DYE MACHINE SCHEDULING AND ROLL SELECTION

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A computer-based information and scheduling system for a major apparel fabric company was successfully developed and implemented. The system was designed to aid management in the scheduling of textile fabric rolls through the process of dyeing (coloring) these fabrics before being cut and sewn into specific apparel products. The system interacts with the automatic storage retrieval system (AS/RS) which is a multimillion dollar automated inventory control and retrieval system.

On a weekly basis, customer orders arrive at a central location in the company where they are prioritized and aggregate scheduled by a rough-cut capacity planning approach that loads each manufacturing plant by capacity. At the plant, the orders are selected daily by an operator. The operator's selection criteria is based on machine and fabric roll availability and the estimated process time requirements for the subsequent operations (e.g., cut and sew). It is important to note that the heavy capital costs associated with a pressure dyeing process, primarily machine and space costs, make maximizing machine utilization the number one scheduling priority at the plant level. Once the given orders are scheduled on machines, the operator must select fabric rolls to meet the target load profile. The roll selection process and subsequent loading instructions are a rather complex series of calculations. Prior to the implementation of the authors' system, operators had to make spot decisions concerning which rolls should be selected and sewn together to build the cloth strands for each port. Hence, the second goal was to automate and streamline fabric roll selection and sequencing operations.

The authors' system is designed to optimize dye machine utilization and material handling. The system is developed on a PC platform for operational simplicity and combines a number of information systems and operations research techniques such as linear programming (LP) in a rather unique way to meet the specific needs of the apparel fabric company in question. It has been in use for the past 18 months to determine the sequence of fabric rolls to select from inventory and the machine schedule for dyeing production at the firm's largest dyeing plant. While the system is designed to meet specific needs for the firm in question and is proprietary to the firm, the approach, methods of analysis, methods of resource selection and allocation, and an executive overview of the system models used are reported. These have general applicability to a number of similar machine scheduling applications found in a number of industries.

THE DYE ORDER ALLOCATION PROBLEM

There are many different processes for adding color to textile fabrics. These fabric dyeing (coloring) processes are technology specific to the production cost and quality requirements of the end products being produced. One group of dyeing process technology is used to dye the textile fabrics that are formed into apparel products for athletic warm-up suits, sweatshirts, jackets, and pants. A widely used technology for dyeing these fabrics is the multiple-port, pressure dyeing machine. These machines bathe long lengths of fabric, sewn together to form strands, in a single dye mixture that is specific to a given machine. Each strand length of fabric is passed through the dye mixture by a device that pulls the length through the bath, as a continuous loop on multiple passes, until the correct color has been imparted to the fabric's total length. Each dyeing machine can accommodate multiple strands (continuous loops) of fabric within the same pressure vessel. For any given machine, each different fabric strand (loop) is assigned to a machine port. All strands in all machine ports share the same total dye bath liquid and pressure conditions for the given machine.

The number of strands a single machine can accommodate is defined by the number of machine ports built into the given machine. Many firms maintain machines with varying numbers of machine ports. These firms maintain small-volume machines with minimal numbers of ports to accommodate small-lot size requirements and large-volume machines with a large number of ports to accommodate large lot-size dyeing requirements. Thus a typical firm will schedule a dye machine capacity that totals a discrete number of machines with a discrete number of machine ports per machine.

In the production scheduling process individual machines are assigned given "dye lots." Consistency of fabric color is critical to a given dye lot. Fabric from the dye lot will be formed into shirts, jackets, and pants where, for example in sweatshirts, the sleeves must have the same color attributes as the body of the shirt. Shirt color attributes must match those of the pants, jacket, etc. To accomplish the required consistency of color attributes the following two conditions must be met for each dye lot within each machine load:

1. Strand lengths across within-machine ports must be of approximately similar lengths (length differences between any two strands within a given machine cannot exceed a given amount). This condition is needed to ensure that each linear foot of strand in a given port passes through the dye bath approximately the same amount of time as each linear foot of strand in other ports.
2. Strand lengths across within-machine ports cannot exceed a maximum number of pounds. This restriction is based on an upper limit of fabric weight that can be consistently pulled through the dye bath in any given port.

Within the above restrictions, the firm wishes to load each machine with the maximum number of fabric pounds that can be effectively processed by that machine. However, the loading of the machine must be consistent with the firm's most profitable needs for given apparel fabric products. In the process of most profitably meeting customer demands, the firm is subject to additional restrictions in scheduling machines for the dyeing processes. For example, it is standard practice to schedule dye lots to machines based on a given number of complete athletic warm-up suits; sweatshirts, jackets, and pants. Thus, a dye lot for a given dye machine must not only meet the above restrictions concerning fabric strand length and weight but, in addition, the total machine load must contain the correct proportion of different width/construction fabrics that will result in the production of some number of complete apparel units with colors that match. This additional restriction often requires strand lengths for a given machine port out of different fabric constructions and widths. For example, in the production of a sweatshirt the fabric for the shirt body requires a different width than the fabric used for the sleeves. The fabric for the collar and waistband is of different width and construction than that used for the body and sleeves, etc. For these cases where a strand of fabric in a given port contains different fabric widths and fabric constructions, since different widths and constructions of fabric have different weights per unit length, it is possible that a standard length strand of fabric in one port could have a significant weight difference from a different strand of a similar length in a different port.

In meeting the above additional fabric proportionality restriction, the ability to control color between machines is assumed sufficient that color coordinated suits do not have to be included for dyeing in a given machine dye lot. Shirts can be dyed in one machine, pants in a second, and jackets in a third to a generally acceptable degree of tolerance. However, whatever the apparel unit dyed, the machine dye lot must contain the correct proportion of different width/construction fabrics required for color matching within that given apparel unit.

Given the above, in scheduling a dye lot that meets the machine port length requirements, weight requirements, and fabric width/construction proportion requirements, the following third condition must be met for each dye lot within each machine load:

3. Strand lengths must be formed from ever increasing fabric widths or ever decreasing widths (broad to narrow or narrow to broad). Subsequent postdye processing operations require that any strand of dyed fabric be sequenced (sewn together) in this way.

Port strands are formed out of fabric width/construction rolls that reside in fabric roll inventory. At any point in time these rolls are of varying sizes (weights) within a given fabric width/construction. Roll size varies in production for a given fabric width/construction and any given roll may have previously been partially used to produce a previous machine dyeing schedule. In forming a strand of fabric for a given port the firm creates the length weight that is required from several rolls of fabric. When rolls are not completely used in either forming a given port strand, or for some different port strand of the machine load, the remaining length/weight of the roll is returned to inventory.

THE MODELS

The nature of the overall dye machine scheduling problem and the interface with the AS/RS demanded a very large mixed integer linear programming [2, 4] formulation to solve the problem optimally. A prototype large mathematical model was developed and tested for speed. As expected, the solution time proved to be excessive for the required application and the model was not pursued. Instead, a two-phase approach that would provide an appropriate trade-off between schedule and material utilization optimality and computer solution time was adopted. Phase I is a scheduling and machine fabric allocation problem where the objective is to maximize dye machine utilization within the production restrictions. Given the results of Phase I, Phase II is defined as a fabric roll sequencing problem where the objective is to minimize material handling operations.

For a given dye order, in order to be able to formulate Phase I and II problems, the following data must be made available:

- Fabric types (width construction) and pounds to be dyed per machine
- Length per pound of each fabric type to be dyed per machine
- Number of machine ports used for the dye lot per machine
- Maximum number of total fabric pounds allowed per machine port
- Maximum variation allowed among fabric strand lengths in ports
- Fabric type rolls and the number of pounds per roll in inventory
- Preferred sequence of rolls per SKU (to optimize AS/RS)
- Order-specific quality specifications.

Given data (files) are in place, the solution procedure progresses in a stepwise manner. The LP system first checks given feasibility requirements, and Phase I begins with the following problem being solved using an LP formulation:

> For a given dye order with one or more fabric types (SKU), allocate the required pounds of each fabric type to a specific machine with multiple ports in order to maximize the machine utilization while maintaining color consistency and quality, and not exceeding port capacity.

The LP formulation for Phase I is included in the appendix. The LP formulation guarantees an optimal solution as long as there is enough material per SKU to satisfy the demand per dye order. The output of the LP solution is a machine load profile which becomes the first key input to Phase II. The second key input for Phase II is the list (file) of previously selected (reserved) rolls for the current dye order problem. The Phase II problem can be best described as:

> Given the optimal LP machine loading matrix (tableau) and available rolls in inventory, sequence the rolls with proper material handling instructions in order to minimize manual operations at the plant floor.

The process of determining the actual sequence of loading a machine with available rolls of varying SKUs begins with the optimal machine load matrix from Phase I results. However, there are additional requirements which make this stage of the total solution very complex. The complexity is best described in the operations research literature as a combination of a knapsack and a traveling salesman [1, 2, 4] problem. Any reader familiar with this literature knows that these problems when applied to real-world applications are well known for their difficulty and lengthy expected solution times. For example, in the authors' application, the roll selection must be done by the AS/RS's main computer (VAX) in order to minimize retrieval delays and maximize space utilization. However, during the actual machine loading, the port selection is not trivial. The ports cannot be randomly selected nor can they be loaded from first to last in order, or vice versa. The selection for the sequence of ports must follow the company's requirements which are independently developed to minimize the manual effort at the plant floor and keep temporary storage space at a minimum. Given the optimal machine load matrix and the available rolls specified by the VAX, reserved rolls are to be sequenced for loading at each port per SKU with the objective of minimizing material handling at the plant floor. To guarantee timely, feasible, and near-optimal solutions for the overall problem, a proprietary heuristic algorithm was developed to solve the roll sequencing and port loading part of the dye order scheduling problem.

The complete system has three integrated subsystems and two databases. The order entry and related information is kept on the AS/400 database at the headquarters where they are prioritized and transmitted to the AS/RS subsystem on the VAX. A large database on the VAX keeps track of all queued orders and fabric roll data. The LP subsystem, driven by an operator, is used to schedule specific orders. The two phases of the LP system use the data retrieved from the database on the VAX and provide roll usage data as well as job-specific messages back to the VAX. The logic flow diagram in Figure 1 shows how pieces of the system are integrated and communicate with each other. The logic flow diagram of the authors' system is shown in Figure 2. To illustrate the overall solution approach, a simple example is presented in the next section.

AN EXAMPLE

A hypothetical dye order of 2,100 pounds composed of three fabric types is scheduled to be processed at a

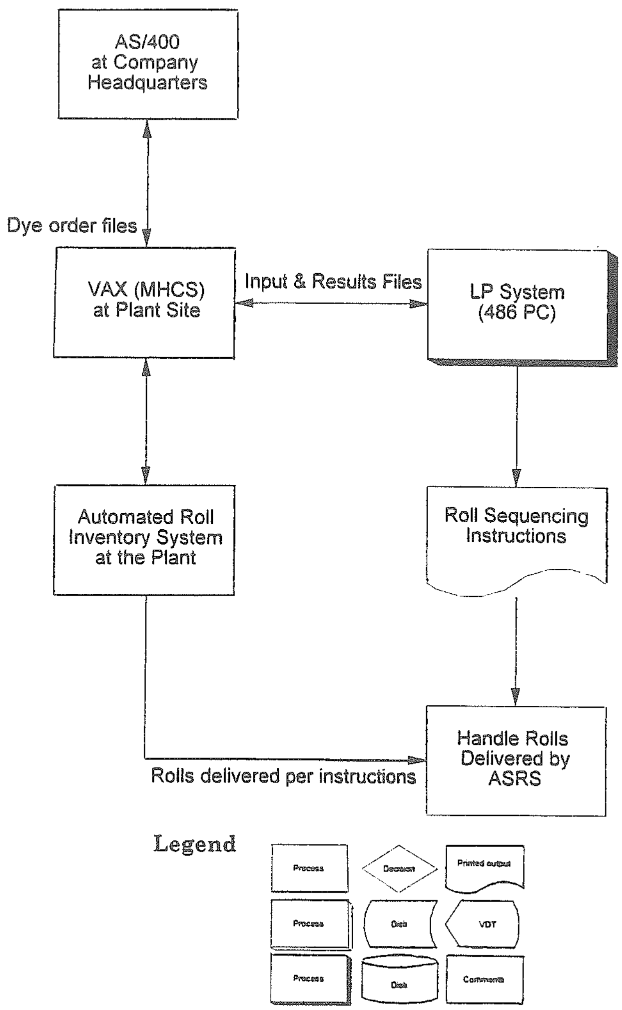


FIGURE 1: The logic diagram for the overall system

dye machine with four ports. The dye order is summarized in Table 1. This information is transmitted from the company headquarters to the VAX, which copies it to a file accessible by the LP system. In order to allow the operator to schedule the dye order #123456, the rolls shown in Table 2 must be exclusively reserved by the AS/RS on the VAX until a final solution is obtained. This reservation scheme is critical to the overall operation since multiple orders might require the same fabric. Therefore, until the current (top priority) dye order is scheduled by the LP system, the rolls reserved for it are not available to any other dye orders. As soon as the LP system completes the schedule, information on the partially used rolls and unused rolls are transmitted to the AS/RS which restocks them and makes them available for the remaining dye orders.

Based on the availability of material in stock, typically more than adequate amount of material per SKU is being reserved for the current dye order. This is illustrated in this example by having a total of 485 pounds of SKU 3 reserved for the required amount of only 300 pounds. Furthermore, the last roll will not

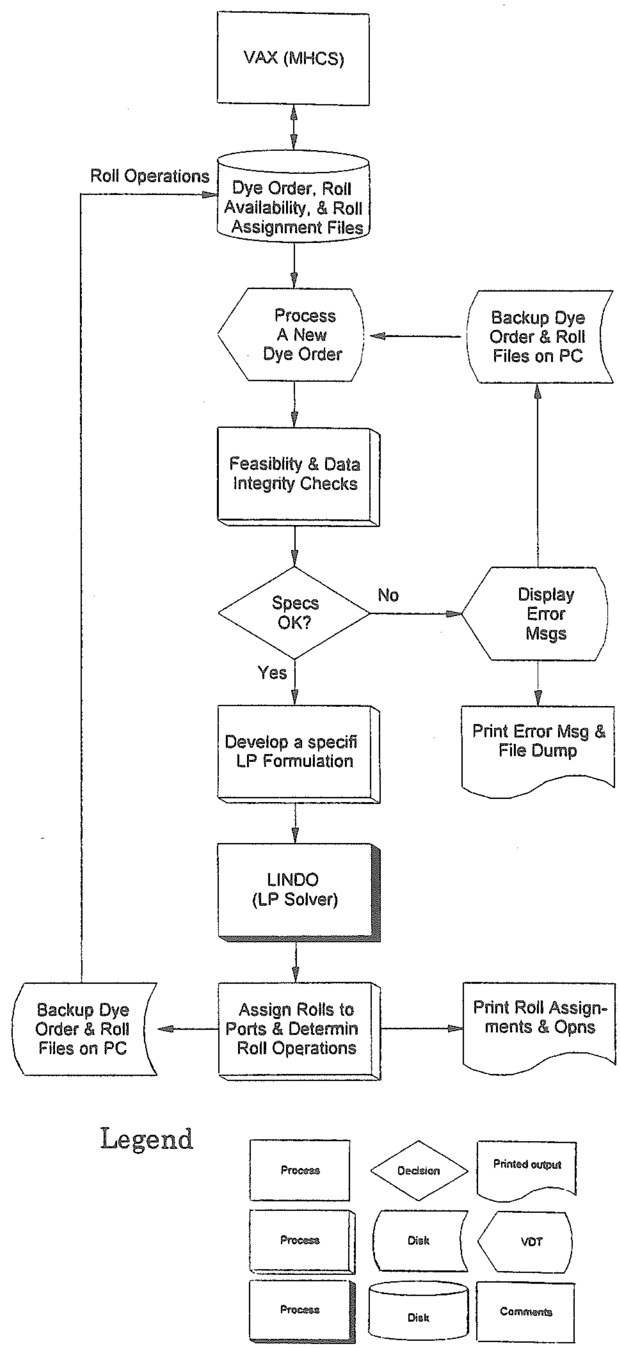


FIGURE 2: The logic flow diagram of the LP system

TABLE 1: A Sample Dye Order

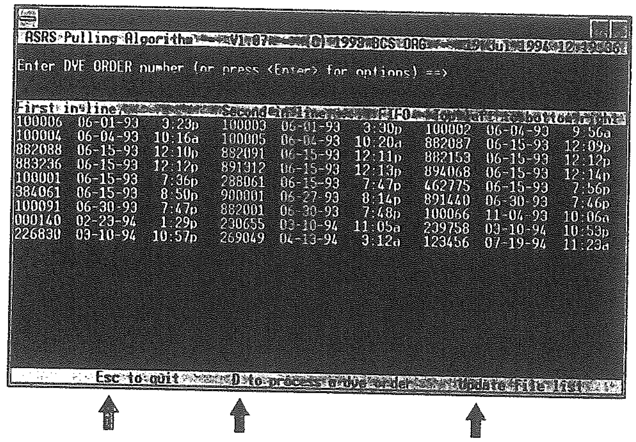
Dye order number:	123456
Machine specifications:	4 port machine
Port capacity:	600 lbs.
Quality specifications:	(proprietary information, omitted)
SKU 1	800 lbs. (detailed specifications, omitted)
SKU 2	1,000 lbs. (detailed specifications, omitted)
SKU 3	300 lbs. (detailed specifications, omitted)

be touched in all likelihood since the previous three rolls add up to 375 pounds.

The process of scheduling the dye order begins with an operator choosing the dye order number from the list on the PC screen (Figure 3). Once the dye order number is entered, the main program fetches the appropriate files from the VAX and the control is passed onto the LP system exclusively. The LP system of programs first checks the problem parameters to verify that at least a feasible solution can be obtained. In the rare event of, for example, incomplete or incorrect data, the operator is alerted and the current problem is aborted. For debugging, the data files are moved to a backup subdirectory and also printed along with the applicable error message. Under normal circumstances, the current dye order is formulated as outlined in Phase I. The resulting LP formulation is automatically fed to a popular linear and integer programming package called LINDO [3]. LINDO solves the current formulation and writes the preselected part of the results to an output file. This file is read by another program which uses a proprietary heuristic to sequence the rolls for final loading to the dye machines. The output of this step is another file for VAX to read and transmit the appropriate instructions to the AS/RS which physically removes the rolls from their bins and delivers them to the operators in the prescribed sequence. A copy of the same file with abbreviated instructions for handling the rolls is printed. The operators use the printed instructions to prepare ahead of time for the prescribed material handling operations for the actual loading of the dyeing machines. Output from the system is definitive and requires little to no fine-tuning of the solution from the scheduler. The system is built to respond to all but very rare data errors which are discovered on the shop floor, corrected, and handled either by substitution on the shop floor or by rerunning the scheduling system with corrected data.

TABLE 2: A Sample Roll Data File

SKU No.	*Roll ID*	*Roll lbs.*
SKU 1	1-000001	220
SKU 1	1-000002	300
SKU 1	1-000003	350
SKU 2	2-000001	250
SKU 2	2-000002	275
SKU 2	2-000003	225
SKU 2	2-000004	275
SKU 3	3-000001	150
SKU 3	3-000002	125
SKU 3	3-000003	100
SKU 3	3-000004	110



The three keys that the operator must know to process a dye order.

FIGURE 3: The only user interface screen of the LP system

Table 3 displays a typical dye machine load matrix. In this example, a four-port machine is loaded with 2,100 pounds of material composed of three different SKUs. The order of SKUs per port are sorted by width (e.g., narrow to wide cloth type). The actual loading of the machine will be done according to the second printout which details all manual operations (Table 4). When applicable, some rolls are used in full and sewn back to back. Others are split and used (consumed) in multiple ports. In the current example the roll oper-

TABLE 3: The Optimal Dye Machine Load Matrix for the Sample Problem

SKU No.	*Port 1*	*Port 2*	*Port 3*	*Port 4*	*Total*
1	407.7			392.3	800.0
2	66.0	467.0	467.0		1,000.0
3	126.3			173.7	300.0
Total	600.0	467.0	467.0	566.0	2,100.0

TABLE 4: Partial Listing of the Recommended Loading Sequence for the Sample Problem

Port	SKU	Roll ID	Action Codes (abbreviated)
1	1	1-000001	Consume (sew) in full 220 lbs.
1	1	1-000002	Consume 187.7 lbs., set aside 112.3 lbs.
1	2	2-000001	Consume 66.0 lbs., set aside 184.0 lbs.
1	3	3-000001	Consume 126.3 lbs., set aside 23.7 lbs.
4	3	3-000001	Consume 23.7 lbs.
4	3	3-000002	Consume 125.0 lbs.
4	3	3-000003	Consume 25.0 lbs., return 75.0 lbs. to AS/RS

ations begin with port one and SKU 1. The required total of 407.7 pounds of SKU 1 is put together by consuming the first roll of SKU 1 and splitting the second roll. The remaining 112.3 pounds of roll two of SKU 1 is set aside until the first port is loaded. When the heuristic completes port one loading, the first roll of SKU 3 is split, with 23.7 pounds remaining to be used. The heuristic jumps to port 4 and begins loading from SKU 3, thus using the leftover portion (23.7 pounds) of the first roll and sewing the second roll of SKU 3 to it in full. Next, the third roll of SKU 3 is split into 25 and 75 pounds. The 25-pound portion is sewn to the current port roll whereas the remaining 75 pounds is returned to the AS/RS. The process continues similarly until all ports are loaded as instructed.

CONCLUSIONS

This LP system is designed to be efficient, robust, and user-friendly. The operator's options are limited to only three choices, which are invoked by pressing a single key. These are D to begin processing a dye order, U to update the dye order list, and Esc to stop the program. A screen capture of the only user interface is show in Figure 3. When the process a dye order option is invoked, the operator must enter a six-digit dye order number and within a few seconds, the LP system completes the entire scheduling and sequencing operations. All the steps are done by several programs written by the authors and run in the background. The LP system replaces tedious manual calculations, thus saving hundreds of man-hours and providing error-free optimized machine loads. It also allows supervisors to schedule a large number of dye orders in a matter of minutes and simulate factory utilization and fabric roll inventory levels. Benefits include increased throughput, increased machine utilization, and increased product quality.

The potential benefits of using various optimization tools such as linear and integer programming to solve industrial problems were always known. The applications of these techniques were not time and cost-effective for numerous problems due to their computational requirements and lack of user-friendly interfaces. Lately, the advent of personal computers and the phenomenal strides made in the software area have combined to bring down the computational and economical barriers of applying operations research techniques. It is now possible to develop a seamlessly integrated "solution system" around personal computers with or without links to other small or large computers.

REFERENCES

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APPENDIX

A generalized representation of the mathematical model of phase I:

Variables:

s_{ij} = Pounds of SKU i loaded to port j

m_k = 0 if machine k is selected, 1 otherwise (for multiple choice constraints)

d_j = The strand length deviation between port j and port j + 1.

Coefficients:

TS_i = Total weight of SKU i

y_i = Number of yards per pound of SKU i

TY_{jk} = Total strand length assigned to port j on machine k

D_{max} = Maximum allowed strand length deviation among ports

PC_{jk} = Capacity (lbs.) of port j on machine k

TW = Total job weight (lbs.)

TMC_k = Total capacity (lbs.) of machine k

M = Maximum number of available (idle) machines

L = Large number.

$$\text{Maximize} \quad z = \frac{1}{TW} \sum_{k=1}^{M} TMC_k(1 - m_k) \qquad (1)$$

Subject to:

$$\sum_{j \in k_j} s_{ij} \leq PC_{jk} + Lm_k \quad \forall j \in k_j, k \qquad (2)$$

$$\sum_{k=1}^{M} m_k = M - 1 \qquad (3)$$

$$\sum_{j \in k_j} s_{ij} \geq TS_i(1 - m_k) \quad \forall i, k \qquad (4)$$

$$\sum_{j=1}^{\max j \in k_j} s_{ij} = TS_i \quad \forall i \qquad (5)$$

$$\sum y_i s_{ij} = TY_j \quad \forall j \qquad (6)$$

$$TY_j - TY_{j+1} = d_j \quad j = 1, \ldots, (\text{Max } j \in k_j) - 1 \qquad (7)$$

$$|d_j| \leq D_{max} \qquad (8)$$

$s_{ij} \geq 0$, $m_k = 0/1$ binary, d_j = free variable with simple upper and lower bounds.

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