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Simulation Modeling of the Textile Supply Chain
Part I: The Textile-plant Models

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In Part I of the series, we describe stochastic computer models that simulate operations in the spinning, knitting, weaving, dyeing and finishing, and cut/sew sectors of the textile industry. The models are scaled to represent a supply chain designed to feed a garment-manufacturing operation involving four or five plants, i.e. part of each plant's output is 'dedicated' while simultaneously providing yarns and fabrics to the industry at large. Each of the sector models is unique because of the very different types of processing technology employed.

The models are linked by means of streams of fabric orders from the manufacturing plants that make a range of garment types requiring many different fabrics for Basic (year-round sales), Seasonal (two or three seasons per year), and Fashion (shelf lives of 8–12 weeks) goods in a broad range of colors.

In addition to each plant's product ranges and order sizes and frequencies, particular attention is paid to the machine-scheduling algorithms, although the models are deliberately kept at a 'high' as opposed to a 'shop-floor' level. The purpose of this modeling is to allow senior management to answer broad questions about the plants' ability to operate in a Quick Response environment. The various model outputs reflect this, having a heavy emphasis on on-time shipments, back-order levels, and service levels.

In Part II of the series, we shall present the QR-related operating results to date, a description of a master-scheduling procedure to orchestrate the operations of the supply chain, ideas on an improved scheduling method, and an account of the construction of neural-network decision surface models as a decision support tool. We also overview ongoing efforts in technology transfer and in using 'fuzzy' mathematics to model the vagueness and uncertainty inherent in the supply- chain decision-making environment.

The research effort of which this is a part is ongoing. We present these results in the hope of encouraging others to help carry the investigations forward.

1. OVERALL APPROACH

In earlier papers (Hunter *et al.*, 1992,1993,1996; Nuttle *et al.*, 1991) we described stochastic simulation models of the retailing and apparel-manufacturing processes. The manufacturing model assumed-perfect supply of fabric, i.e. the manufacturer received exactly what was ordered from the dyehouse after a short, specified lead-time.

This is a major assumption. One of the most critical factors in the supply pipeline is, in fact, the speed with which dyed or printed fabric can be supplied in the requested yardages. Normal practice is for the textile producer to ship large yardages ahead of, or early in, the season, based on the retail-buyer position. Part of the reason for this is tradition, and part is caused by the fabric production (weaving, more so than knitting) times, which are long compared with cutting and sewing. A further factor is the additional cost to the textile producer of small yardages. But Quick Response (QR) requires that each part of the supply chain be responsive to its customers.

Accordingly, we undertook a program to model the up-stream processes — yarn spinning, knitting, weaving, and fabric and finishing of fabrics. Our approach has been to build and study stand-alone models for each of these entities and then to explore approaches to link and operate them as a kind of integrated 'corporation' (see Fig. 1).

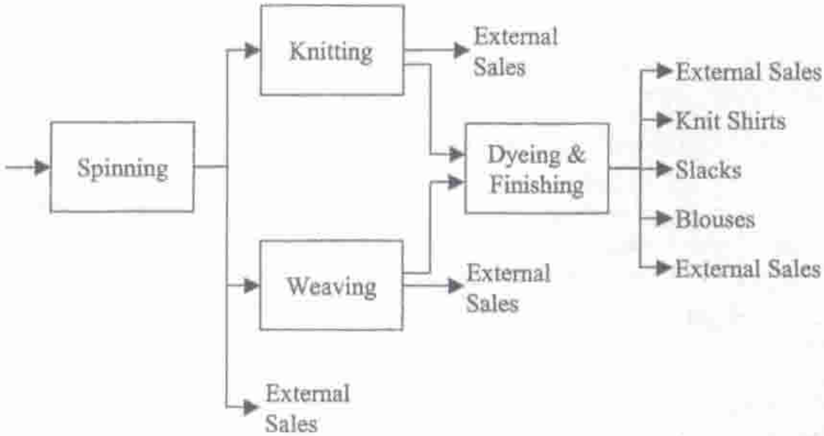

Fig. 1 An apparel supply chain

The work is still ongoing, though the stand-alone models are well advanced and some results, so far as QR is concerned, are available. In Part II, we shall describe in more detail a method designed to link the models together. In brief, it is a 'Master Schedule' generator that simulates the results of the booking of fabric orders placed by the corporation (called pipeline orders), as well as external, or outside, orders placed by other firms in the industry. The schedule provides a sliding 'x-weeks-ahead' view of orders to the textile-producing operations, allowing them to develop their own production schedules. As consumer demand re-estimates and the resulting reorders change at retail, the Master Schedule changes too.

The Master Scheduling technique is of interest because it resembles closely the world of 'close partnerships' advocated by QR, thus allowing examination of the necessary elements of such partnership, how they tie together, and their dependency, one on the other.

The 'corporation' is sized to produce/process about 25 million pounds of yarn per year, about a quarter of which is consumed as finished fabric by the corporation's four or five apparel-manufacturing plants, with the rest of the yarn and fabric (greige and finished) being sold to outside companies. A test-bed set of garments — including Basic, Seasonal, and Fashion — to be assembled in the captive apparel plants specifies the variety of yarns, fabrics, and colors to be produced in the textile plants at any time during the year.

The plant models are data-driven, i.e. they require inputs such as customer order streams, machine capacities, and production rates. They produce the relevant output data, including empirical frequency distributions of order lead-times, back orders, and inventories by SKU. The plant models are also constructed to allow exploration of alternative scheduling procedures — a very important part of the modeling paradigm — as well as the impacts of capacity utilization.

One important feature of the models is the considerable number of products they can handle. The spinning model has been exercised by using up to 36 different yarns, the weaving model with up to 20 different fabrics, the knitting model with as many as nine fabrics, and the dyeing and finishing model with as many as 120 colors on a set of 20 fabrics (woven and knitted). These are larger numbers than are met with in most industrial operations; the models' scope is not trivial.

Pipeline orders are referred to as 'contract' orders, i.e. orders consisting of regular weekly requirements for some known number of weeks. External orders may also be either regular on-going business or 'spot' orders that arrive sporadically. The 'sliding '*x*-week-ahead' view of orders provided to the plants includes (random) weekly call-outs against contract orders and (random) spot orders.

Daily plant activity is directed by routines that generate weekly or daily schedules for key processes. Activity is also influenced by randomness in such factors as cycle times and yields.

We describe four different simulation models of operations (yarn-spinning, weaving, knitting, and dying and finishing) because their structures are different from each other and, we believe, cover a wide variety of the situations found in many businesses other than textiles. We also include a brief description of related work in the modeling of apparel-manufacturing.

The models provide vehicles for:

- understanding the interactions of decisions made within one firm with those of a supplier or customer,
- analyzing and comparing operational practices within individual firms or across sub-sets of firms,
- developing CEO-type information systems, and
- training personnel in making intelligent operational decisions.

In describing the models, we often give specific, representative values for operational parameters such as capacity, order size, picks per minute, dye lot size, etc. However, in most cases, these parameters are input variables for the models that can be changed at data entry.

2. YARN-SPINNING MODEL

2.1 Scope

The purpose of this model is to analyze the relationships between input-control parameters and plant performance, to determine optimal operational policies, and to study the ability of a cotton-spinning factory to satisfy QR requirements. By operational policies, we mean management guidelines such as: capacity utilization, scheduling rules/procedures, numbers of products, minimum order size, and order lead-times.

2.2 Processes

We assume that the reader is familiar with the processes involved in spun-yarn production: opening and cleaning, carding, drawing, roving, and the spinning itself. The final products from the spinning plant are yarns of specific counts (a measure of the thickness of a yarn) and twist levels. A given product can be used to create a variety of apparel items. The spinning plant need not be concerned with the size, color, or style of the garment in which the yarn will be used. Changes in the original demand forecast with regard to these attributes will therefore not affect it. However, the plant must be able to react quickly to changes involving the demand in a whole product line by producing more or less yarn of a certain count and twist.

2.3 The Simulation Model

The model simulates the basic activity of a ring-spinning plant capable of producing around 25 million pounds of cotton yarn per year (Powell, 1993). The plant capacity can include up to 100 frames producing up to 36 different yarn counts. Blended yarns, e.g. polyester-fiber/cotton, have been excluded at this point because they gave complications in the fiber-preparation stages that are assumed to provide a perfect supply of roving to the spinning frames.

The activities modeled include frame-scheduling, schedule execution, changeovers, coning (winding), inspection, and shipping (see Fig. 2). At present, spinning is modeled as a make-to-stock operation (as opposed to made-to-order), with about 50% of the demand coming from external, non-pipeline customers. Orders are either call-outs against contracts, randomly generated on a weekly basis, or spot orders generated on a daily basis. Orders vary as to yarn count and quantity. The count mix and average weekly volume can be varied throughout the year to reflect seasonality in the use of different yarn weights. The plant can be made to operate for up to 24 hours per day, seven days per week.

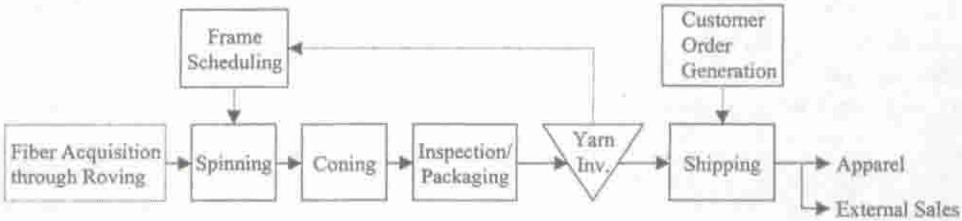

Fig. 2 Overview of spinning model

So far, we have modeled two alternative strategies for controlling the inventory levels of finished yarns: a 'Max/Min' system (Powell, 1993) and a 'Target Level' system (Brain, 1995). The goal is to satisfy customer orders within a target lead-time, as well as to keep the inventory at the user-specified level. It is important for a spinning plant to control accurately the amount of yarn in stock because it incurs carrying costs as well as acting as safety stock in cases of demand variations or machine failures.

Under the Max/Min system (commonly used in industry), if the inventory level of a yarn rises above its nominal maximum level, then production is curtailed until the inventory level falls to its nominal minimum level. Spinning frames are loaded or scheduled on the basis of management's knowledge or forecast of demand volume and mix. A management-specified portion of the frames is dedicated to those high-volume yarn counts that are produced continuously until otherwise indicated by the inventory-control system. Dedication may be adjusted to reflect shifts in demand mix. The remaining frames are regarded as 'flexible capacity' and are scheduled reactively, based on current need. Algorithms to generate the desired number of dedicated frames, and schedule the non-dedicated frames, are given in Sections 2.3 and 2.4.

With the Target Level system, production is incrementally raised or lowered periodically in order to try to maintain a specified inventory level by using the concepts of proportional derivative (PD) process control (Olsson and Piani, 1992). In this case, all frames are reactively scheduled. More information on PD control will be given in Part II of this series.

Orders are shipped daily in the morning, five days per week, limited by shipping capacity. Priority is given to contract orders and to older orders. Measures of performance (Table I) include production levels, order response times, inventory levels, frame utilization, and margin.

Table I
Input and Output Variables — Spinning Model

Inputs	Outputs
Number of frames	Weekly average lead-time for contract orders
Number of yarn counts	Weekly average lead-time for spot orders
Spindle efficiency	Weekly average lead-time for all orders
Target capacity utilization	Overall average lead-time for contract orders
Average order size	Overall average lead-time for spot orders
Schedule re-evaluation period (AT)	Overall average lead-time for all orders
Minimum inventory target (if Max/Min)	Lead-time distribution for contract orders
Maximum inventory target (if Max/Min)	Lead-time distribution for spot orders
Target inventory level (if Target)	Lead-time distribution for all orders
Percentage of contract orders	% of time on scheduled frames by yarn count
Number of dedicated frames	% of time spent changing over frames
Coning/packaging time	Number of frame changeovers
Production rate by yarn count	% of time dedicated frames shut down
Percentage of demand by yarn count	Weekly average inventory level by yarn count
Average daily demand	Overall average inventory level by yarn count
Inventory holding % by yarn count	Inventory distribution by yarn count
Inventory carrying-cost rate	Revenue generated by yarn count
Production cost rate by yarn count	Total poundage shipped by yarn count
	Inventory carrying cost

2.4 Frame Dedication

The procedure attempts to allocate N_a (policy variable) of the N_f frames consistent with the 'time-weighted mix' of yarn counts, i.e. the forecast fractions of capacity required for each yarn count. If $N_{d(i)}$ is the number of machines dedicated to yarn i, an allocation policy consistent with the time-weighted mix would be integers $N_{d(i)}$, $i = 1,2,...n$, such that

$$\sum_{i=1}^{n} N_{d(i)} = N_a \tag{1}$$

$$\frac{N_{d(i)}}{N_a} = w_i \quad i = 1,\dots,n \tag{2}$$

where $w = \left(w_i, i = 1,\dots\ n \middle| \sum_{i=1}^{n} w_i =, \middle| \right)$ is the time-weighted mix.

However, because each $N_{d(i)}$ must be an integer, this is not generally possible. Instead, a two-phase procedure is used to determine the machine dedication. If there is a solution to (1)–(2), the problem is solved. If not, the allocation requirement is 'approximately' satisfied with

$$\sum_{i=1}^{n} N_{d(i)} \le N_a$$

$$\frac{N_{d(i)}}{N_f} \le w_i \quad i = 1,\dots\ n$$

i.e. the fraction of total machine capacity allocated to yarn i does not exceed w_i. The allocation is accomplished with the following two-phase procedure.

Phase 1:
Set $N_{d(i)} = xw_i N_a x$ for all i, where x denotes the largest integer less than or equal to x.

It is possible to end Phase 1 with $\sum_{i=1}^{n} N_{d(i)} < N_a$. When that occurs, Phase 2 is used in an attempt to allocate the rest of the N_a machines.

Phase 2:
(i) Calculate $\Delta w_i = w_i - (N_{d(i)}/N_j)$, for all yarns.
(ii) Determine the largest Δw_i such that $w_i - (N_{d(i)} + 1/N_j) \geq 0$.
(iii) If no yarn satisfies the restriction in Step (ii), STOP. No additional frames may be dedicated without over-allocation.
(iv) For the yarn that satisfies Step 2, set $N_{d(i)} = N_{d(i)} + 1$.
(v) If $\sum_{i=1}^{n} N_{d(i)} = N_a$, STOP. Otherwise GOTO 1.

2.5 Rescheduling 'Scheduled' Frames

'Scheduled' or undedicated frames act as flexible backup to the dedicated frames. They meet the demand that the dedicated machines cannot meet alone. Once every T (user-specified) days, inventory levels and outstanding orders are checked, and the machine status is evaluated to determine the next yarn to run.

Yarn is assigned to a scheduled machine based on the relative need of each yarn. Eligible yarns are those for which production is not currently curtailed, i.e. the inventory level has not exceeded R_i (maximum inventory level for fabric i) and all dedicated machines for this yarn are running. The relative need for each yarn is determined as follows:

The net inventory position, NIP_i, is calculated for each yarn i,

$$NIP_i = Net_i / \lambda_i O$$

where $Net_i = I_i - (\lambda_i O - s_i m_i)T$ and I_i is the inventory level of yarn i including yarn in post-production processing and net of back orders, 1_i is the average number of orders for yarn i received per day, O is the average size in pounds of an order, s_i is the production rate per frame (lb/day) of yarn i, and m_i is the number of machines (dedicated and scheduled) currently running yarn i. The yarn i^* with the smallest NIP_i is next selected to run on the frame. Note that NIP_i is an estimate of the number of days supply in inventory T days into the future if yarn i is not scheduled to run next on that frame.

If the yarn chosen is the same as that which had been running previously, spinning will resume with no delay. However, if the yarn chosen is different, there will be a changeover delay before spinning resumes. If no yarn is chosen, the frame remains idle for the following T days, at which time it is checked again.

3. WEAVING MODEL

3.1 Scope

The weaving model (Chen, 1994) is designed to simulate the basic daily activity of a mill with capacity to convert 6–7 million pounds of yarn into fabric over the course of a year. The simulated activity includes loom-scheduling, schedule execution, major/minor loom changeovers, inspection and grading, and shipment of orders. Scheduling/rescheduling is performed weekly, based on a current 'x-weeks ahead' view (from the Master Schedule) of firm orders plus knowledge of the remaining quantities associated with existing contract orders.

The loom-scheduling procedure attempts to mimic a strategy used by schedulers, i.e. it focuses on minimizing loom changeovers while satisfying fabric orders. The model has the capability to schedule and execute an around-the-clock operation or a nominal five-day operation with possible overtime on the weekend.

Actual daily fabric production may differ from scheduled production due to (random) downtime (e.g. yarn breaks). From the looms, fabric passes through inspection (modeled as a y-day delay), where rolls are (randomly) classified as first- or second-quality, before entering greige inventory. Shipment of greige fabric is carried out daily against current (from the Master Schedule) and past-due orders. Limited shipment of second-quality and short/over shipment is permitted. Performance measures include production levels, on-time shipping performance, machine efficiencies, inventory levels, and (given financial data) margin.

It should be noted that we have not yet attempted to model the very important preparation steps — creeling of yarns, section-beam preparation, sizing, and warp-beam preparation, though others are now contributing to the understanding of these processes (Goddard *et al*, 1996). This is a critical area for scheduling, as well as being time-consuming from a manufacturing point of view. However, work in this area has been delayed for want of time and manpower. The simulated steps in the weaving process are shown in Fig. 3, along with those that are not included (in the box to the left) in the model at this time.

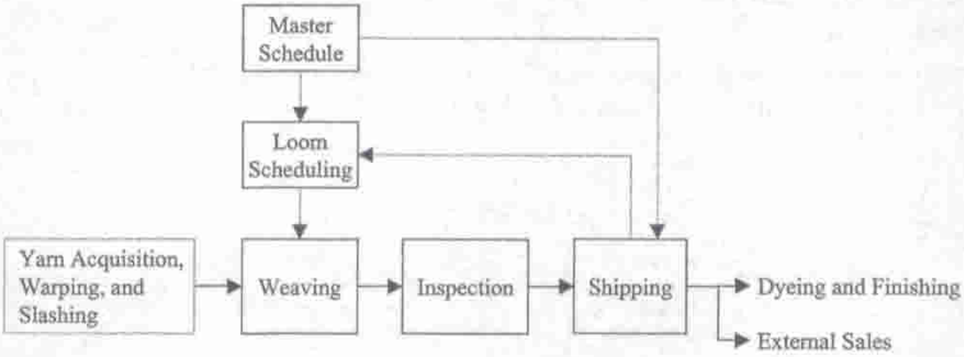

Fig. 3 Overview of weaving model

3.2 Processes

Weaving is a complicated process, and the model described in this section is the most ambitious of the textile, modeling projects. For those outside the industry, a few notes might be in order. Referring to Fig. 3, yarn is either purchased from an outside spinner or produced internally and placed in inventory. Most of this is used as delivered, but, for 'fancies', yarn is dyed prior to fabric formation.

The cones of yarn are mounted on a creel, and the yarn is wound onto 'section beams', each of which is of the correct yarn length, but only a fraction of the number of yarn threads, or 'ends'. These section beams are then wound onto a 'loom' beam and placed on the back of the weaving machine or loom. In between these processes, a binding agent (size) is applied (slashing) to each thread (end) of yarn to facilitate weaving and reduce yarn breakage. Each end on a loom beam is passed through devices to allow raising and lowering of the 'shed'. The weaving process can now take place, i.e. the filling yarns are inserted. Each insertion is referred to as a 'pick'. The fabric is wound on a roll and goes to inspection and, if passed, to inventory.

There are many types of loom and here we use two — air-jet and Sulzer. Each type operates at a specified number of picks/minute (ppm). The model allows for any number of each type of loom to be specified. Up to 100 different fabrics can be input, though in simulation runs we have used no more than 40. The normal maximum time horizon is 52 weeks.

Other parameters, which are user-defined, include the following.

- Fabrics contain between 45 and 100 picks per inch.
- The ends of warp yarn per loom beam range between 4800 and 9000.
- Completed fabric-roll lengths range from 800 to 2500 yards.
- Loom set-up time is one day.
- Changeover times are: two days for a conversion to a new fabric with a different number of warp ends and/or weave pattern; 30 minutes for the introduction/tying-in of a similar warp.
- For yarn breaks, the repair time ranges (randomly) from one to five minutes.
- Average yarn-breakage rate is 0.2 break/100 ends/1000 yards.
- The allowable-range order quantity actually shipped is from 90% to 110%.
- The minimum shipping percentage for first-quality fabric is 90%.
- The inspection department can handle 800 000 yards of fabric per day.

3.3 Simulated Activities

3.3.1 Sequence of Events

The steps executed in the weaving model and the sequence of events are shown in Fig. 4. The most important of these are described briefly.

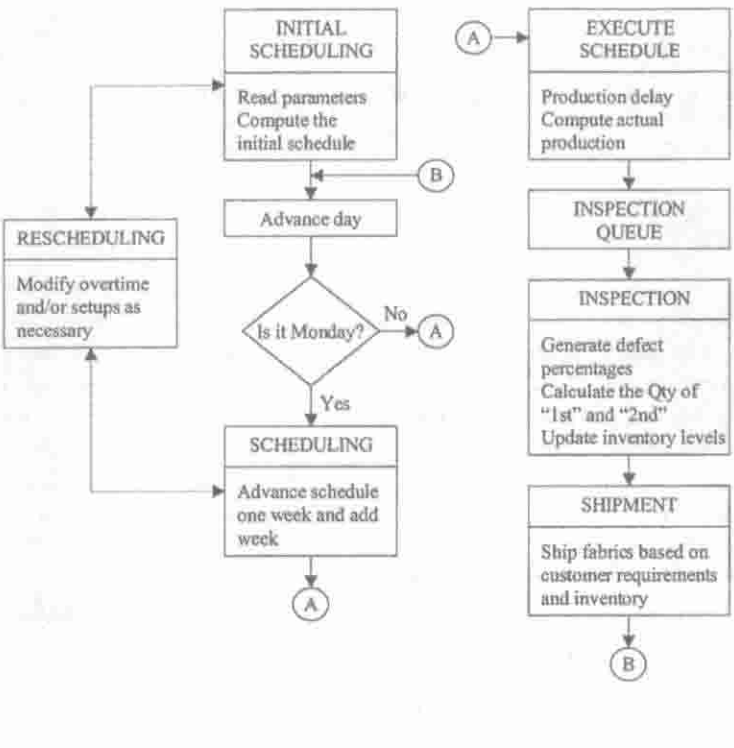

Fig. 4 Flowchart of weaving - scheduling activities

3.3.2 Scheduling

A loom schedule specifies the number of looms assigned to each fabric and the number of working days (5–7) in each week of a rolling 'scheduling horizon'.

(*a*) *Initial Scheduling* If an initial loom assignment is input, this is projected to the weeks in the initial-scheduling horizon. If there is no initial assignment, then the assignment is done from scratch. Note that, unlike the other models, there is no dedication of machines. The number of looms assigned to a fabric is based on the maximum average cumulative demand for that fabric as of any week in the scheduling horizon. Fabrics are prioritized for loom assignment with the slower-production, high-demand fabrics having highest priority.

The computed number of looms for each fabric is applied to all weeks in the scheduling horizon. The net inventory for each fabric is now computed throughout the weeks of the scheduling horizon. If negative values are found, then the rescheduling procedure is invoked.

(b) *Rescheduling* The main function of this procedure is to bring the loom schedule into line with requirements by using the following sequence:

- assign available looms, if any, that require no setup;
- assign available looms, if any, that require setup;
- increase number of working days to include week-end days;
- change over currently assigned looms;

Again, inventory values are computed and checked for negative values, and, if necessary, the process is repeated until each fabric has an adequate loom assignment or all looms are assigned. Requirements that cannot be met on time are backordered and added to those in subsequent weeks.

(*c*) *Weekly Scheduling* At the beginning of each subsequent week, the first week of the previous schedule is dropped and a new week added. The previous loom assignment for each fabric is projected to the new week and reduced where possible. If the assignment for any fabric comes up short, the rescheduling procedure is evoked to try to bring it into line.

3.3.3. Inspection

The weaving schedule is executed on a three-shift basis and creates three 'fabric-shift lots' of each scheduled fabric each day. These lots are inspected on a FIFO basis by an inspection team working eight hours on second shift, Monday through Friday.

The procedure classifies fabric production as first-quality (approximately 90%) and second-quality. Quality is a stochastic process.

3.3.4 Shipping

Fabrics are shipped Mondays through Fridays against a list of orders due in the current week plus any past due. Total, first-quality, and second-quality fabric inventories are compared with the corresponding order quantities to determine the percentage of order quantity actually shipped and the composition with respect to first-quality and second-quality. Priority is given to pipeline orders, large orders, and orders with earlier due-dates.

3.4 Performance Measures

These include the following.

- On-time shipping performance, which includes the average order tardiness, average delayed quantity, and detailed tardiness and quantity for each order. Average tardiness does not count the fabric shipments before or within the week due. The average backlogged quantity is the sum of the product of the order tardiness and backlogged quantity for each order divided by the total number of tardy orders.

- Loom utilization, which details the production capacity, in loom hours, used for change over, production, and idle.
- Inventory-level statistics, including average value, variance, and minimum/maximum values.

4. KNITTING MODEL

4.1 Scope

This model (Hinshaw and McGoogan, 1993; Shippy and Sands, 1993) is designed to simulate the daily activity of a circular-knitting operation with capacity to convert 5–6 million pounds of yarn into fabric over the course of a year, in a made-to-order fashion. The simulated activity includes yarn acquisition, scheduling of knitting machines, schedule execution, changeovers, inspection, and shipping.

4.2 Model Structure

Fig. 5 shows the model structure and its interactions with the Master Schedule (see later for more on this topic).

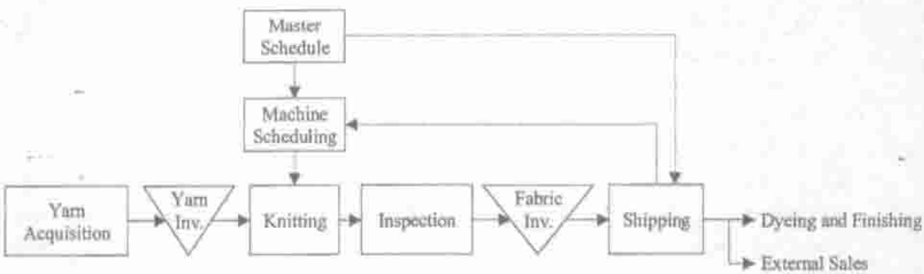

Fig. 5 Overview of knitting model

A knitting plant is, in many ways, simpler than the other models described. Fabric production is rapid, and the number of different fabric types is small. The model described here limited the types of circular-knitted fabrics to two — single-jersey (e.g. for T-shirts) and interlock (e.g. for polo shirts). Fabric weights within these groups can be changed by using different yarn counts (thicknesses), depending on the season. Three fiber blends are also used in the model: 100% cotton, 50/50 polyester-fiber/cotton, and 65/35 polyester-fibre/cotton. There are thus six types of fabric.

The annual demand placed on the plant suggested 30 machines running six days per week, 300 days per year, with the possibility of overtime. The machines are considered to have 96 feeds (cones of yarn), with duplicate creels tied into those in use. Typical production rates are 235 yards/hour for single-jersey, and 85 yards/hour for interlock fabric. The maximum lengths of the tubes of fabric (usually slit at a later stage to give flat rolls) are determined by the machine geometry — 100 yards for single-jersey, and 80 yards for interlock.

Machine downtime is small. Topping up the overhead creel as cones of yarn runout during a run is regarded as having no effect on utilization. When there is a change of fabric type, however, a user-specified delay is built into the model to allow for machine adjustments and recreeling.

4.3 Simulated Activities

As with the other models, there are two types of fabric orders, contract and spot. Though the model allows knitting machines to be dedicated always to produce certain fabrics, to date we have operated them in a manner similar to that for the 'scheduled' spinning frames. Specifically, when a machine becomes available, it is assigned to knitted fabric based on a current 'x-weeks ahead' view (from the Master Schedule) of firm orders plus knowledge of the remaining quantities associated with existing contract orders. Priority is given to pipeline orders with earlier due-dates. The knitting of an order is not begun unless sufficient yarn inventory is in stock. If the fabric is different from the previous run on that machine, a changeover is required. Once an order is completed, after a delay for inspection time, the fabric is placed in finished-fabric inventory, and the order is placed on a list of orders available to ship.

Shipping is executed five days a week. The user can specify the maximum number of orders to ship Monday through Thursday. On Friday, all orders that are due and can be filled are shipped. This procedure was first used in the spinning model so that the order-filling process would be spread out through the week, thus emulating delivery constraints due to truck capacity.

The inventory for each yarn is controlled by a target-level policy to minimize carrying costs. At intervals, each yarn inventory is checked and, if it is below target level, enough is ordered to raise it to target level. The yarn-order lead-time is user-defined. Moreover, when a machine begins production of a new roll of fabric, the total amount of yarn needed is removed from the yarn inventory.

The principal model inputs and outputs are shown below in Table II.

Table II
Knitting-model Inputs and Outputs

Inputs	Outputs
Number of fabrics	Average lead-time by fabric type
Weight of each fabric	Distribution of lead-time by fabric type
Number of knitting machines	Over-all average lead-time
Production rate of each fabric	Over-all lead-time distribution
Knitting efficiency	Machine utilization
Roll length for each fabric	Number of orders processed by fabric type
Target capacity utilization	Number of fabric changeovers
Master schedule of fabric orders	
x weeks of schedule visibility	
Average order size	
Number of dedicated machines	
Daily shipping capacity	
Fabric-inspection time	
Target inventory level by fabric type	

The knitting model has also been linked with that of spinning as a first attempt at integrating separate models. In the integrated model, yarn orders from knitting are merged with external orders and are filled as described in Section 2.3. Thus the yarn-order lead-times depend on the spinning-plant status at the time of order.

5. DYEING-AND-FINISHING MODEL

5.1 Scope

This model is designed to simulate the daily activity of a dyehouse with capacity to dye around 12 million pounds of fabric per year. The simulated activities includes customer-order entry, scheduling of dyeing machines, schedule execution, machine-cleaning (boilouts), inspection, and shipment of orders (Kuhl, 1995).

Though seemingly straightforward, a dyehouse presents two major differences from those discussed previously. The first of these relates to the problem of scheduling and queuing colors. There is big difference between cleaning a machine between batches of pale shades (say, going from pale green to pale yellow), medium shades, or dark shades, and going from, say, a dark shade to a pale or medium shade, when a very thorough cleaning is needed, and the machine is down for a considerable period of time.

The second difference has to do with the nature of the dyeing operation. Getting the color right the first time is not guaranteed; in the case of dyeing in a 'beck', it is quite usual to have to redye the fabric up to half the time.

The dyehouse is a dye-to-order operation. Orders are created from the output of the Master Schedule generator by randomly splitting weekly orders into daily quantities for various colors. Based on the implied *x*-days' worth of known orders, scheduling is done daily to create a '*y*-day' company schedule of dye lots for each machine. Depending on order backlog, overtime may be included. The current scheduling strategy, based on discussions with an industry scheduler, attempts to keep a given machine running the same color or shade category for as long as possible.

In schedule execution, nominal cycle times are dependent on the machine type and the shade of fabric. Actual cycle times may be (randomly) lengthened to reflect added dyeing time required to achieve the desired color — this for fabrics that have failed the first inspection. Shipment of finished fabric is carried out daily against the outstanding order backlog.

It should be noted that orders are placed in terms of fabric lengths, but dyeing is scheduled in terms of fabric weights.

5.2 Model Characteristics

These include the following.

- *Operating Hours*. 24 per day (three shifts), Monday through Friday. Overtime is scheduled as needed on the weekend.
- *Machinery*. Becks and jets. The number of each can be specified by the user.
- *Dye Lots*. A dye lot is the amount of a specific fabric to be dyed to a given color and shade. The maximum size of a dye lot is machine-dependent.
- *Dedication*. Fabrics that will dye better on one type of machine are considered 'dedicated' to that machine group and cannot be processed on the other type. When there is no preference, the fabrics are 'undedicated'.
- *Colors*. Colors in which a fabric must be dyed are associated with the fabric style. Styles and associated colors are specified by the user. The model allows 120 colors. The shade of each color must be specified as light, medium, or dark.
- *Machine Cleaning*. There are three cleaning processes, as follows.
  Type 1 = Cleaning between dye lots of the same color; trivial downtime.
  Type 2 = Cleaning between dye lots of different colors if either the colors are the same shade, or a lighter shade is followed by a darker shade. Downtime is relatively short.
  Type 3 = Cleaning between dye lots of different colors when a darker shade is followed by a lighter shade. Cleaning time in this case is in the order of 8 hours.
- *Customer Orders*. Received by the dyehouse on weekdays. Quantities must equal or exceed a minimum length, depending on the fabric, and be multiples of a specified length.

- *Due-date*. This is the maximum desirable time from receipt of order to shipping. This time is user-specified.

5.3 Simulated Activities

A flowchart of the simulated dyehouse operations is shown in Fig. 6. The descriptions and examples that follow relate to this chart.

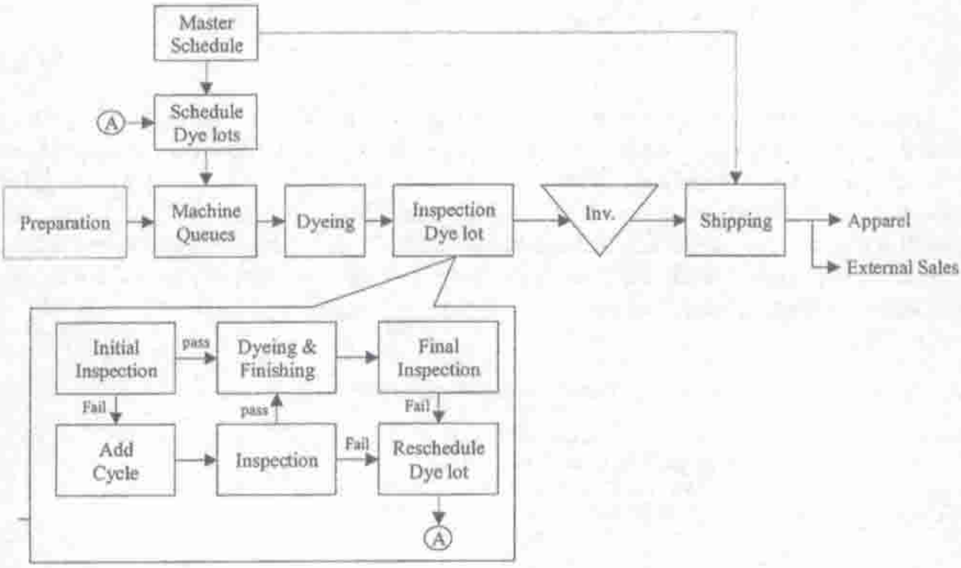

Fig. 6 dyeing-and-finishing model

Greige Fabric This is unbleached or undyed cloth — the raw material for the dyehouse. There is a perfect supply of the fabric, available as needed for processing. The outputs from the weaving and knitting models are not yet being used as inputs to the dyehouse model.

Dye-lot Scheduling The customer orders for Monday–Friday of each week are generated from the Master Schedule quantities for each fabric for the week L weeks out. The Master Schedule quantities are split into a randomly generated number of smaller dyed-fabric order quantities (of at least a minimum order size). These order quantities are then randomly assigned a color and an order day (from Monday to Friday). Order due-dates are assigned to be Friday, L weeks hence.

Machines are scheduled each day, just prior to the first shift, for a two-day period. Schedules are prepared to try to minimize both order lateness and the cleaning downtime. Between consecutive days, the unprocessed dye lots that were scheduled previously remain in the machine queues, and additional lots are scheduled until the two-day capacity is reached. One or two week-end days of overtime are scheduled as needed to complete orders on time. If less than two days of overtime is called for, the machines go through a major cleaning over the week-end, machine queues are emptied, and the lots are added to the material waiting to be scheduled. Scheduling starts from scratch on Monday mornings.

Machine Queues Each machine has an associated queue that is the two-day schedule of work for that machine.

Dye Fabric Schedule execution is simulated for each machine. The time required to dye a lot is a function of the machine type and the fabric shade. Typical values are shown in Table III.

Table III
Dyeing Time (h)

	Jet	Beck
Light shade	2.5	6.0
Medium shade	3.5	8.0
Dark shade	4.5	10.0

Inspection An initial inspection is carried out by examining the amount of dyestuff remaining in the bath. If a sufficient amount has been absorbed, the lot is passed and the machine unloaded. Otherwise, additional time — called 'Add Cycle' — is given. After this, there is a second inspection; if the fabric passes, it is dried and finished; if not, the model scraps the dye lot and reschedules a new batch. Table IV shows typical probabilities of passing the various inspections, including the one carried out after drying and finishing, just before sending to inventory.

Table IV
Pass-inspection Probabilities

	Jet	Beck
First inspection	0.65	0.50
Inspection after Add Cycle	0.98	0.95
Final inspection	0.95	0.95

Shipping All orders that can be filled from inventory are shipped each weekday, with priority given to those with earlier due-dates.

5.4 Performance Measures

These include the following.

- The maximum, minimum, average, and standard deviation of the weekly quantity of finished-goods inventory.
- The number of dye lots processed each week.
- Machine utilization as percentage of time spent dyeing fabric, being cleaned, and idle for becks and for jets.
- Overtime usage as number of 5–7-day weeks worked.
- The maximum, minimum, total, average, and standard deviation of the weekly quantity of fabric shipped.
- Order lead-times, including and excluding week-end days.

6. APPAREL MODELS

The modeling of apparel-manufacturing has been described by Hunter *et al.* (1992). We envision the modeling of five good-sized apparel plants, each specializing in one or more lines such as pants or knitted shirts, with the collective capacity to require around 6.25 million pounds of fabric per year, but this is some way off. Before going on to this work, it is important to bear in mind the short-yardage price premiums. These influence the ways in which fabric producers, dyehouses, and manufacturers relate and interact.

The QR research group at NC State University has a close working relationship with the Textile Clothing Technology Corporation $[TC]^2$, a joint US Government (DOC)/industry-sponsored research and trade education facility. $[TC]^2$ has developed detailed shop-floor-level models of three types of apparel-production system: the Progressive Bundle System, the Stand-Up, Hand-off Modular Manufacturing System, and the Unit-production Mover System, which can be used to provide production-capability data for apparel-plant simulations. They can also be used to generate the data for creating response surfaces to characterize and compare system performance under various demand scenarios.

As many companies move away from high-work-in-process, large-batch processes toward more flexible manufacturing, 'team sewing' has emerged as a transitional production system. Team sewing is characterized by smaller batches, lower work-in-process, and teams of operators with low-to-moderate levels of cross-training. The details and complexities of line-balancing in these environments are being addressed. A generic, shop-floor-level simulation model, dubbed TAPS (Mazziotti, 1995), was developed for use in team-sewing research and training. The model has a data-driven, Windows-based user interface that allows an apparel manufacturer to define quickly and simulate proposed production lines. It includes automatic animation and generation of statistics and a way to customize and define new movement rules.

Recently, $[TC]^2$ has created an Apparel Enterprise modeling 'template' that serves as a flexible test-bed for analysis and as a user-friendly tool that can be used directly by industry. The program was created with the new hierarchical simulation-modeling tool, ARENA. The development environment allows a programmer to create 'modules' that are object-like building blocks and are available for an end-user to assemble into a specific scenario for analysis. The template consists of three types of module, which specify a particular scenario: (i) process modules that define specific resources in an apparel enterprise (cutting, sewing, finishing, shipping), (ii) product modules that define the set of products that can be produced in the enterprise (styles, routings, fabrics), and (iii) information modules that describe the actual demand (order stream).

A user builds a module through a graphical interface that contains buttons for each module. A scenario is built by selecting module types and entering information into dialogue boxes to customize the module. In this way, the modeling template provides the capability to define a very large number of scenarios and thus accurately represent almost any apparel manufacturer. The template also allows users to explore the effect of department-level sequencing/scheduling options, different processing-batch sizes, transportation lot sizes, fabric-reordering policies, and production-system alternatives (Modular Manufacturing, Team Sewing, Progressive Bundle, and Unit Production System). Animation and the generation of statistics are automatic, but can be easily customized by a user without requiring programming (Benjamin and Mazziotti, 1996; Benjamin *et al.*, 1994; Mazziotti, 1993; Mazziotti and Armstrong, 1994).

Work in this area is very active, and more on these models will be reported shortly.

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