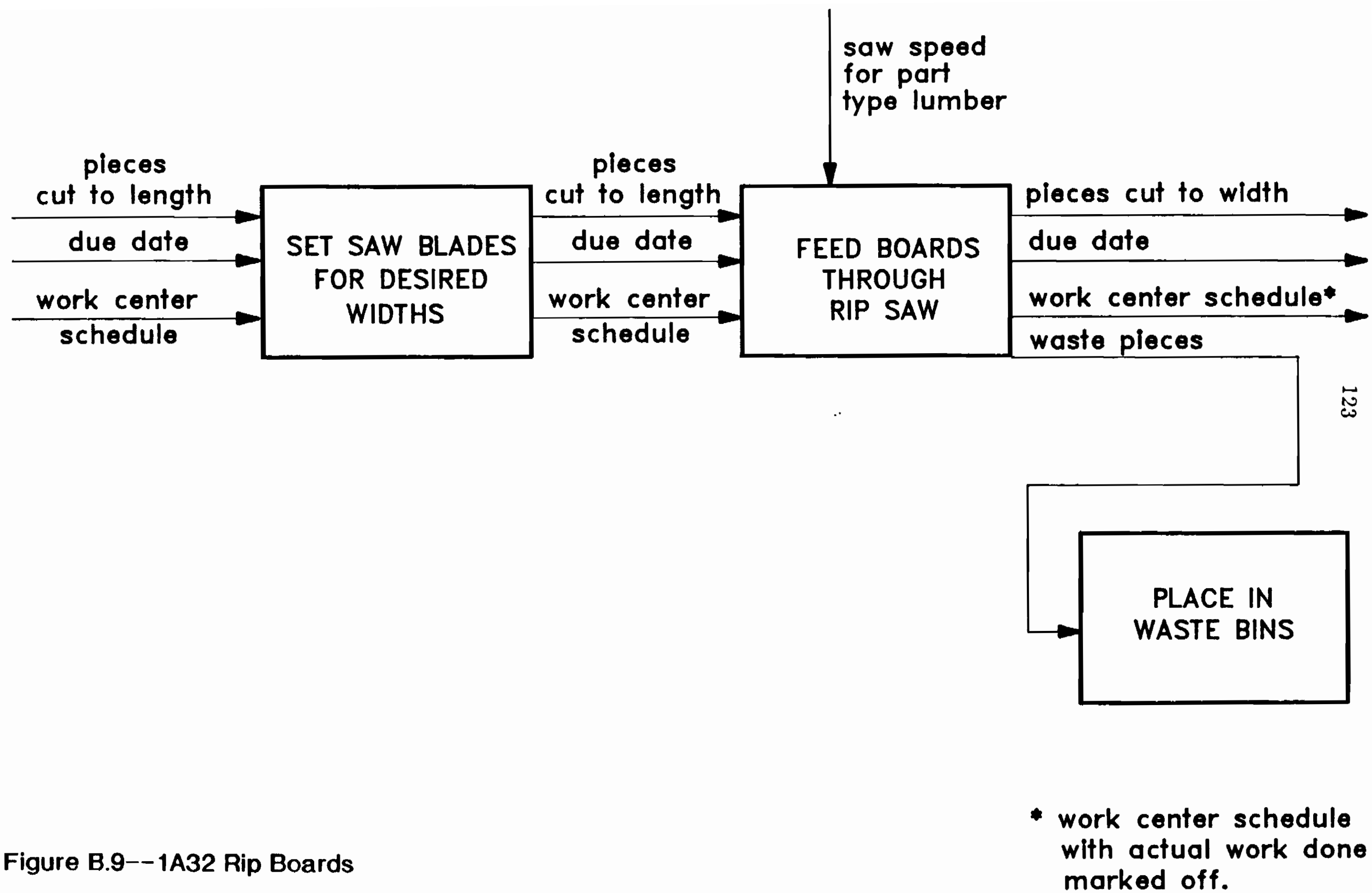


Figure B.9--1A32 Rip Boards

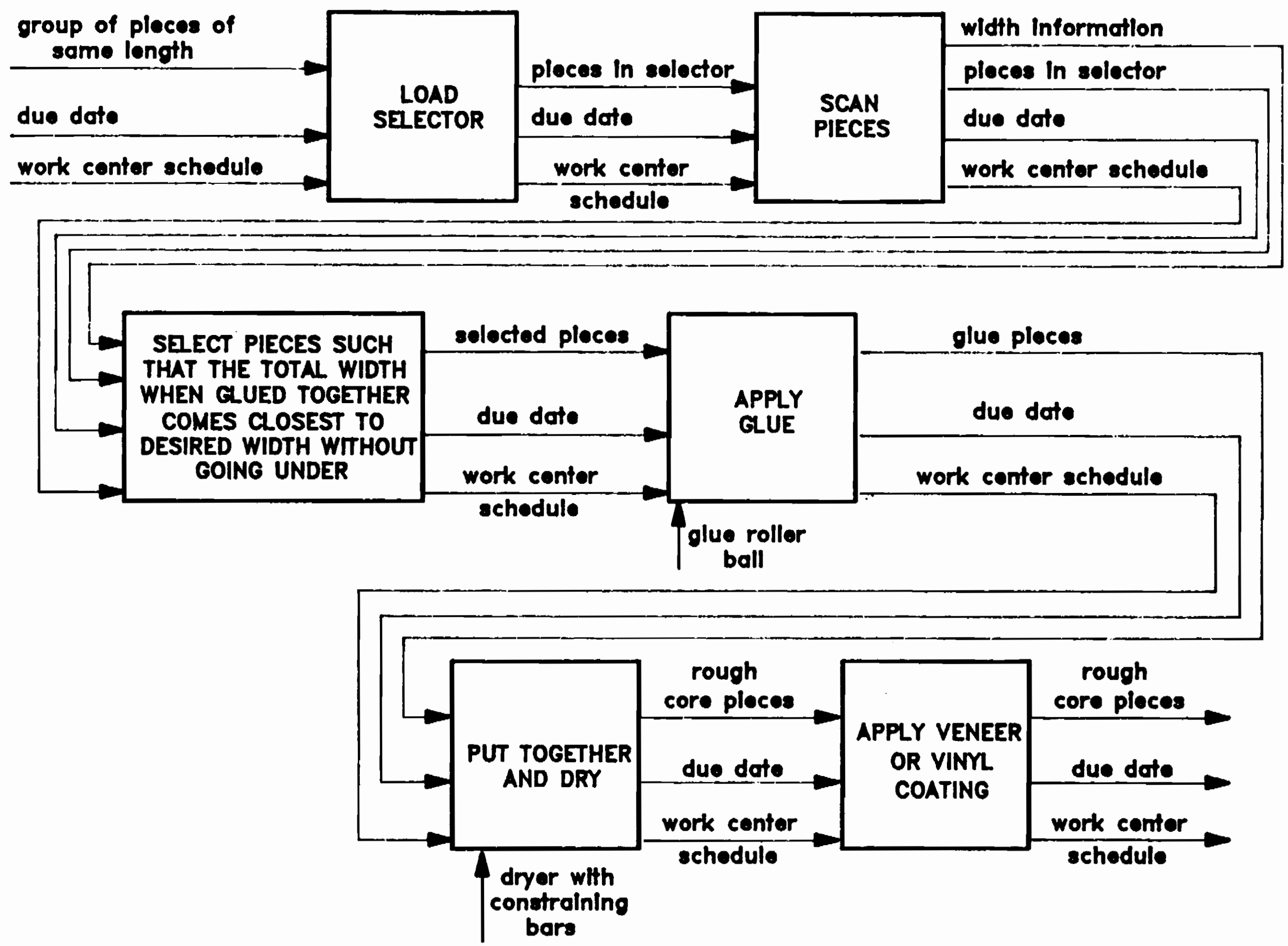
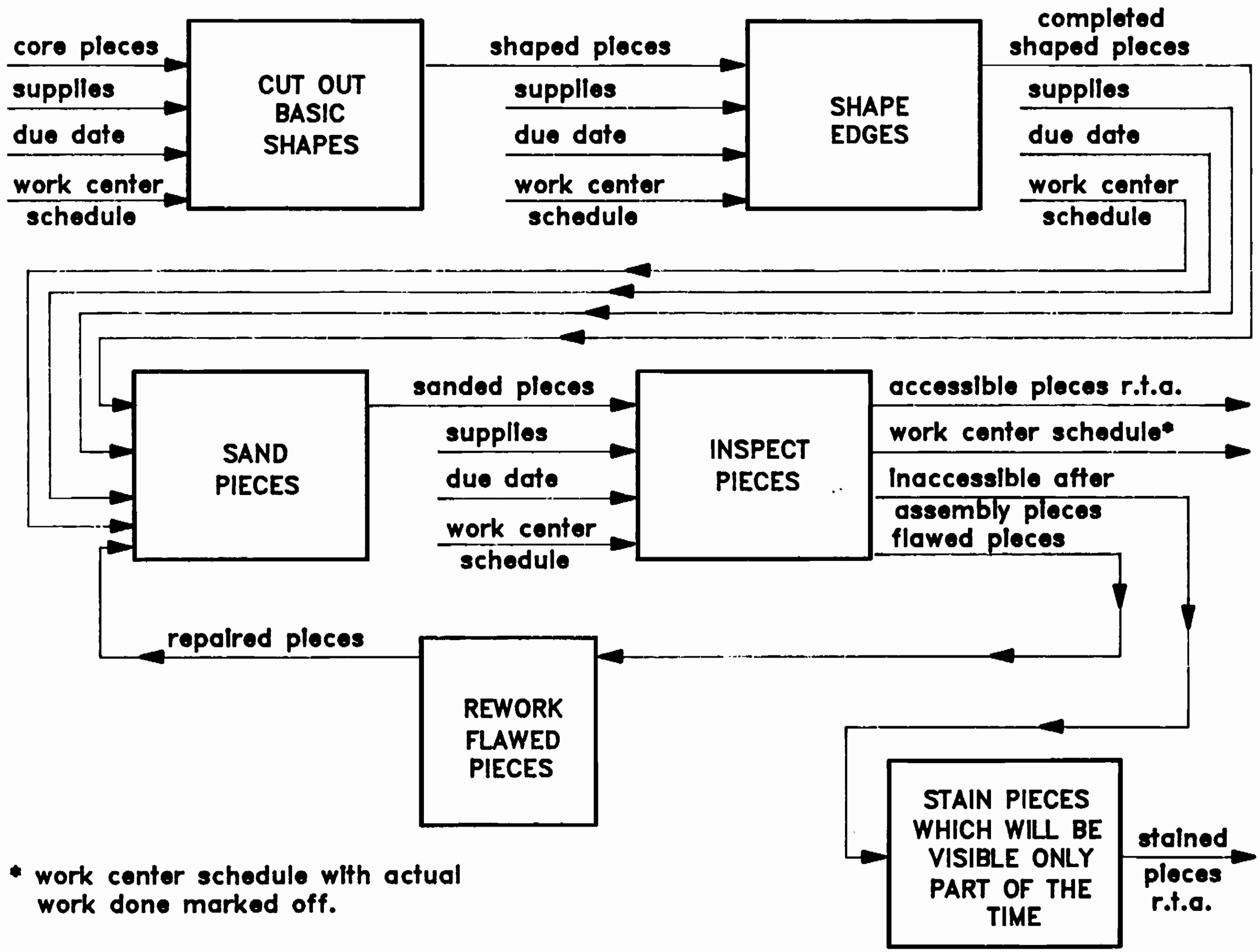


Figure B.10--1A34 Glue Boards Together



* work center schedule with actual work done marked off.

Figure B.11 1A4 Shape Pieces

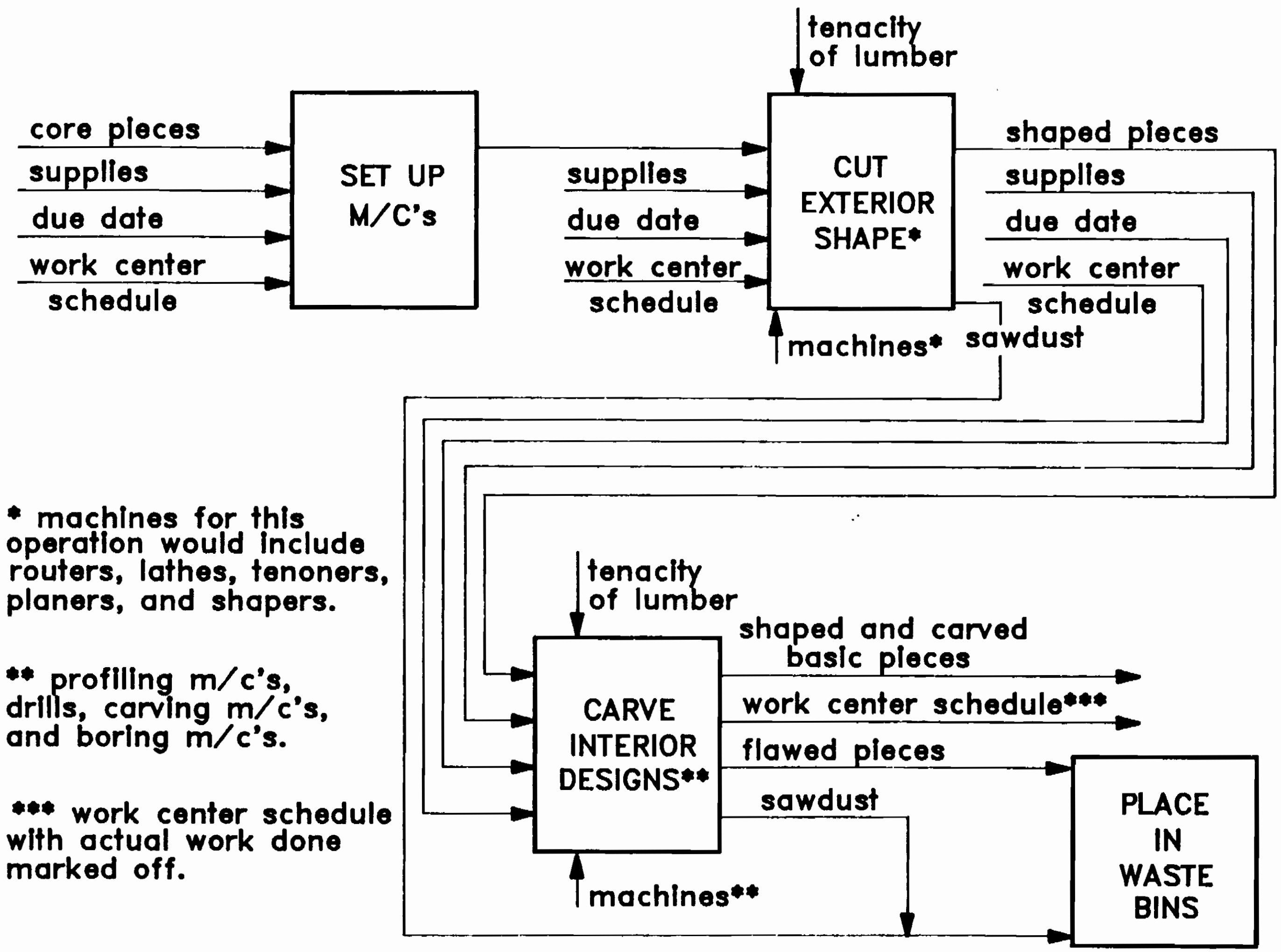
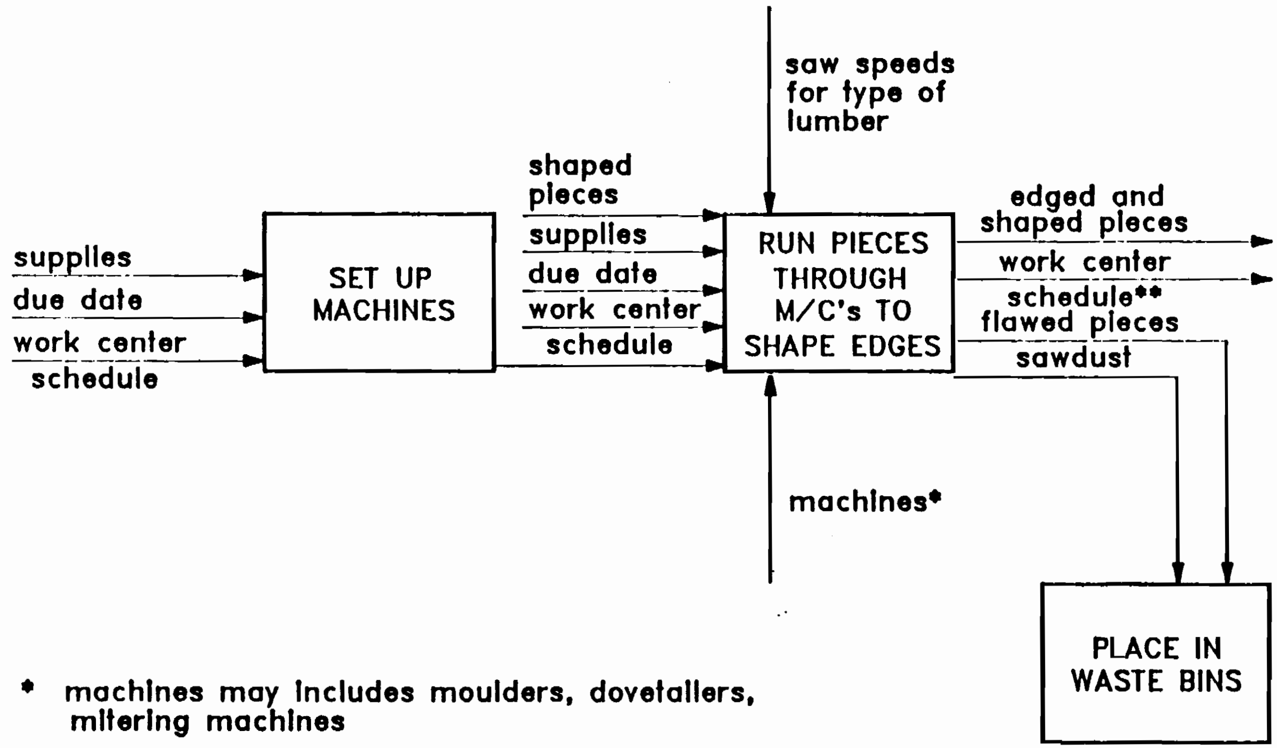


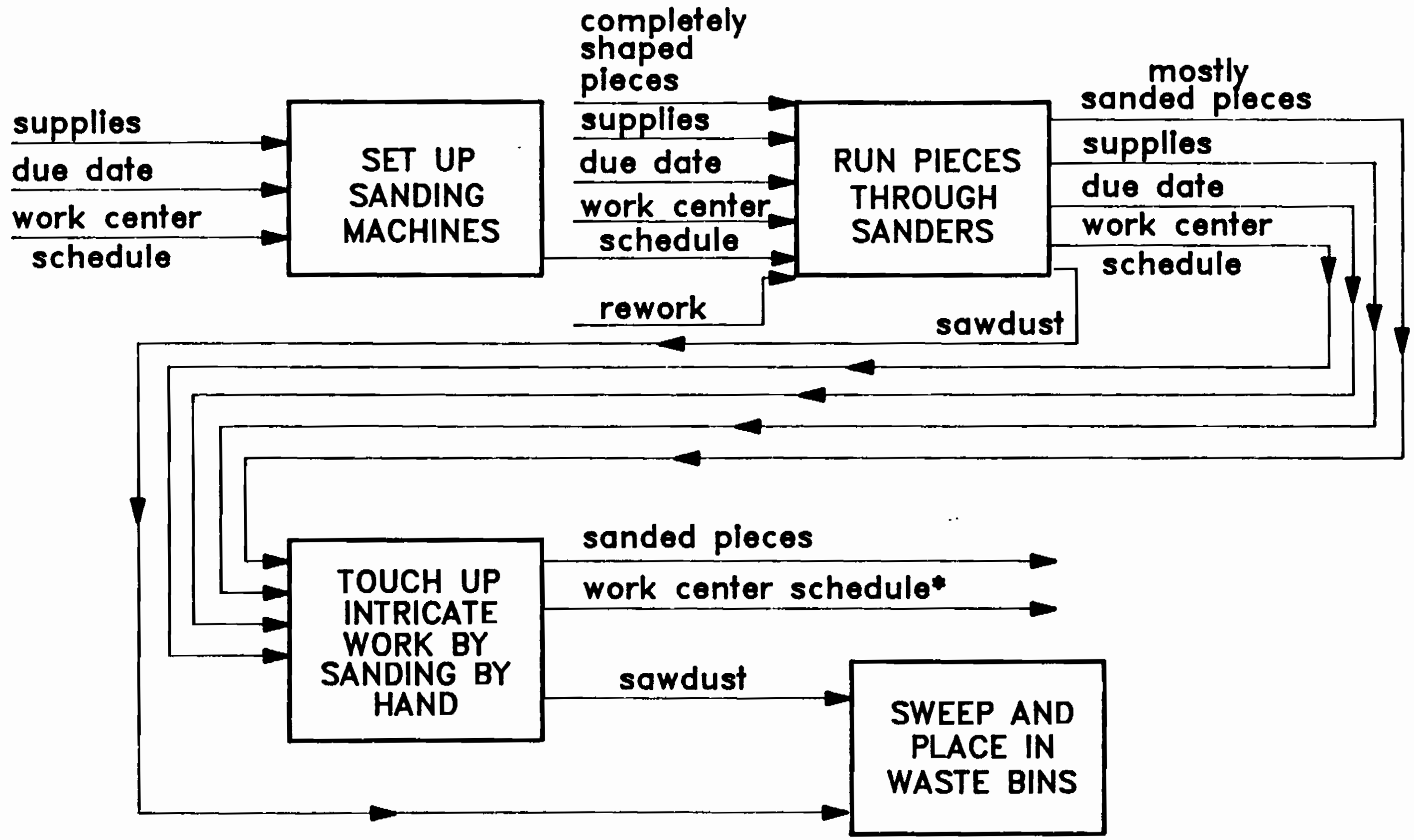
Figure B.12--1A41 Cut Out Basic Shapes



* machines may includes moulders, dovetailers, mitering machines

** work center schedule with actual work done marked off.

Figure B.13--1A42 Shape Edges



* work center schedule with actual work done marked off.

Figure B.14--1A43 Sand Pieces

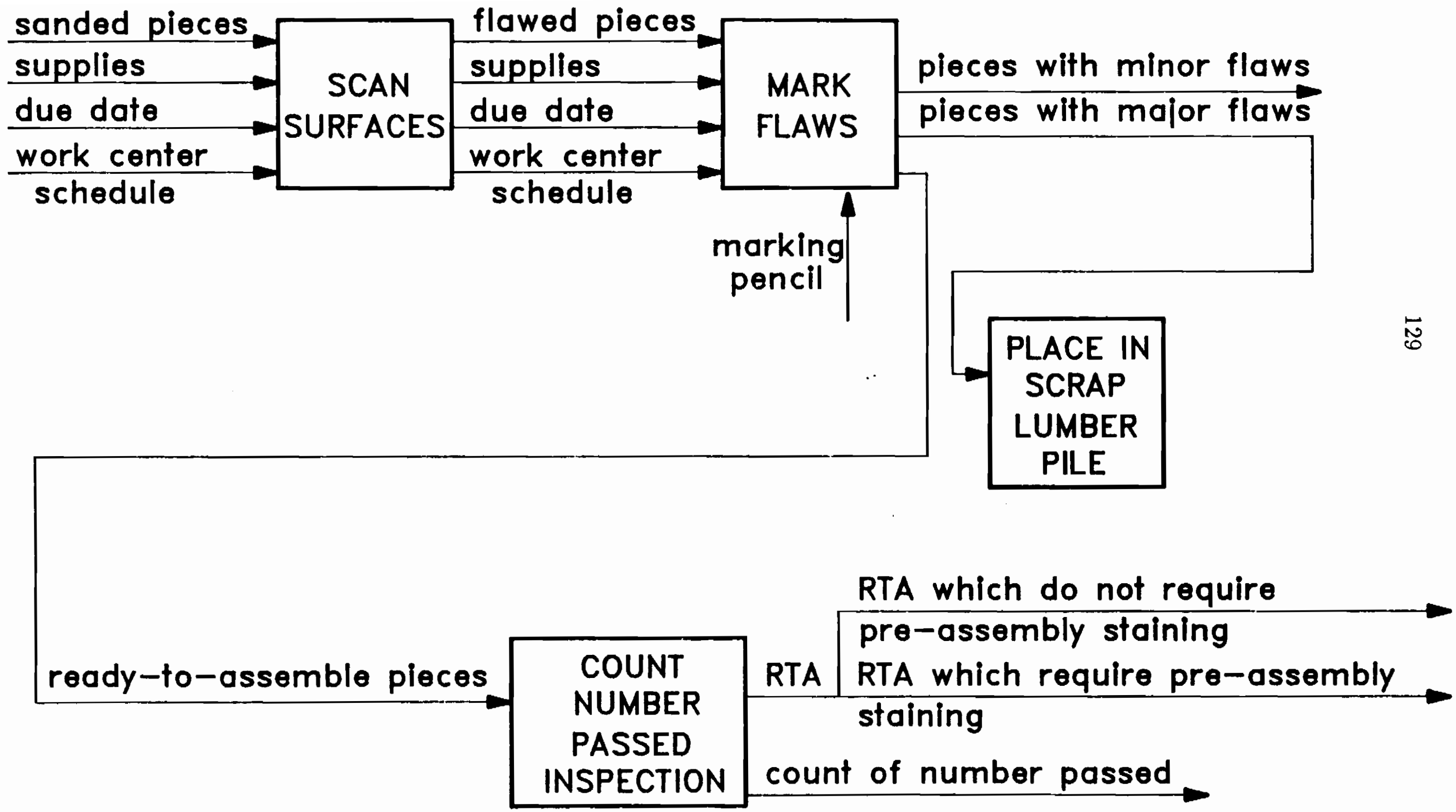


Figure B.15--1A44 Inspect Pieces

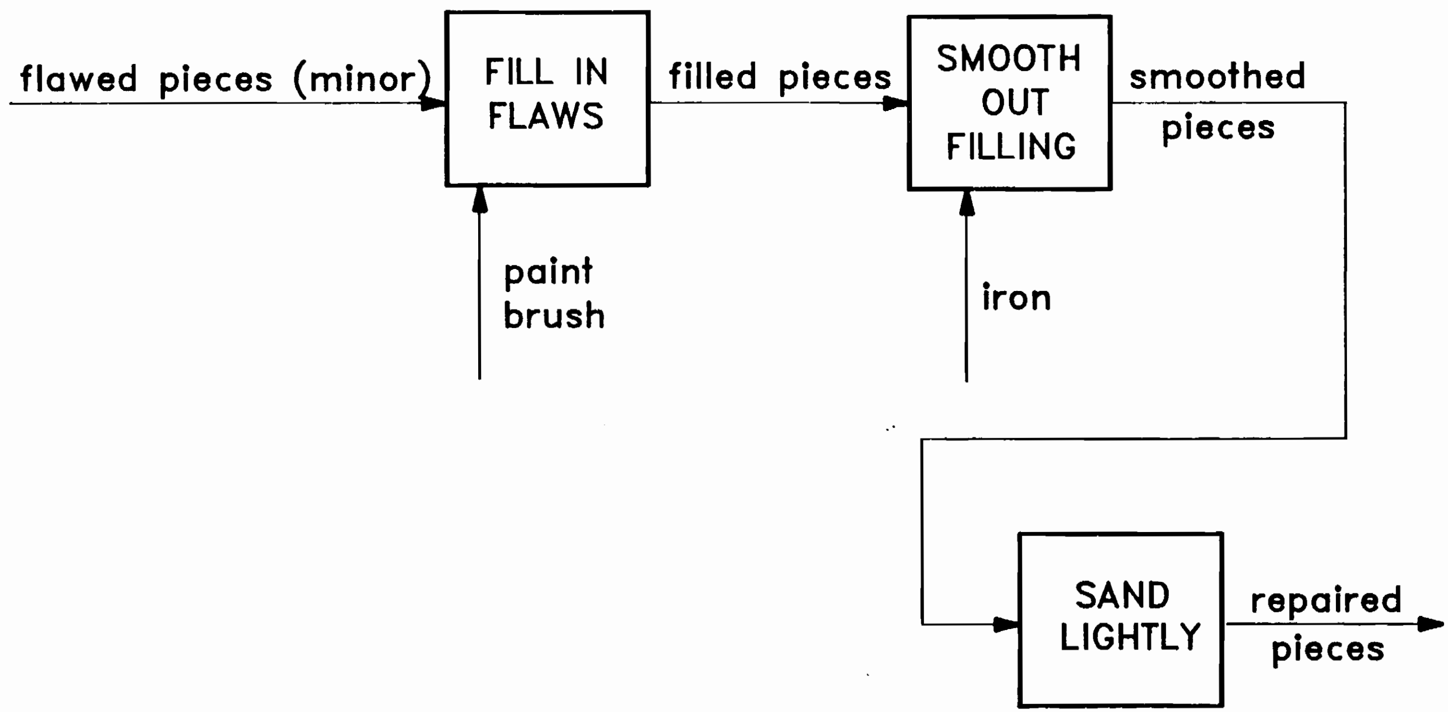


Figure B.16--1A45 Rework Flawed Pieces

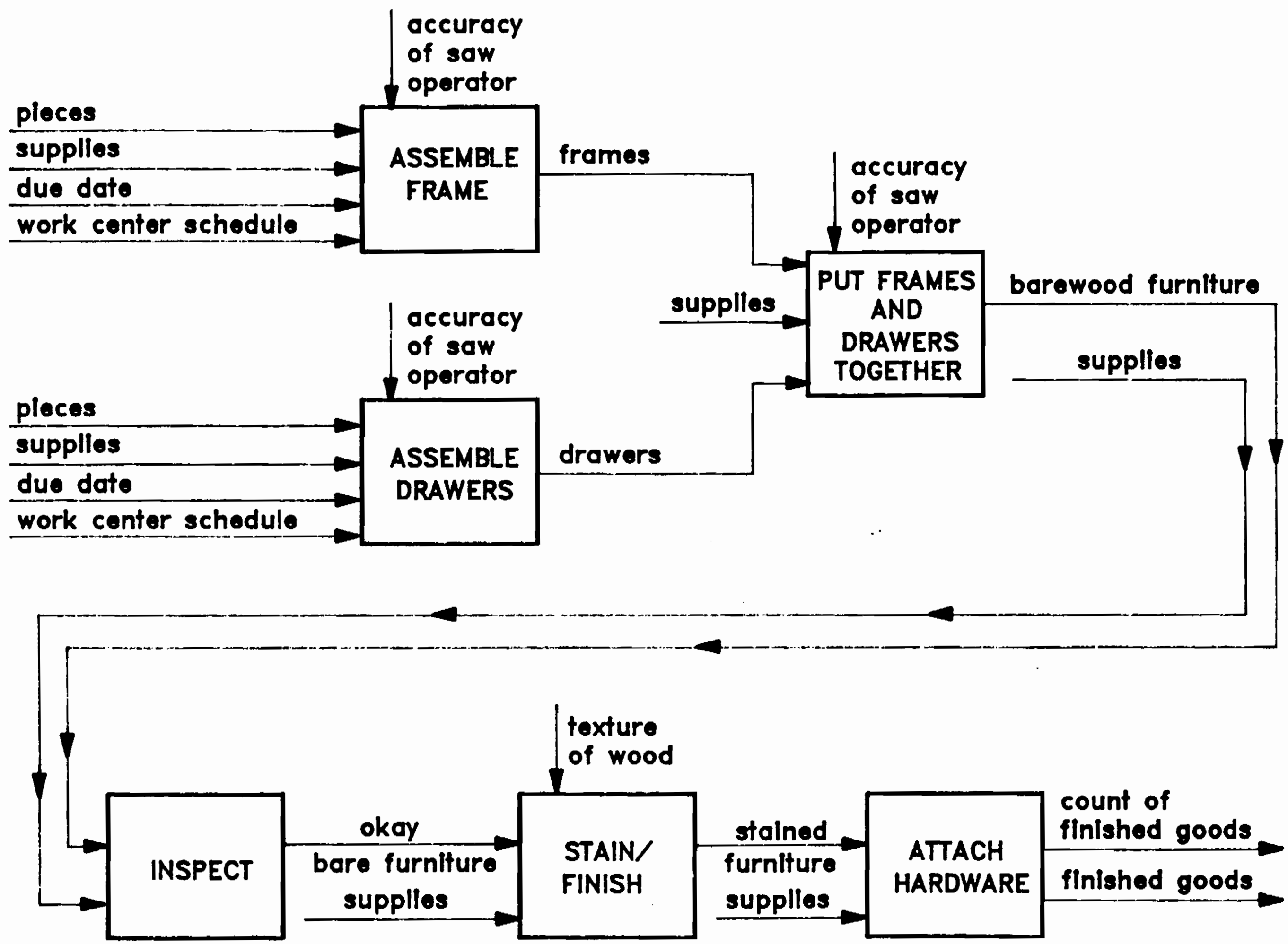


Figure B.17 1A5 Assemble Parts

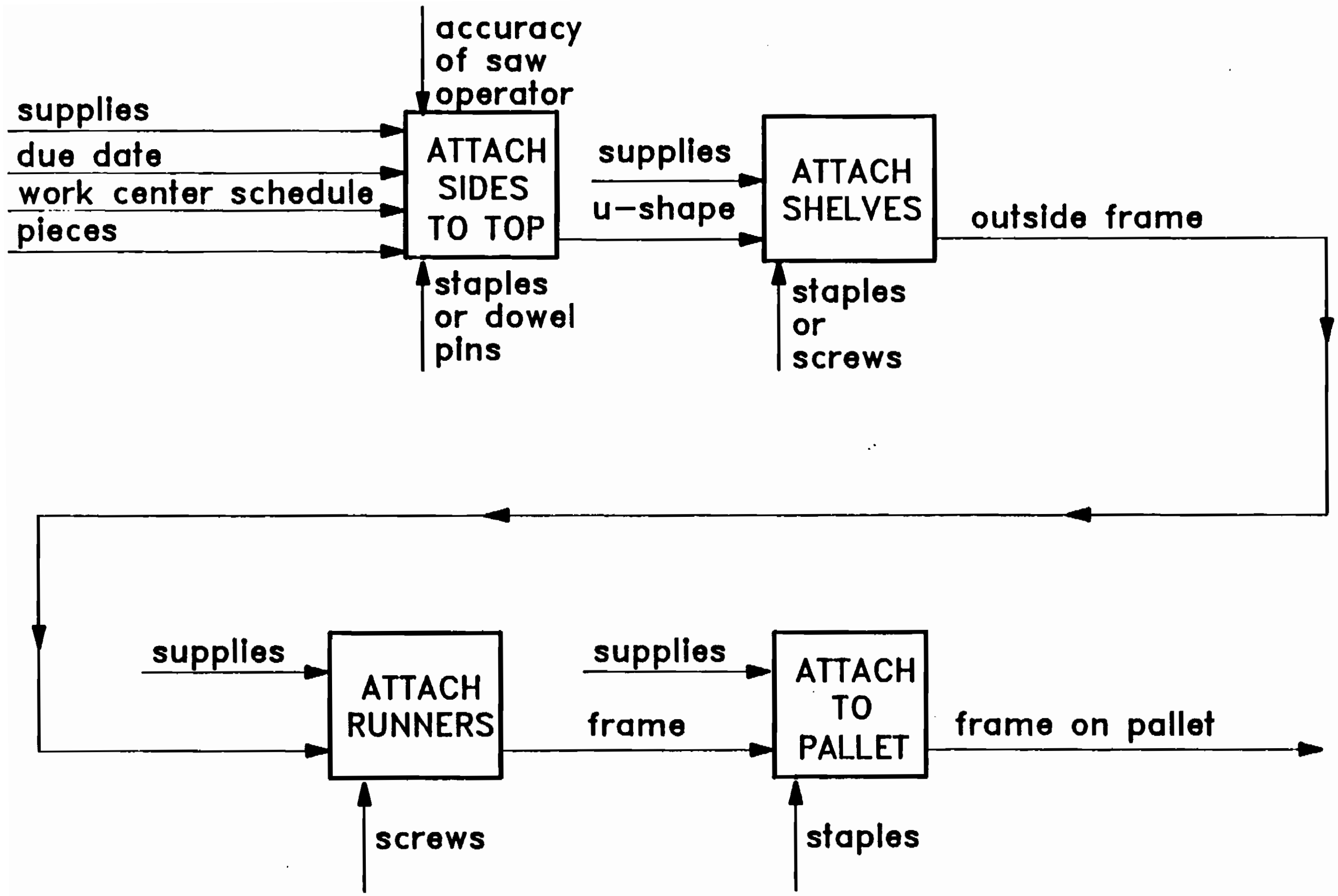


Figure B.18--1A51 Assemble Frame

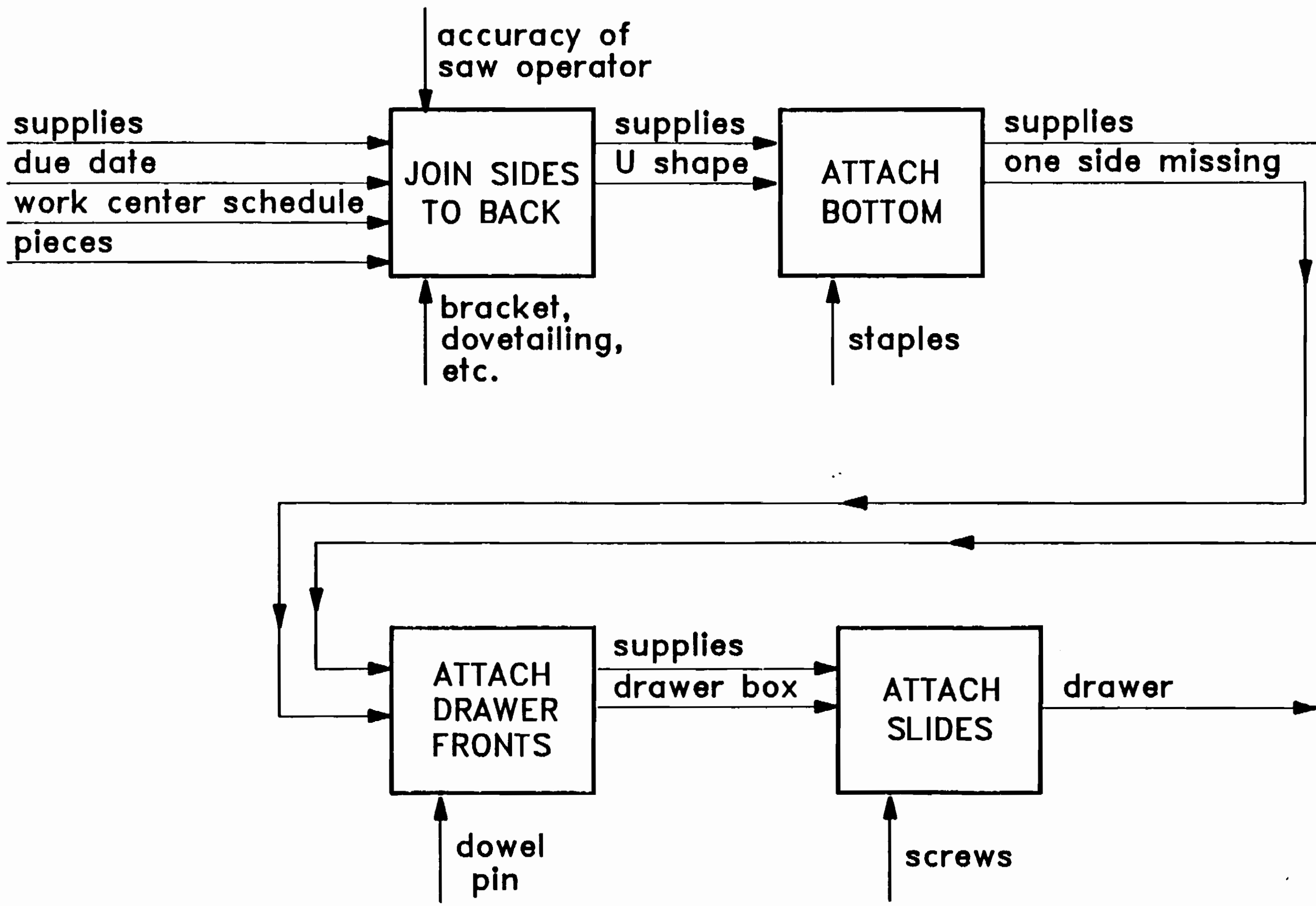


Figure B.19--1A52 Assemble Drawers

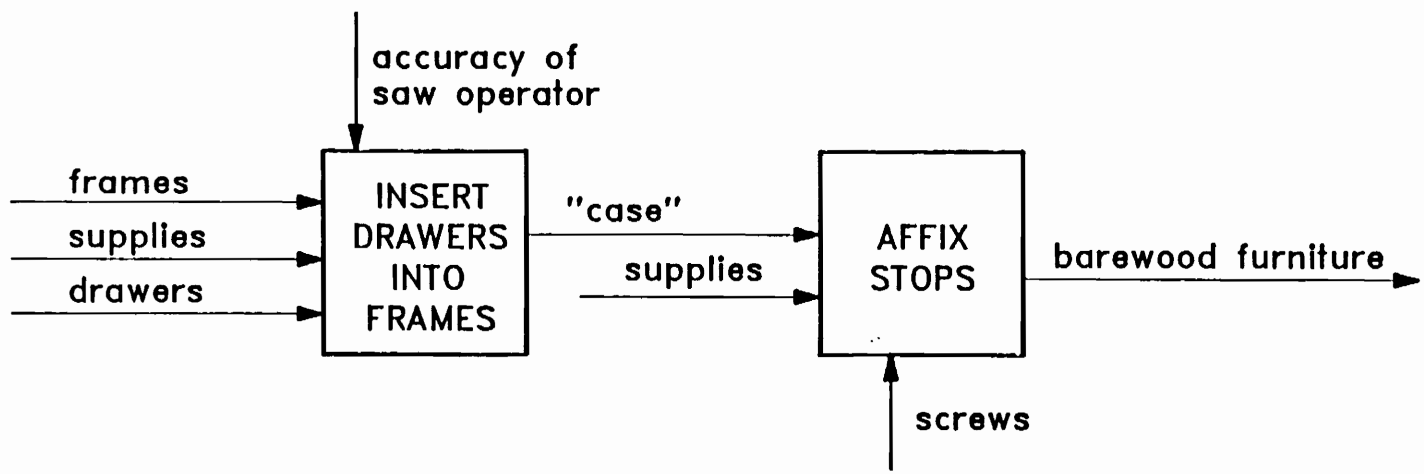


Figure B.20--1A53 Put Frames and Drawers Together

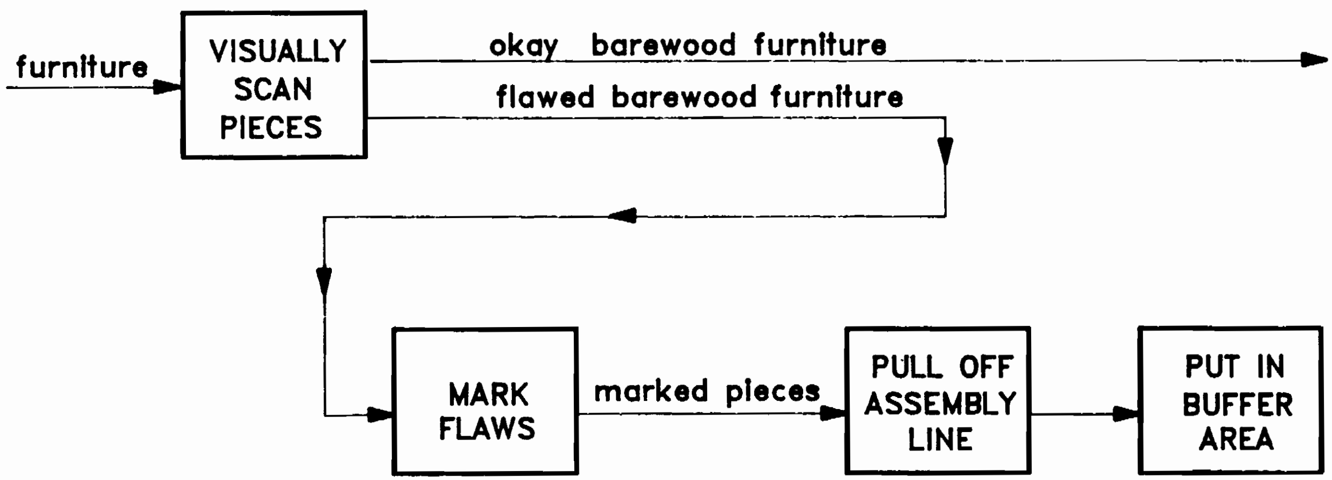


Figure B.21 1A54 Inspect

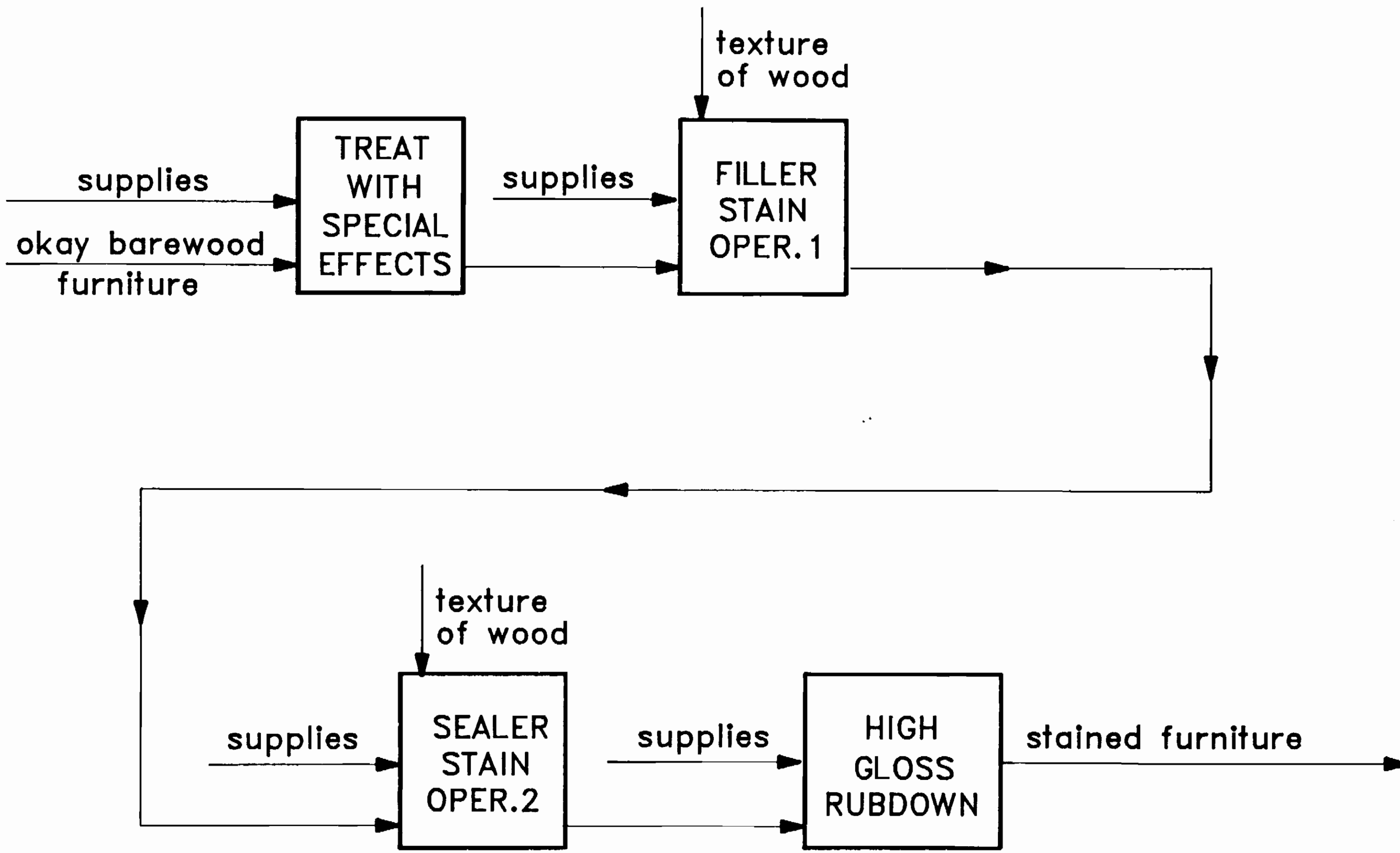


Figure B.22--1A55 Stain/Finish

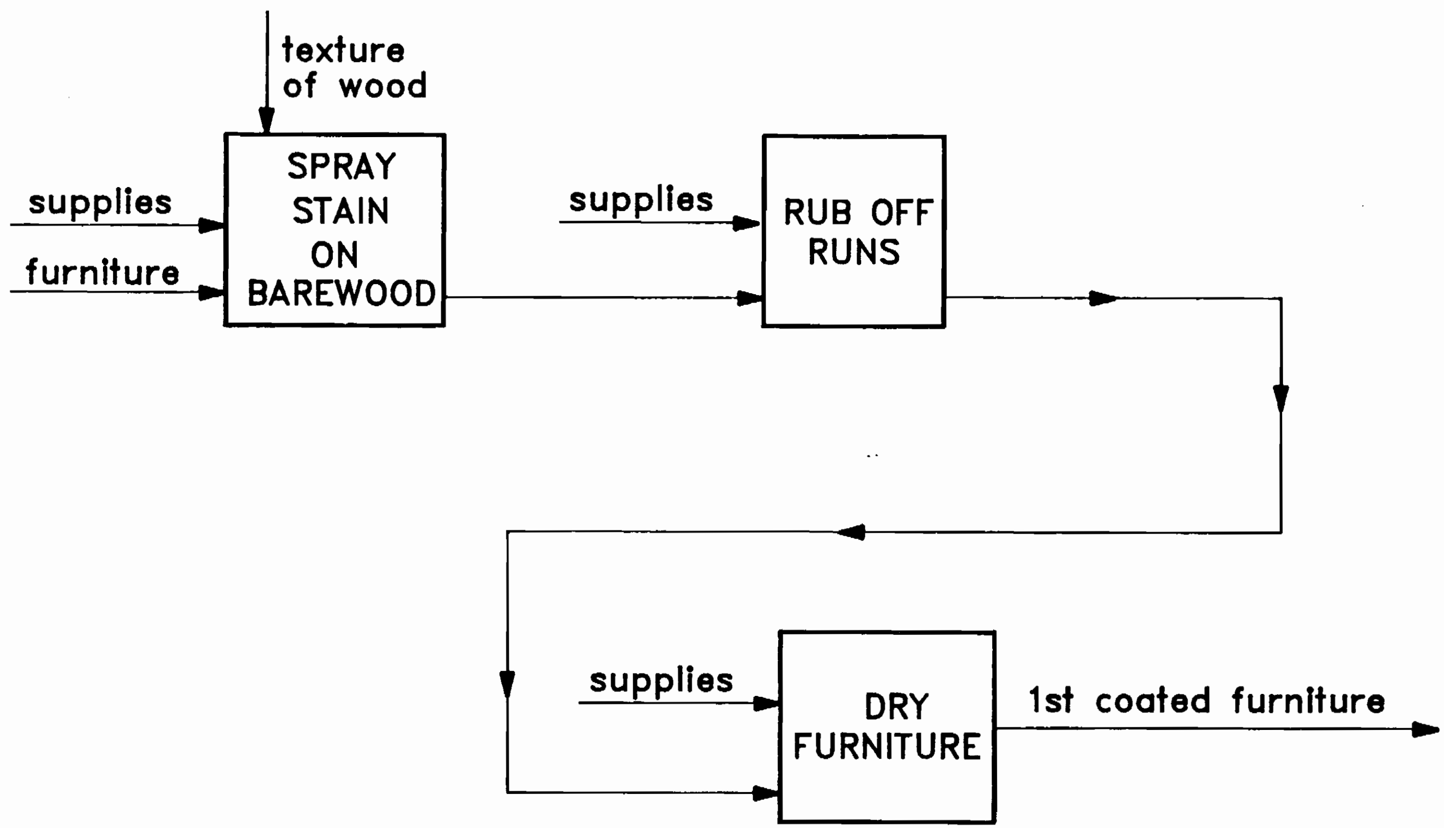


Figure B.23--1A552 Filler Stain (Operation 1)

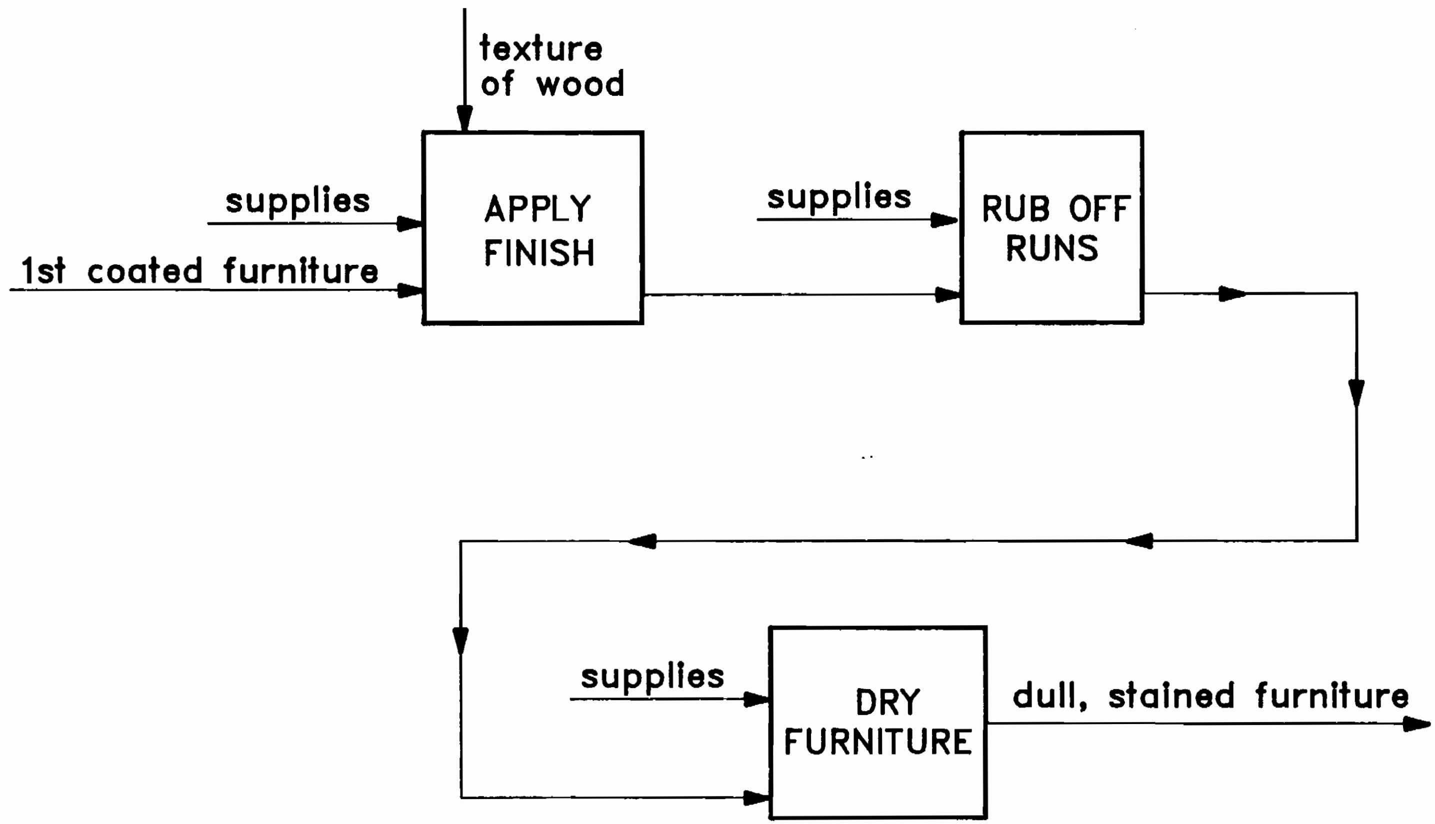


Figure B.24--1A553 Sealer Stain (Operation 2)

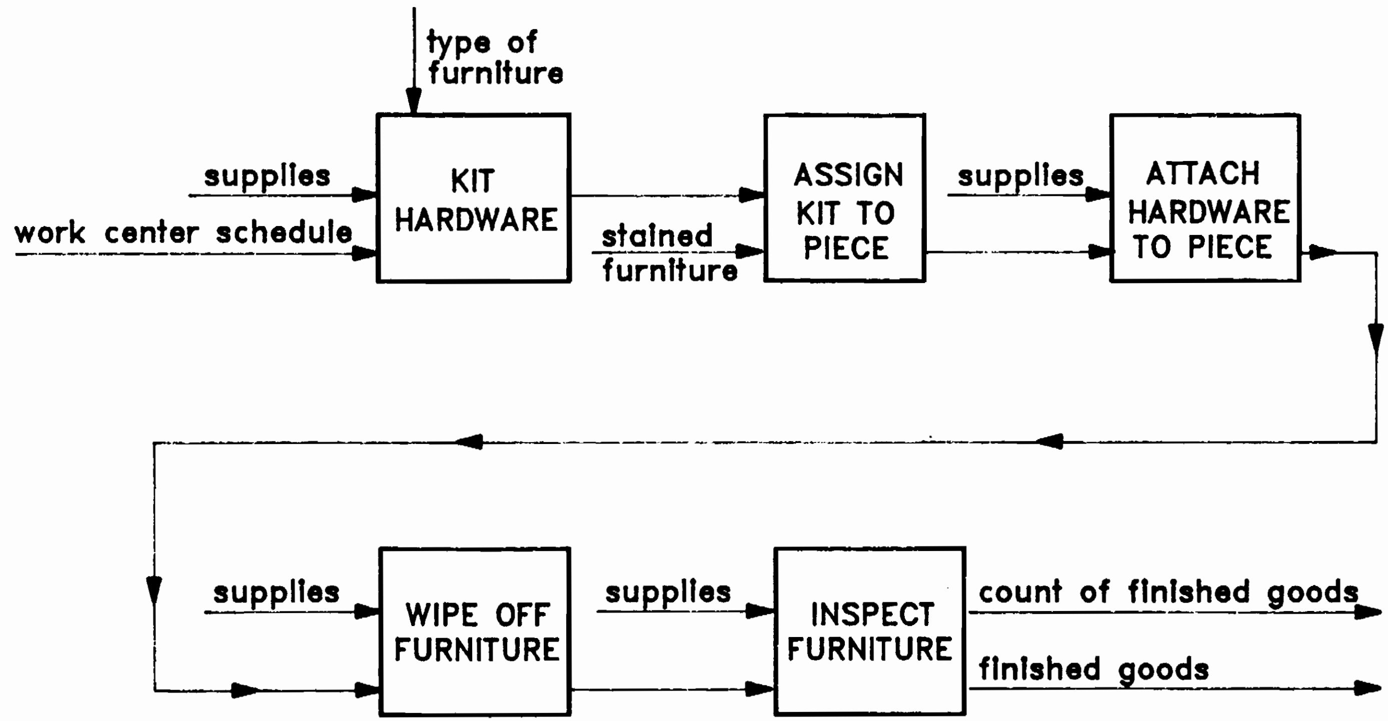


Figure B.25 1A56 Attach Hardware

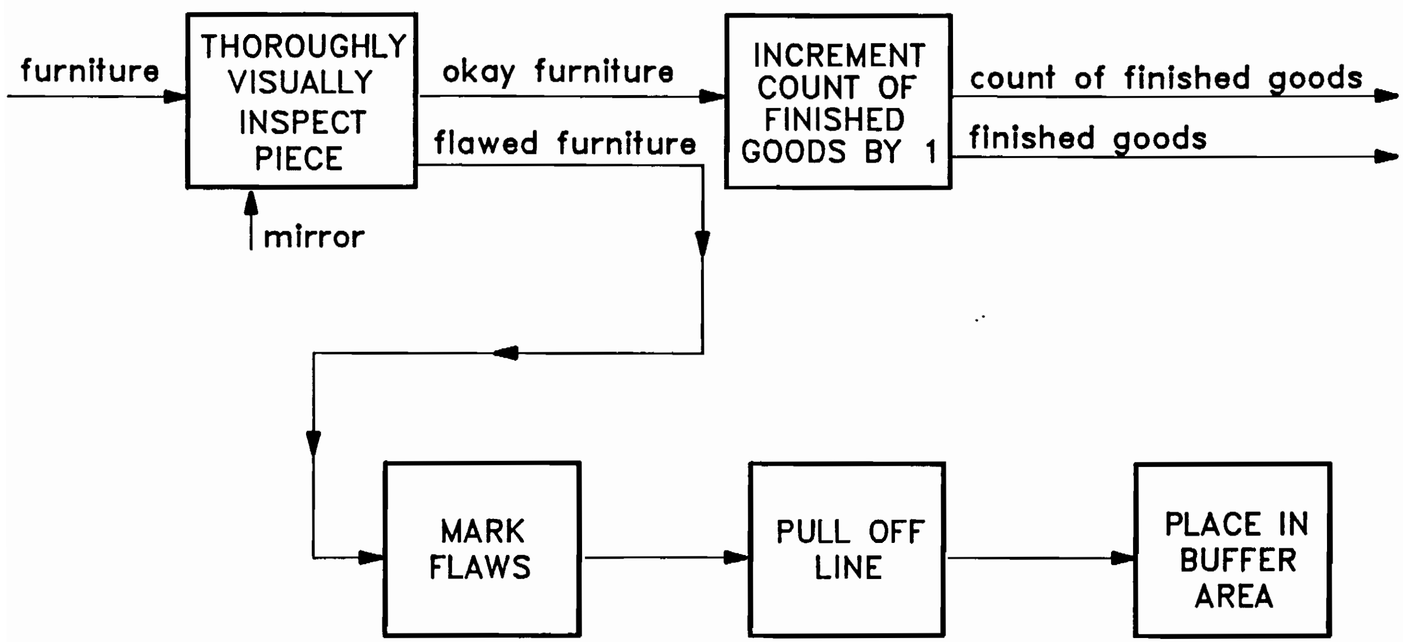


Figure B.26--1A565 Inspect Furniture

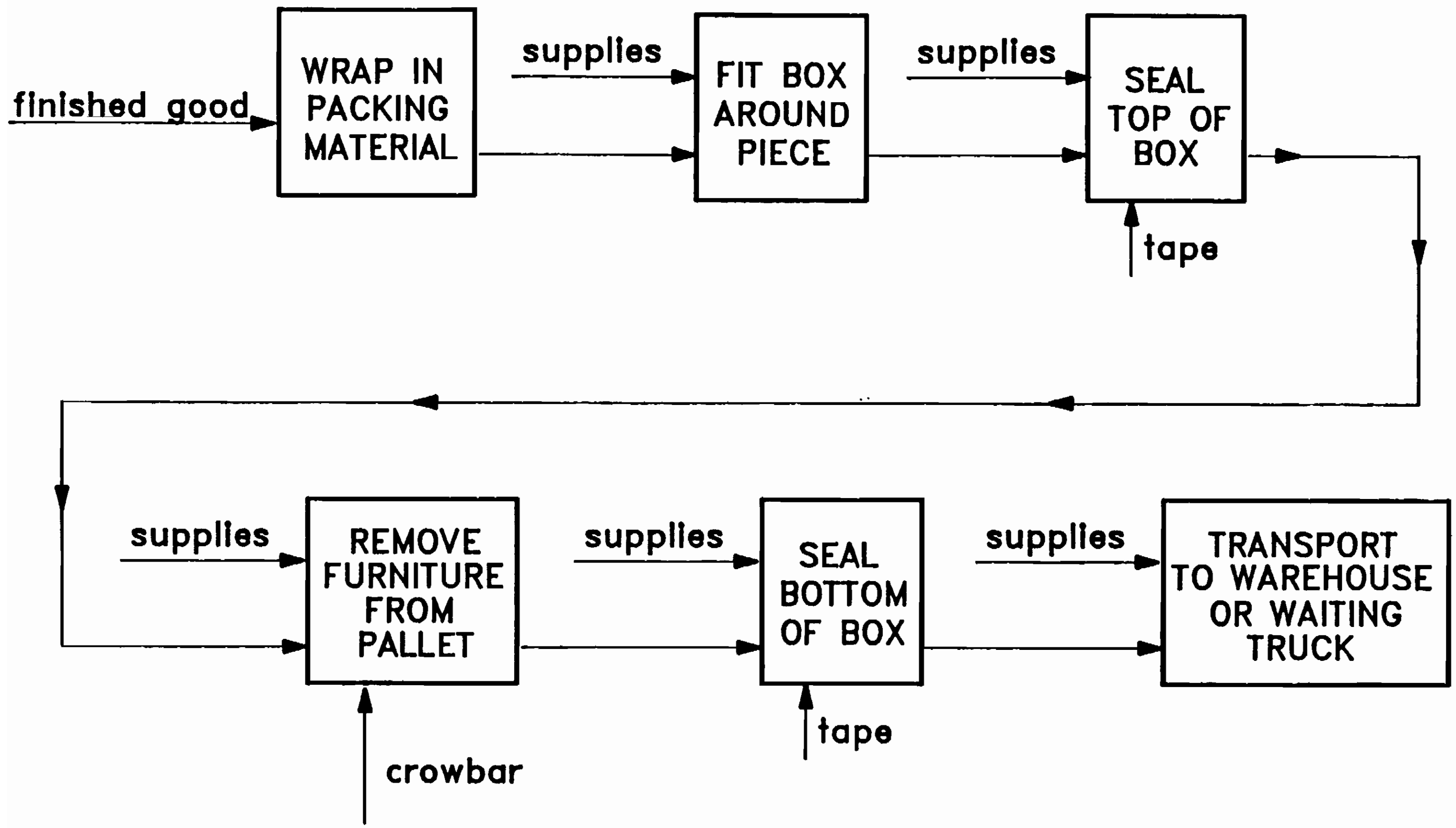


Figure B.27--1A6 Pack and Ship

Appendix C

Node Index

1A. Overview

1A1. Prepare order

1A11. Prepare cutting order

1A111. Determine where on (master) schedule order is to be placed

1A112. Determine bill of materials

1A113. Establish work center schedules

1A12. Procure supplies

1A121. Deduct on-hand inventory from bill of materials *and* update on-hand inventory records

1A122. Cut purchase orders

1A123. Place order with vendor

1A2. Prepare lumber

1A21. Stack boards of one kind of lumber

1A22. Kiln dry boards

1A221. Get stack(s) of boards of type of lumber specified on work center schedule

1A222. Move/put in kiln and adjust controls

1A3. Dimension pieces

1A31. Crosscut boards

1A311. Scan board for defect information

1A312. Determine where crosscuts should go to get largest clear area of desired length

1A313. Crosscut boards

1A314. Place in waste bins

1A32. Rip boards

1A321. Set saw blades for desired widths

1A322. Feed boards through rip saw

1A323. Place in waste bins

1A33. Separate boards by length

1A34. Glue boards together

1A341. Load selector

1A342. Scan pieces

1A343. Select pieces such that the total width when glued together comes closest to desired width without being under desired width

1A344. Apply glue

1A345. Put boards together and dry

1A346. Apply veneer or vinyl coating

1A35. Trim pieces

1A4. Shape pieces

1A41. Cut out basic shapes

1A411. Set up machines

1A412. Cut exterior shape

1A413. Carve interior designs

1A414. Place (flawed pieces and sawdust) in waste bins

1A42. Shape edges

1A421. Set up machines

1A422. Run pieces through machines to shape edges

1A423. Place (flawed pieces and sawdust) in waste bins

1A43. Sand pieces

1A431. Set up sanding machines

1A432. Run pieces through sanders

1A433. Touch up intricate work by sanding by hand

1A434. Sweep (sawdust) and place in waste bins

1A44. Inspect pieces

1A441. Scan surfaces

1A442. Mark flaws

1A443. Place in scrap lumber pile

1A444. Count number passed inspection

1A45. Rework flawed pieces

1A451. Fill in flaws

1A452. Smooth out filling

1A453. Sand lightly

1A5. Assemble parts

1A51. Assemble frame

1A511. Attach sides to top

1A512. Attach shelves

1A513. Attach runners

1A514. Attach to pallet

1A52. Assemble drawers

1A521. Join sides to back

1A522. Attach bottom

1A523. Attach drawer fronts

1A524. Attach slides

1A53. Put frames and drawers together

1A531. Insert drawers into frames

1A532. Affix stops

1A54. Inspect

1A541. Visually scan pieces

1A542. Mark flaws

1A543. Pull off assembly line

1A544. Put in buffer area

1A55. Stain/Finish

1A551. Treat with special effects

1A552. Filler stain (operation 1)

1A5521. Spray stain on bare wood

1A5522. Rub off runs

1A5523. Dry furniture

1A553. Sealer stain (operation 2)

1A5531. Apply finish

1A5532. Rub off runs

1A5533. Dry furniture

1A554. High gloss rubdown

1A56. Attach hardware

1A561. Kit hardware

1A562. Assign kit to piece

1A563. Attach hardware to piece

1A564. Wipe off furniture

1A565. Inspect furniture

1A5651. Thoroughly visually inspect piece

1A5652. Increment count of finished goods by one

1A5653. Mark flaws

1A5654. Pull off line

1A5655. Place in buffer area

1A6. Pack and ship

1A61. Wrap in packing material

1A62. Fit box around piece

1A63. Seal top of box

1A64. Remove furniture from pallet

1A65. Seal bottom of box

1A66. Transport to warehouse or waiting truck

Appendix D

Table D.1--Selected Research on the SLUR Problem

Description of Work	Classification Criteria[a]					Strength	Weakness
	C	G	O	S	T		
Harris (1915): Economic Order Quantity (EOQ)	Good	Poor	Yes	Fair	N/A	First quantitative formulation for lot sizing	Optimal only for constant demand rate and static cost parameters
Wagner-Whitin (WW) (1958): Optimal lot sizing with varying demand pattern	Poor	Good	Yes	Poor	N/A	Optimal for discrete demand pattern	Compared to other SLUR techniques, more difficult to understand and requires more computation effort
Kaiman (1969): Compares EOQ with WW	N/A	N/A	N/A	N/A	Fair	Tests control for demand variations and setup times	Tests limited to 25 sample problems
Berry (1972): Compares EOQ< POQ, PPB and WW	N/A	N/A	N/A	N/A	Fair	Tests control for demand variations and EOQ/average demand ratio	As above
Silver and Meal (1973): Proposes heuristic based on average cost per period	Good	Good	No	Good	Fair	Simplicity and computational effort make it attractive for capacity constrained problems	As above
Carlson, Jucker and Kropp (1979): Propose heuristic to dampen system nervousness	Poor	Good	Yes	Poor	N/A	Revise WW to include schedule-change cost	Same as WW
Blackburn and Millen (1980): Compare PPB, Silver-Meal, WW	N/A	N/A	N/A	N/A	Good	Test in rolling schedule environment	Tests assume perfect demand forecasts

[a] C = computational effort, compared to other SLUR procedures, G = generality to all SLUR problems, O = optimality, S = simplicity in understanding, T = thorough testing, if heuristic.

Table D.2 Selected Research on SLCR Problem

Description of Work	Classification Criteria[a]					Strength	Weakness
	C	G	O	S	T		
Manne (1958): Lot sizing with resource constraints	Poor	Good	No	Fair	Poor	Novel problem formulation amenable to linear programming	Large number of variables; nonoptimal solution
Dzielinski, Baker and Manne (1963): Simulation tests of using EOQ vs Manne's model	N/A	N/A	N/A	N/A	N/A	Tests Manne's approach	Tested with only one real-life problem
Dzielinski and Gomory (1965): Applies Dantzig-Wolfe Decomposition to Manne's model	Fair	Good	No	Poor	Fair	Larger problems are amenable to solution	Lacks simplicity in understanding
Lasdon and Terjung (1967): Applies Column Generation methods to Manne's model	Good	Good	No	Poor	Fair	Computational efficiency over earlier approaches; better bounds on solution	Lacks simplicity in understanding
Newson (1975): Heuristic method for lot sizing problem	Good	Fair	No	Fair	Fair	Computational savings	Not tested for multiple work centers
Haessler (1979): Simple heurisitc for ELSP	Good	Poor	No	Good	Poor	Simple and efficient	Assumes constant demand and single resource
Dixon and Silver (1981): Single-resource heuristic	Good	Poor	No	Good	Good	Very good solutions with little computational effort	Single resource; setup times assumed negligible

Table D.2--Selected Research on SLCR Problem (cont'd)

Description of Work	Classification Criteria[a] C	G	O	S	T	Strength	Weakness
Aras and Swanson (1982): Single-resource heuristic to expanded problem	Good	Good	No	Good	Fair	Incorporates sequencing decisions; setup times apply to capacity constraints	Single resource and limited testing
Bahl and Ritzman (1983): Heuristic method for Manne's formulation	Good	Good	No	Good	Fair	Additional computational savings	Limited testing
Bahl (1983): Heuristic method for Manne's formulation	Good	Good	No	Poor	Fair	Efficiency gains over column generation	Limited testing
Daniels (1983): Multiple-resource heuristic to expanded problem	Good	Good	No	Fair	Fair	Incorporates sequencing decisions; sequence dependent setups are part of capacity constraints; multiple resources	Heuristic method, and lacks transparency in understanding

[a] C = computational effort, compared to other SLCR procedures, G = generally to all SLCR problems, O = optimality, S = simplicity in understanding, T = thorough testing, if heuristic.

Table D.3--Selected Research on MLUR Problem

Description of Work	Classification Criteria[a]					Strength	Weakness
	C	G	O	S	T		
Schussel (1968): Proposes Economic Lot Release Size model	Fair	Fair	No	Good	Poor	Introduces notion of multi-pass heuristic	One end item, no commonality, and untested
Zangwill (1969): Dynamic programming model with back-logging	Poor	Poor	Yes	Poor	N/A	Provides optimal solution to specialized MLUR subproblem	Limited to one-parent, one component system and excessive computational requirements
Crowston, Wagner and H-nnhrey (1972): Compares single, multi-pass and modified multi-pass procedure	Fair	Fair	No	Fair	Fair	Demonstrates near optimality of heuristic procedures	No commonality; limited set of test problems
Crowston and Wagner (1973): Crowston, Wagner and Williams Dynamic programming models when demands are at a constant rate, or vary	Poor	Fair	Yes	Poor	N/A	Provides benchmark for testing subsequent heuristics	No commonality; excessive computational requirements
McLaren (1976): Develops cost parameter adjustment rules for single pass application of SLUR heuristics	Good	Fair	No	Good	Good	Simplicity in use for single-pass procedures	Commonality not allowed
Steinberg and Napier (1980): Constrained generalized network formulation	Poor	Good	Yes	Poor	N/A	Allows for commonality	Excessive computational requirements

Table D.3--Selected Research on MLUR Problem (cont'd)

Description of Work	Classification Criteria[a]					Strength	Weakness
	C	G	O	S	T		
Afentakis, Gavish and Karmarkar (1984): Branch-and-bound algorithm using Lagrangian relaxation	Fair	Good	Yes	Poor	Good	Optimal solutions for at least moderately sized problems	Excessive computational requirements
Graves (1981): Multi-pass heuristic allowing for commonality	Fair	Good	No	Fair	Fair	Allows for commonality and computational time may be attractive	Untested for larger problems with commonality
Blackburn and Millen (1982): Extends McLaren's ideas on modifying cost parameters	Good	Fair	No	Good	Good	Allows a single-pass procedure with simple SLUR rules	Commonality not allowed. Departures from optimality increase with product levels

[a] C = computational effort, compared to other mLUR procedures, G = generality to all MLUR problems, O = optimality, S = simplicity in understanding, T = thorough testing, if heuristic.

Appendix E

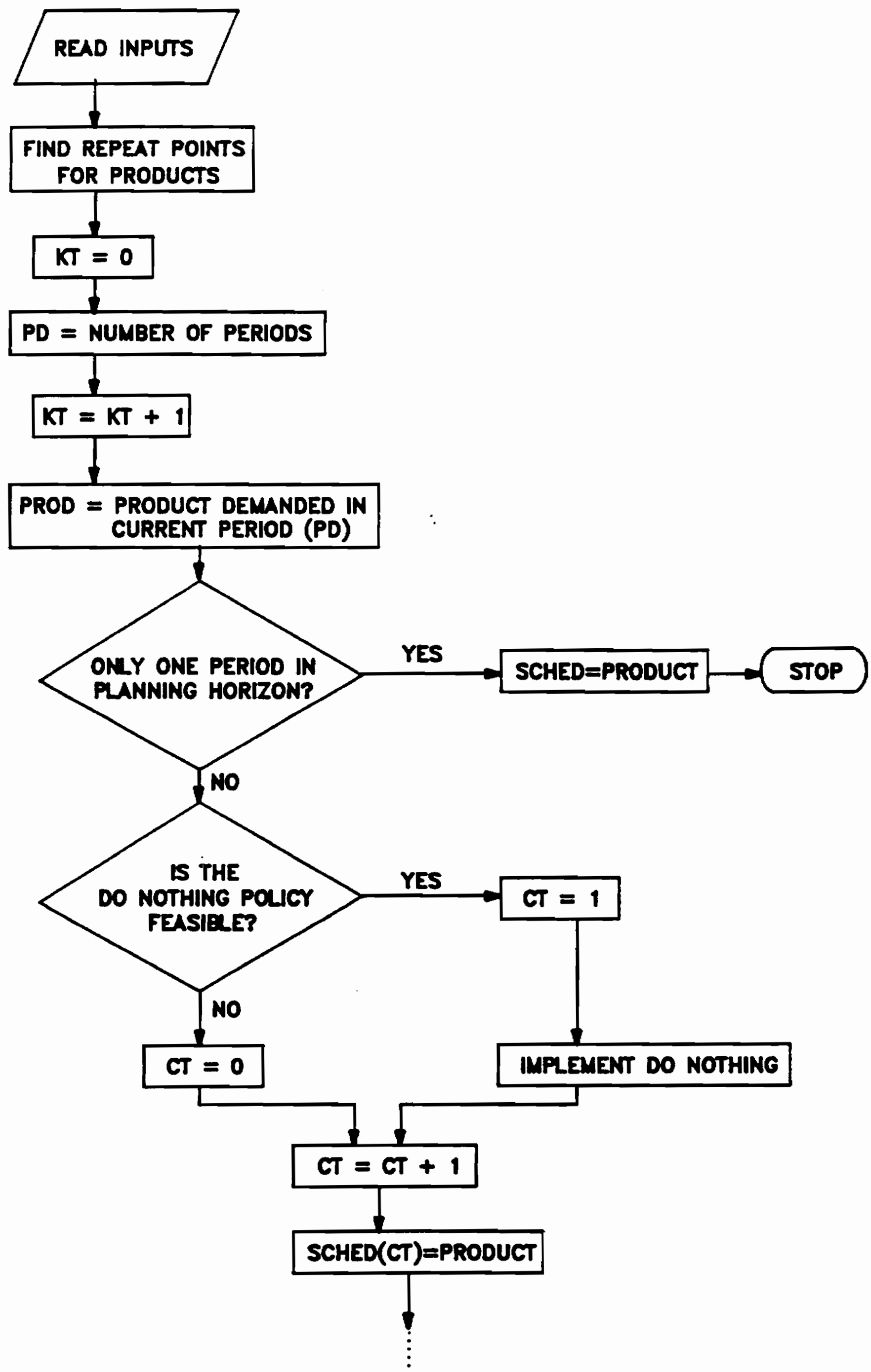
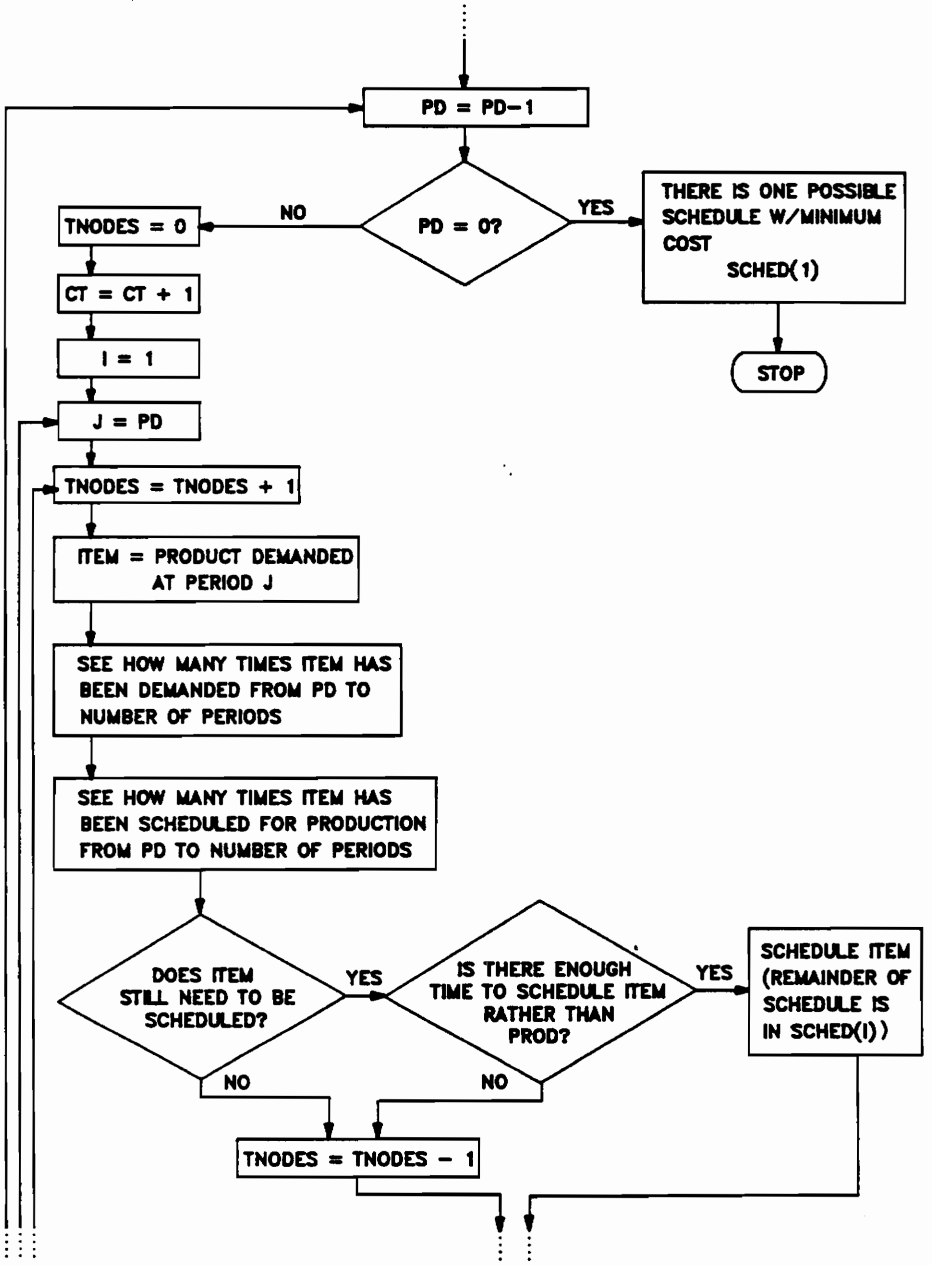
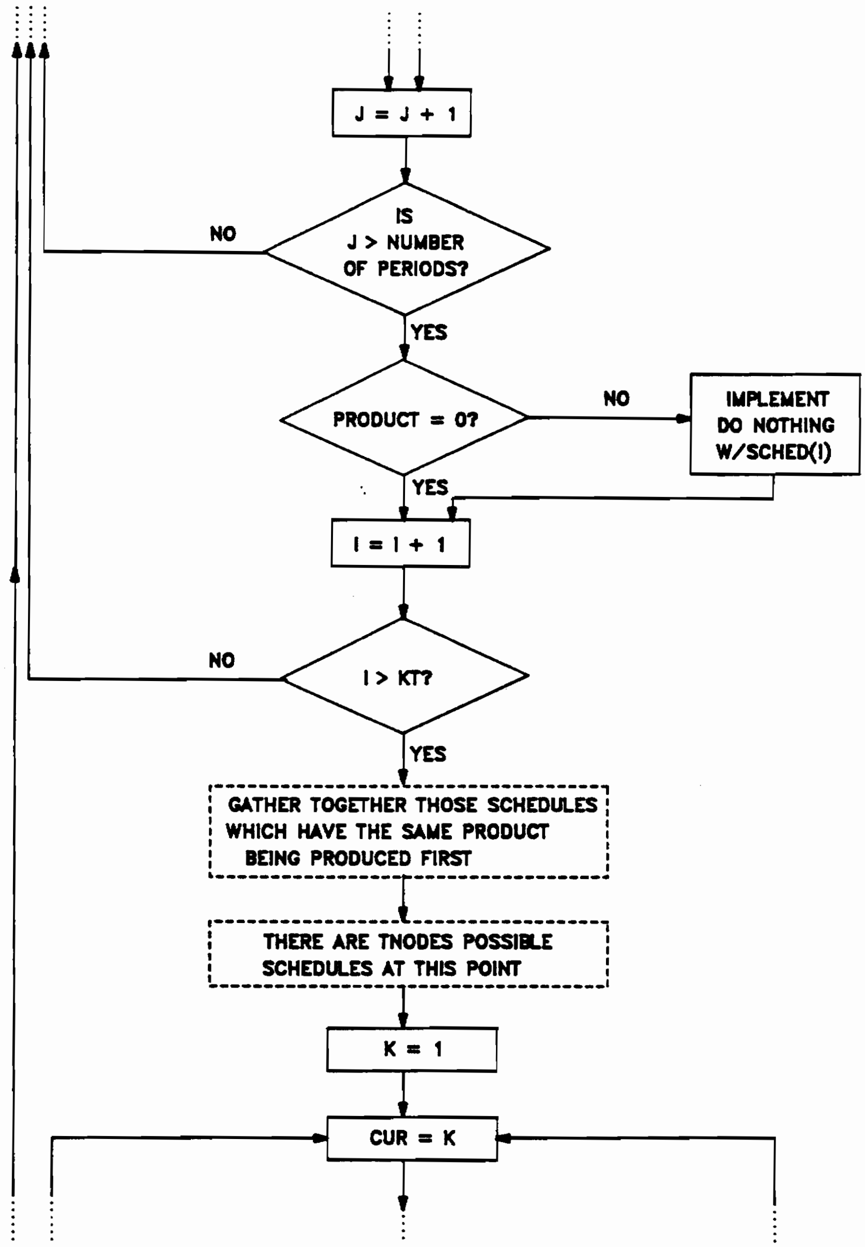
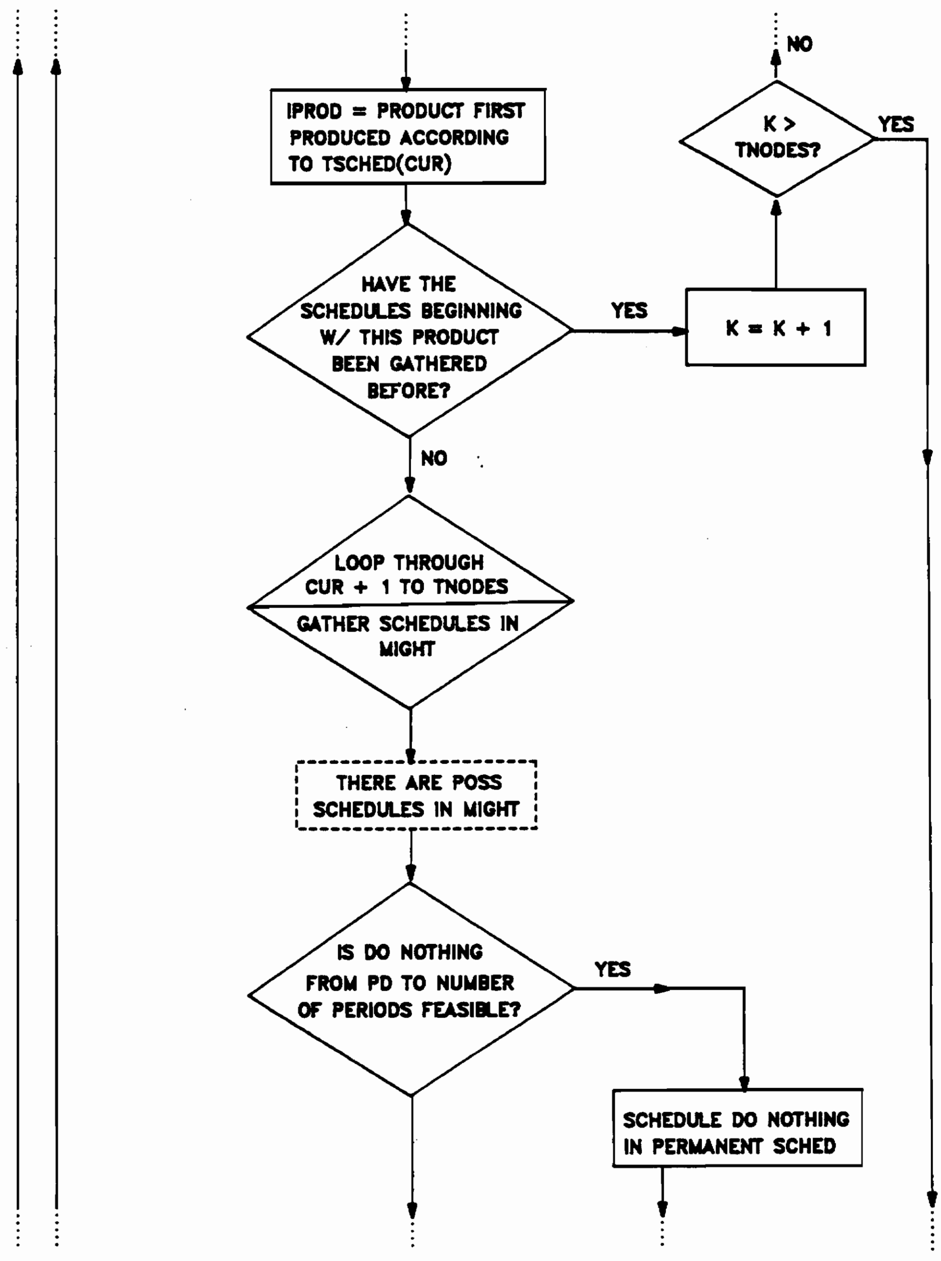


Figure E.1--Flow Chart of DP Logic

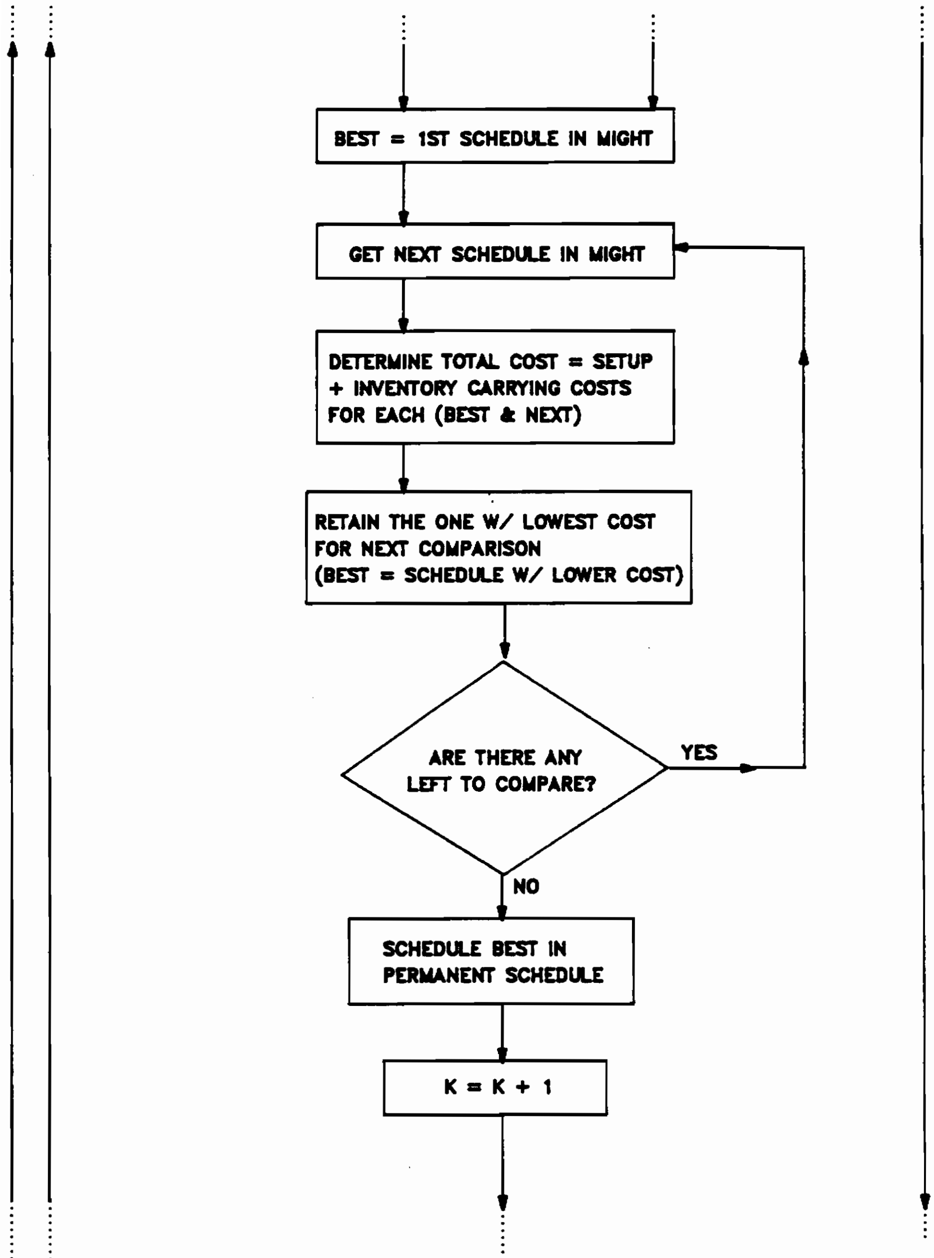

PD = PD-1
PD = 0?
YES
NO
THERE IS ONE POSSIBLE SCHEDULE W/MINIMUM COST
SCHED(1)
STOP
TNODES = 0
CT = CT + 1
I = 1
J = PD
TNODES = TNODES + 1
ITEM = PRODUCT DEMANDED AT PERIOD J
SEE HOW MANY TIMES ITEM HAS BEEN DEMANDED FROM PD TO NUMBER OF PERIODS
SEE HOW MANY TIMES ITEM HAS BEEN SCHEDULED FOR PRODUCTION FROM PD TO NUMBER OF PERIODS
DOES ITEM STILL NEED TO BE SCHEDULED?
YES
NO
IS THERE ENOUGH TIME TO SCHEDULE ITEM RATHER THAN PROD?
YES
NO
SCHEDULE ITEM (REMAINDER OF SCHEDULE IS IN SCHED(I))
TNODES = TNODES - 1

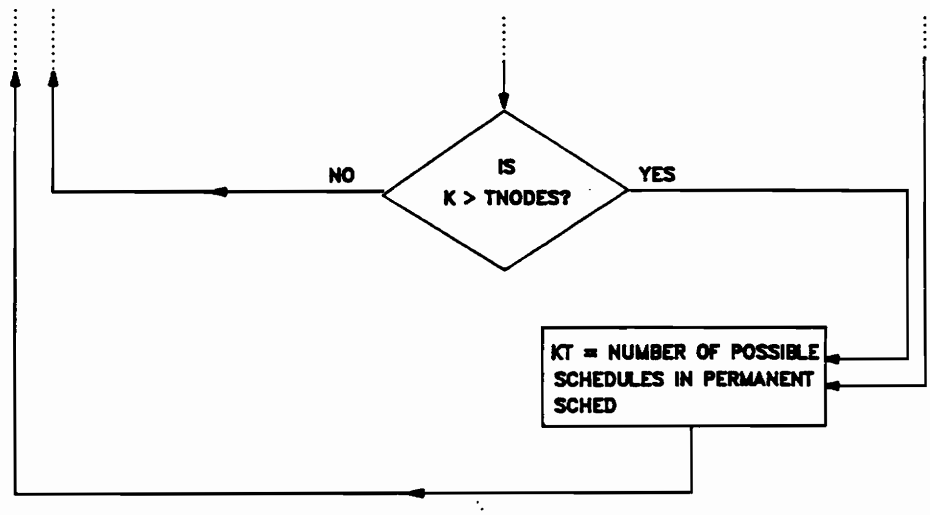


J = J + 1
IS J > NUMBER OF PERIODS?
NO
YES
PRODUCT = 0?
NO
IMPLEMENT DO NOTHING W/SCHED(I)
YES
I = I + 1
I > KT?
NO
YES
GATHER TOGETHER THOSE SCHEDULES WHICH HAVE THE SAME PRODUCT BEING PRODUCED FIRST
THERE ARE TNODES POSSIBLE SCHEDULES AT THIS POINT
K = 1
CUR = K



NO
IPROD = PRODUCT FIRST PRODUCED ACCORDING TO TSCHED(CUR)
K > TNODES?
YES
HAVE THE SCHEDULES BEGINNING W/ THIS PRODUCT BEEN GATHERED BEFORE?
YES
K = K + 1
NO
LOOP THROUGH CUR + 1 TO TNODES
GATHER SCHEDULES IN MIGHT
THERE ARE POSS SCHEDULES IN MIGHT
IS DO NOTHING FROM PD TO NUMBER OF PERIODS FEASIBLE?
YES
SCHEDULE DO NOTHING IN PERMANENT SCHED


BEST = 1ST SCHEDULE IN MIGHT
GET NEXT SCHEDULE IN MIGHT
DETERMINE TOTAL COST = SETUP + INVENTORY CARRYING COSTS FOR EACH (BEST & NEXT)
RETAIN THE ONE W/ LOWEST COST FOR NEXT COMPARISON (BEST = SCHEDULE W/ LOWER COST)
ARE THERE ANY LEFT TO COMPARE?
YES
NO
SCHEDULE BEST IN PERMANENT SCHEDULE
K = K + 1


IS
K > TNODES?
NO
YES
KT = NUMBER OF POSSIBLE SCHEDULES IN PERMANENT SCHED

Appendix F

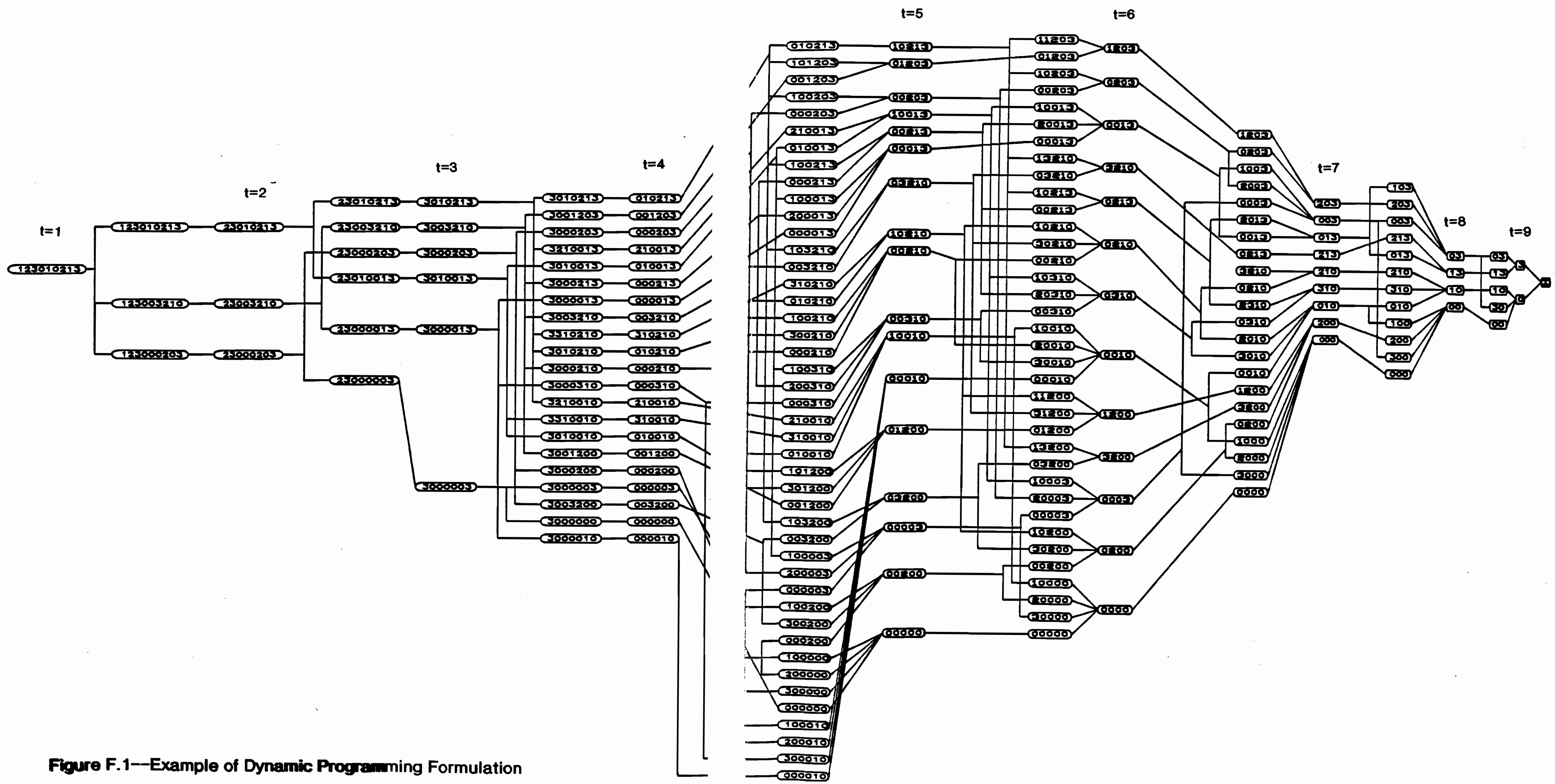


Figure F.1--Example of Dynamic Programming Formulation

Appendix G

Run 1
Setup Data is the same as in Table 4.3

Demand Schedule

125 Units of Product	7 at EOP	1
150	5	2
50	1	3
50	7	4
50	3	5
200	10	6
80	9	7
50	3	8
110	4	10
90	5	11
120	3	12
75	5	13
250	2	14
100	7	15
124	10	16
50	6	17
50	7	18
50	4	19
100	2	20

Inventory Carrying Cost/Unit Product 1/Period is	$2.00
2	2.10
3	2.30
4	3.00
5	3.20
6	3.40
7	2.70
8	2.50
9	2.90
10	2.00

Run 2
Setup Data is the same as in Table 4.3

Demand Schedule

Units	of Product	at EOP
125	3	1
150	1	2
50	6	3
75	3	4
50	5	5
200	2	6
50	10	8
75	7	9
110	8	10
90	6	11
200	9	13
50	10	14
100	9	15
124	2	16
120	7	17
75	8	18
50	7	19
100	2	20

Inventory Carrying Cost/Unit Product 1/Period is $5.00

Product	Cost/Unit/Period
1	$5.00
2	4.25
3	7.20
4	5.50
5	7.10
6	4.20
7	2.50
8	3.20
9	4.10
10	3.10

Run 3 in Table 4.11
Setup Data is the same as in Table 4.3

Demand Schedule same as in Run 1

Inventory Carrying Cost/Unit Product	1/Period is	$5.00
	2	4.25
	3	7.20
	4	5.50
	5	7.10
	6	4.20
	7	2.50
	8	3.20
	9	4.10
	10	8.90

Run 4
Setup Data

	0	1	2	3	4	5	6	7	8	9	10
0	0	795	620	1050	1100	895	925	500	575	690	1400
1	0	0	700	720	845	520	600	400	500	500	970
2	0	700	0	600	800	925	200	725	700	525	1200
3	0	720	600	0	650	500	650	625	600	550	800
4	0	845	800	650	0	840	780	725	900	700	500
5	0	520	925	500	840	0	1200	400	430	850	800
6	0	600	200	650	780	1200	0	500	975	1075	1000
7	0	400	725	625	725	400	500	0	1000	400	500
8	0	500	700	600	900	430	975	1000	0	700	600
9	0	500	525	550	700	850	1075	400	700	0	970
10	0	970	1200	800	500	800	1000	500	600	970	0

Demand Schedule

Units		Product		EOP
125	Units of Product	7	at EOP	1
150		5		2
50		1		3
50		7		4
50		3		5
200		10		6
80		9		7
50		3		8
110		4		10
90		5		11
120		3		12
75		5		13
250		2		14
100		7		15
124		10		16
50		6		17
50		7		18
50		4		19
100		2		20

	Product		Cost
Inventory Carrying Cost/Unit Product	1	/Period is	$2.00
	2		2.10
	3		2.30
	4		3.00
	5		3.20
	6		3.40
	7		2.70
	8		2.50
	9		2.90
	10		2.00

Run 5
Setup Data is the same as in Table 4.3

Demand Schedule

125	Units of	Product	7	at EOP	1
150			1		2
50			7		3
75			2		4
50			3		5
200			10		6
80			9		7
50			3		8
110			4		10
90			5		11
120			3		12
200			6		13
250			2		14
100			7		15
124			10		16
50			6		17
75			7		18
50			4		19
100			2		20

Inventory Carrying Costs are the same as in Run 3

Run 6
Setup Data is the same as in Table 4.3

Demand Schedule

125 Units of Product	9	at EOP 1
125	4	2
125	4	4
125	8	5
125	4	6
125	8	8
125	5	9
125	8	10
125	5	12
125	8	13
125	2	14
125	8	15
125	2	16
125	5	18
125	1	19
125	5	20

Inventory Carrying Costs/Unit Product	1/Period is	$5.00
	2	4.25
	3	4.40
	4	5.50
	5	7.10
	6	4.20
	7	2.50
	8	3.20
	9	4.10
	10	4.48

Run 7
Setup Data is the same as in Table 4.3

Demand Schedule

125 Units of Product	3	at EOP 1
125	1	2
125	6	3
125	3	4
125	5	5
125	2	6
125	10	8
125	7	9
125	8	10
125	6	11
125	9	13
125	10	14
125	9	15
125	2	16
125	7	17
125	8	18
125	7	19
125	2	20

Inventory Carrying Costs are the same as in Run 6

Run 8 in Table 4.11
Setup Data is the same as in Table 4.3

Demand Schedule

125 Units of Product	3 at EOP	1
150	1	2
50	6	3
75	3	4
50	5	5
200	2	6
50	10	8
75	7	9
110	8	10
90	6	11
200	9	13
50	10	14
100	9	15
124	2	16
120	7	17
75	8	18
50	7	19
100	2	20

Inventory Carrying Costs are the same as in Run 6

Run 9
Setup Data is the same as in Table 4.3

Demand Schedule

Units	Product	EOP
125 Units of Product	3 at EOP	1
150	1	2
50	6	3
75	3	4
50	10	5
200	2	6
50	10	8
75	7	9
110	8	10
90	6	11
200	9	13
50	10	14
100	9	15
124	2	16
120	7	17
75	8	18
50	7	19
100	2	20

Inventory Carrying Costs are the same as in Run 2

Run 10
Setup Data is the same as in Table 4.3

Demand Schedule

100	Units of Product	1	at EOP 1
200		4	3
125		10	4
150		4	5
75		8	7
100		7	8
75		1	9
75		8	10
100		1	12
100		1	13
75		3	14
50		7	15

Inventory Carrying Costs are the same as in Run 3

Run 11
Setup Data is the same as in Table 4.3

Demand Schedule

125 Units of Product	3 at EOP	1
150	1	2
50	6	3
75	3	4
50	10	5
200	2	6
50	10	8
75	7	9
110	8	10
90	6	11
200	9	13
50	10	14
100	9	15
124	2	16
120	7	17

Inventory Carrying Costs are the same as in Run 3

Run 12
Setup Data is the same as in Table 4.3

Demand Schedule

125	Units of Product	3	at EOP	1
150		1		2
50		6		3
75		3		4
50		10		5
200		2		6
50		10		8
75		7		9
110		8		10
90		6		11
200		9		13
50		10		14
100		9		15
124		2		16
120		7		17

Inventory Carrying Costs are the same as in Run 3

Run 13
Setup Data is the same as in Table 4.3

Demand Schedule

100	Units of Product	1	at EOP 1
200		4	3
125		10	4
75		8	5
50		4	7
100		7	8
75		1	9
75		8	10
100		1	12
100		1	13
75		3	14
50		7	15

Inventory Carrying Costs are the same as in Run 3

Run 14
Setup Data is the same as in Table 4.3

Demand Schedule

100	Units of Product	1	at	EOP	1
100		4			3
100		7			4
125		5			5
75		4			6
100		10			7
75		4			10
50		1			11
50		7			13
100		4			14
100		3			15

Inventory Carrying Costs are the same as in Run 3

Run 15
Setup Data is the same as in Table 4.3

Demand Schedule

125 Units of	Product 3	at EOP 1
150	1	2
50	6	3
75	3	4
50	5	5
200	2	6
50	10	8
75	7	9
110	8	10
90	6	11
200	9	13
50	10	14
100	9	15
124	2	16
120	7	17

Inventory Carrying Cost/Unit Product 1/Period is	$5.00
2	4.25
3	7.20
4	5.50
5	7.10
6	4.20
7	2.50
8	3.20
9	4.10
10	4.02

VITA

The author was born on March 12, 1963 in Addis Ababa, Ethiopia. She received a Bachelor of Science in Mathematics/Computer Science from Concord College, Athens, West Virginia in 1985. She began her career with the USDA Forest Service, Northeastern Forest Experiment Station in 1987 as a computer programmer. In 1989, she entered the Industrial Engineering program at Virginia Polytechnic Institute and State University to acquire training necessary for her new position as a research industrial engineer.