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Production planning and scheduling for injection moulding of pipe fittings
A case study

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Abstract

The present study considers the development of a production planning and scheduling model for injection moulding of PVC pipe fittings in a local factory. The objective is to minimize the total costs of production, inventory, and shortages. A three-stage sequential procedure is used to solve the problem. The total problem domain is divided into three subproblems by mould-machine grouping. Each subproblem is then solved as a single-machine, multi-product, capacity lot-sizing problem, with a three-month planning horizon. A linear, zero–one goal programming approach is used to generate the solution. Finally, the production plan of the first month is decomposed and scheduling for each individual machine is carried out by a heuristic procedure. Comparison of the results show that the new procedure can substantially reduce both shortage and inventory costs.

Keywords: Production planning; Scheduling; Moulding; Goal programming

1. Introduction

PVC pipes and fittings are extensively used in agricultural, and construction sectors. Whenever there is a boom in these sectors, as is the situation in the country where the factory taken for this case study is located, the demand for the pipes could be very high. This puts a pressure on the corresponding production units to step up their production by making their facilities more efficient, and by even increasing their capacities.

This case study involves production planning and scheduling for injection moulding of pipe fittings in a local factory. The factory is experiencing great surge in the demand. There is an urgent need to increase the production. Better planning and management are needed for improving the productivity of the existing facilities.

Production of PVC pipes is a continuous process, and usually, there are only a few distinct, different sizes to make. On the other hand, production of PVC pipe fittings is a batch process and is

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done by injection moulding. The number of different types of fittings could be large. In the present factory, there are about 200 types produced on a regular basis. It has about 140 moulds. These are single cavity, with one item per cycle, or multi-cavity, with multiple, identical types per cycle, or family moulds with multiple and different types per cycle. There are 14 machines on which moulds can be mounted according to their compatibilities. The compatibility factors are technical factors like tonnage, pressure, tie bar space, quality requirements, etc., and economic factors like shot weight size. Batch sizes depend on the demand and inventories. Setup times are sequence dependent; they vary from 15 minutes to 2 hours. Customers tend to buy pipes and fittings from the same manufacturer, so the fittings influence the overall sales also. Manufacturers have to keep stock of even those fittings that have very low demand. The above description of the production environment for the pipe fittings shows the complexity of their production planning.

This case study involved a careful analysis of the current planning procedures. Various alternative procedures and models were examined in detail. The concerned personnel from the production planning and the operational control were involved at every step of the modeling process. The various stages of analysis, suggested production planning and scheduling procedures, comparison of the results, and subsequent conclusions are presented in the following sections.

2. Existing production planning procedure

At present, the production planning tasks are carried out by a clerk in the marketing department. He is helped by the marketing and production departments in obtaining information regarding the demand, availability of production capacity, and inventories. Using an intuitive procedure based on his own experience, he determines the production plan and schedule. The planning period for the master schedule is four weeks, rolling each week. The minimum lot-size scheduled for any product is kept as one week, to reduce the set-up costs.

One of the main problems with the present procedure is that 1-month planning horizon is rather short. A planning of longer term, coupled with a good forecasting technique would be more effective in smoothing production. In addition, the existing procedure has one week as the minimum production lot. Because of these two factors, there are some products which stay at zero inventory for a long time without any fresh production, while some other products build up huge inventories. Thus, on one hand, there are losses of sales due to shortages, while on the other hand, there are high inventory costs. Moreover, it is difficult for the planner to keep track of all of about 200 products, and plan efficiently. Another drawback is that a product is too often scheduled on a machine that is very large compared to the size of the shot weight of the product. Such an underutilization of the equipment capacity results in lower productivity.

It is felt that valuable information regarding long-term demand should be considered in the planning process. This, coupled with proper production smoothing would reduce both shortage, and inventory costs. The company feels that customer satisfaction by prompt deliveries is essential for sustainable business.

For production planning, the following aspects of the system are taken into account:

(a) The factory operates continuously 7 days a week and three shifts a day.
(b) The minimum production time can be relaxed from 7 to 3 days if necessary.
(c) For each product, its initial inventory, demand forecast for the next 3 months, and production yield can be obtained.
(d) Capacity of each machine is known.

3. Proposed planning procedure

Production planning for injection moulding is a complicated procedure, as shown in a previous section. Caie et al. (1980) modelled it as a mixed binary integer programming problem, with the objective function taken as the sum of setup costs, holding costs, and overtime costs over the planning horizon. The problem is then modified to a pure integer programming problem by using a method suggested by Manne (1958). A subgradient algorithm and a binary integer assignment algorithm are used in sequence to determine economic lot sizing. This method is computationally difficult when the problem size is large. In addition, it cannot be used when demand is not constant.

Van Wassenhove and De Bodt (1983) describe a case study of injection moulding, where the problem is as large as the current problem. Using machine-mould compatibility, the problem domain is divided into five subproblems. Each subproblem is then considered as a single machine problem. Demand is a variable changing from period to period. This capacitated lot-sizing problem is solved by heuristic procedures of Lambrecht and Vanderveken (1979), and Dixon and Silver (1981), which are modified versions of a heuristic suggested by Eisenhut (1975). They do not consider any shortage or backorder costs.

Nam and Logendran (1995) analyze some switching rules for aggregate production planning problems. Based on the net amount of the product to be produced, the rules specify whether the production rate should be high, normal, or medium. The rules give some simple, practical approaches to the managers for decision making, but they apply only to single-product problems. Kalpic et al. (1995) describe a multi-period, multi-criteria production planning problem in a thermoplastics factory. Two objectives, financial contribution and duration of the longest resource engagement are considered. The model is formulated and solved as a linear programming problem, with proper weights to the objectives. A goal program variation is also applied and the two methods are compared.

It was concluded from the analysis of the current system that the shortages for some of the products, and large inventories for the some others were partly caused by planning that is based solely on short-term demand. The planning should take longer-term forecasts into consideration and smoothen the production levels accordingly. It was also desired that any procedure developed for planning and scheduling should be computationally efficient to generate timely solutions and to perform any necessary sensitivity analyses. A three-stage sequential procedure was adopted for the model.

3.1. Decomposition of the problem

In the first stage, the problem is divided into subproblems using mould-machine compatibility. The procedure is similar to that of Van Wassenhove and De Bodt (1983). Since there is a one-to-one relationship between products and moulds, these two terms are used synonymously in the paper. A set of machines and their compatible moulds are grouped into one subproblem. The compatible factors are technical like tonnage, pressure, open distance, tie-bar space, mould dimension, temperature, etc., and are economical factors like shot weight size. There is more or less a clearcut demarcation in the compatibility matrix, so that the decomposition is straightforward. In cases where there is no exclusiveness and a mould is compatible with machines in more than one subproblem, the mould is assigned to a specific subproblem based on load balancing among the groups. Some efficiency and flexibility is lost in ignoring overlapping, but the advantages gained by simplification for the case of mathematical maneuverability offset the loss in accuracy. In addition, the decomposition makes it more convenient for the practical, real-life, dynamic allocation.

The original problem has been divided into three subproblems by using the compatibility factors. An example of the grouping is shown for the subproblem No. 2, in Table 1.

3.2. Production planning

The second stage involves determination of lot sizes for each product (mould) in a subproblem.

Each subproblem is now treated as a one machine, multi-product lot-sizing problem. The original (200 products, 140 moulds, 14 machines) problem is thus reduced to three one-machine multiproduct problems. In each subproblem, the machine capacities are summed up to obtain the aggregate capacity. A machine within a subgroup can handle all the moulds of that group. Among the

Table 1
Mould–machine compatibility of subproblem 2

Product code	Machine No.													
	4	5	7	8	9	2	11	14	3	10	1	13	12	15
2 545 064	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 531 407	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 531 106	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 531 406	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 530 506	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 530 006	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 530 606	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 530 507	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 530 508	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 530 707	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 530 509	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 530 006	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 530 007	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 531 507	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 367	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 541 166	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 504 103	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 504 004	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 504 303	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 504 204	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 504 105	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 504 403	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 504 304	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 504 205	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 563	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 564	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 664	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 565	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 566	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 541 963	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 541 864	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 542 163	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 542 064	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 541 965	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 541 566	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 165	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 166	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 167	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 545 063	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 545 065	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 531 108	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 365	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 863	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 541 863	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 066	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 541 263	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 541 164	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 540 065	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 532 408	0	0	0	0	0	1	1	1	1	1	0	0	0	0
2 533 108	0	0	0	0	0	1	1	1	1	1	0	0	0	0

machines within a subgroup, individual differences in characteristics like cycle time, setup time, etc., are ignored.

The demand for each product varies from period to period. The planning is a dynamic lot-sizing problem with capacity constraints. For such problems, heuristics like Lambrecht and Vanderveken (1979), and Dixon and Silver (1981) are available, and these generally take into account set-up costs also.

Multiplicity of objectives is modeled through goal programming approach. Several goals were identified for the current problem situation. Decision makers were actively involved in the selection and prioritizing of the goals. The criteria of importance, viability, and utility were considered in selection and ranking of the goals.

From the perspective of the management, the first goal involves the minimization of backorders and ending inventories. Backorders reflect the product shortages and hence indicate a measure of customer dissatisfaction. Since the products differ in terms of profitability and goodwill, their backorders have been subjectively weighted by management whereas their ending inventories have been weighted by inventory carrying costs.

The second goal is the minimization of overutilization and underutilization of a machine because under the present situation the machine capacity is fully utilized and cannot be increased in short-term period, and, the machine underutilization also should be avoided under this situation.

Constraints on the model are as follows:
(1) the inventory balance constraints,
(2) the machine capacity constraints,
(3) the lower and upper bounds for production time for each product in each period, set by management.

The planning horizon is taken as three months for a better production smoothening. The management feels confident about the accuracy of forecasts for any succeeding 3 months, as most of the orders come from regular retailers who are encouraged to submit their orders well in advance. The basic period for implementation is fixed at one month.

A mixed, linear zero–one goal programming model is formulated, and lot sizes of each product per period (month) are taken as the decision variables. The demand forecast, initial inventory, production rates, and available machine capacity, are some of the inputs to the model.

3.2.1. *Goal programming formulation*

The mixed linear, zero–one goal programming problem formulation is shown below:

Variables:

X_{it} number of injection cycles (shots) for mould i in period t

D^{+}_{1it} amount of overachievement for goal 1, i.e., meeting the demand, for product i, in period t

D^{-}_{2it} amount of underachievement for goal 2, product i, period t

D^{+}_{2t} amount of overachievement for goal 2, i.e., exact utilization of capacity, for period t

D^{-}_{2t} amount of underachievement for goal 2, period t

$$Y_{it} \quad \begin{cases} 1 & \text{if } X_{it} > 0, \\ 0 & \text{otherwise.} \end{cases}$$

Parameters:

d_{it} demand for product i in period t, given in number of injection cycles (shots)

a_{it} backorder cost per item of product i in period t

b_{it} Backorder cost per injection cycle of product i in period t
- a_{it} for single-cavity moulds
- $r\ a_{it}$ for moulds with r identical cavities
- $\sum_{j \in S} a_{it}$ for family moulds with a set S of different cavities

c_{it} inventory carrying cost per item of product i in period t
- e_{it} for single-cavity moulds
- $r\ e_{it}$ for moulds with r identical cavities
- $\sum_{j \in S} e_{it}$ for family moulds with a set S of different components.

k_i cycle time for mould i, in minutes

I_{i0} initial inventory expressed in injection cycles of mould i

LB_{it} lower bound of lot size of product i in period t in minutes

UB_{it} upper bound of lot size of product, i, in period t in minutes

TT_t available capacity in period t, in minutes
N total number of moulds
T Number of periods in a planning horizon

The constraints:

Goal constraints:
(1) *Meet the demand of all customers*

$$I_{i0} + X_{i1} - D_{1i_1}^{+} + D_{1i1}^{-} = d_{i1}, \quad i = 1, \dots, N,$$

$$D_{1i,t-1}^{+} + X_{it} - D_{1it}^{+} + D_{1it}^{-} - D_{1i,t-1}^{-} = d_{it},$$

$$t = 2, \dots, T, \quad i = 1, \dots, N.$$

(2) *Utilize exact productive time available*

$$\sum_{i=1}^{N} K_i X_{it} + D_{2t}^{-} - D_{2t}^{+} = \mathrm{TT}_t, \quad t = 1, \dots, T.$$

System constraints:

$$K_i X_{it} \geqslant Y_{it}\mathrm{LB}_{it}, \quad i = 1, \dots, N,$$

$$K_i X_{it} \leqslant Y_{it}\mathrm{UB}_{it}, \quad t = 1, \dots, T,$$

$$Y_{it} = \begin{cases} 1 & \text{if } X_{it} > 0, \\ 0 & \text{otherwise.} \end{cases}$$

$$X_{it}, D_{1it}^{-}, D_{1it}^{+}, D_{2t}^{-}, D_{2t}^{+} \geqslant 0,$$

$$i = 1, \dots, N, \quad t = 1, \dots, T.$$

Objective function:

Pre-emptive priorities are assigned to the goals depending upon the preferences of the management. Different weights are used to reflect the cardinal importance within a given priority level.

The following priority structure is finalized:

Priority 1: *Utilize exact productive time available*

Due to the market situation, the production capacity should be exactly utilized. Therefore, the total time for production should be achieved exactly as defined. i.e.

$$\text{Minimize} \quad \sum_{t=1}^{T} (D_{2t}^{+} + D_{2t}^{-}).$$

Priority 2: *Meet demand*

Due to the difference in importance of requirement of products, different weights are assigned to the products' underachievement and overachievement from their demands. The backorder and inventory carrying costs for each product in each period are used as the underachievement and overachievement weights, respectively. So, the second priority will be

$$\text{Minimize} \quad \sum_{t=1}^{T} \sum_{i=1}^{N} (b_{it} D_{1it}^{-} + c_{it} D_{1it}^{+}).$$

The overall objective function can be represented as

$$\text{Minimize} \quad Z = \mathrm{P1}\left(\sum_{t=1}^{T} (D_{2t}^{+} + D_{2t}^{-})\right) + \mathrm{P2}\left(\sum_{t=1}^{T} \sum_{i=1}^{N} (b_{it} D_{1it}^{-} + c_{it} D_{1it}^{+})\right),$$

where P1 and P2 are priority 1 and priority 2, respectively.

The above problem is solved by using the sequential linear goal programming problem (SLGP) procedure presented by Ignizio and Perlis (1979). The procedure is summarized below. The symbol K represents the total number of priority levels.

Step 1: Set $k = 1$ (where k is the priority level under consideration)
Step 2: Establish the linear programming formulation for priority level k only. Such a problem is equivalent to the conventional linear programming problems.
Step 3: Solve the linear programming problem associated with level k by any appropriate linear programming code.
Step 4: Set $k = k + 1$. If $k > K$ go to step 7.
Step 5: Establish the equivalent linear programming model for this priority level k. All the solutions obtained from previous steps are included as additional constraints.
Step 6: Go to Step 3.
Step 7: Stop. The solution vector associated with the last programming problem solved is the vector for the original linear goal programming model.

The SLGP is solved by MPSX/MIP software package on IBM 3083. The output is the production quantities for each product in subproblem, for each period of the planning horizon. Since the planing is on a rolling basis, only the output for the first period (month) is taken for implementation.

3.3. Disaggregated production scheduling

In the third stage, a detailed schedule is worked out. The input is the production plan for each product for the first period in the planning horizon, which is obtained from the results of the previous stage. Whereas the second stage considers all the machines in a subproblem as a single entity, this stage disaggregates that entity into single, individual machines and schedules jobs on them for moulding.

The problem of scheduling single-stage jobs with parallel processors contains both allocation and sequencing dimensions. The determination of optimal schedules is often rendered somewhat difficult by the need to make both kinds of decisions, and the thrust of analytical methods have been aimed primarily at makespan problems for good reason; makespan problems are, in fact, relatively simple.

From a practical viewpoint the emphasis on makespan is quite reasonable. A sound heuristic procedure for nonpreemptive tasks is to solve the allocation problem first and then the sequencing problem. In the present work, the allocation is carried out by distributing the processing load among machines as evenly as possible. Although an even distribution of the load is not necessarily optimal, it will make the task of allocation quite simple and easy to implement in a dynamic environment. It will also ensure fair work distribution among the workers. Once the allocation is carried out, the optimal sequence on each machine is determined separately.

The parallel identical machine scheduling problem of minimizing makespan with nonpreemptive policy is not easy to solve and no direct algorithm is available for an optimal makespan or for an optimal schedule. A simple yet effective heuristic procedure for constructing a schedule involves the use of longest processing time (LPT) scheduling as a dispatching mechanism, which is selected for this study also.

However, some subproblems in this case study are parallel nonidentical machine scheduling problems for which a heuristic algorithm is developed as no direct algorithm is available. Because some products cannot be produced in all machines in a subproblem, a flexibility index (FI) for each product is considered. The flexibility index of a product is defined here as the number of machines in which that product can be produced. The priority for scheduling is given to the products which have the lowest flexibility index. For products with the same index, the LPT rule is exercised, in which the top priority is given for the product with longest processing time, and so on.

The heuristic for scheduling and sequencing is as follows:

Step 3a: Rank the jobs according to their flexibility index from low to high. Jobs which have the same flexibility index are ranked according to LPT rule, in the decreasing order of their processing times.

Step 3b: Assign the first job on the list to the compatible machine with the maximum amount of processing time still available. Repeat assignments until all the jobs have been assigned.

Step 3c: Sequence the jobs on each machine fusing individual judgement.

Sequencing is not included in the current study. For sequencing, the planner can even include, if necessary, additional criteria like due dates and real-time inventory status. The scheduling algorithm is coded by using macrocommands of Lotus 1-2-3 release two package run on an IBM or IBM-compatible personal computer.

4. Estimation of parameters of the model

To formulate the model, the parameters used for input to the model or for comparison, should be given or else estimated by the company. Therefore, the management is encouraged not only to get involved but also to take a major role in formulation. The parameters and estimation of their values are described below.

4.1. *Demand forecast (d_{it})*

The demand is forecast by the marketing department of the company, and is assumed to be deterministic. The planning horizon is taken as 3 months, which is acceptable to the management. A rolling plan of a 3 months horizon is suggested and the plan is adapted for the first month.

4.2. *Available initial inventory (I_{i0})*

This parameter must be updated periodically for the rolling production plan.

4.3. *Average cycle time (K_i)*

The average injection cycle time for each mould on each machine is obtained from the manufacturing data. This parameter should be updated periodically when the machine or mould conditions are changed or modified.

4.4. *Inventory carrying cost (C_i)*

This is taken as the sum of the opportunity cost of the capital blocked in inventory and the warehousing cost. In this study the former is charged at a 15% rate on the production cost and the latter is estimated at about 5% rate on the production cost. Thus, the total charge is 20% annual rate on the production cost, per injection cycle. This cost is assumed to be constant over the planning horizon.

4.5. *Backorder cost (b_i)*

This cost occurs when there is a failure to meet customer demand on time, resulting in tangible loss of profits and in intangible loss of goodwill. It is difficult to assign the exact monetary value to the second factor. In our case, this cost is defined as loss of goodwill, which is much more than and includes the loss of profit contribution. Moreover, each product is not equally important, the importance depends upon individual customers' relations with the company and long-term marketing strategies in running the business. Therefore, the backorder costs for all products are not the same. This cost is a product of profit contribution margin which is the expected profit on the sale of a single item, and subjective weights given to individual products to indicate their relative importance to the company. The following factors are considered for giving subjective weights: (1) Strategic management concerns about the importance of the products to be produced under a limited capacity. (2) Business practices such as trying to satisfy the product demands of some special customers. (3) Tactical factors such as the need for some types of pipe fittings to be sold as complementary products for some types of pipes. The backorder cost is taken as constant for every period.

4.6. *Machine time available (TT_t)*

The time available in each planning horizon for a subproblem is the sum of capacities of all machines in the subproblem. Factors such as allowances for planned maintenance and average breakdown downtimes are calculated from past data. Festival days, and average setup times of the products are also taken into consideration in the computation of net available times of the machines.

4.7. *Lower and upper bounds on production time (LB_i, UB_i)*

These parameters depend upon demand characteristics of the products. They are the lower and upper bounds for production times for producing a single lot of a product. The objective of setting these parameters is to control the setup cost of the production system, which makes the model more reasonable and practical in real-life situations. These bounds are fixed by the management in consultation with the marketing department, as

Table 2
Data for subproblem 2

Mould No.	dl1 (July) (shot)	dl2 (August) (shot)	dl3 (September) (shot)	I0 (shot)	*k*1 (min)	*ci* (baht)	*bi* (baht)	LB*l* (min)	UB*l* (min)
X1	1250	1250	1563	3224	1.78	0.11	18.06	7200	20160
	625	625	781	4230	1.78	0.23	38.74	7200	20160
X2	700	700	875	1452	1.62	0.17	34.00	4320	10080
X3	2000	2000	2500	20785	1.07	0.10	13.28	7200	20160
X4	7500	7500	9375	9168	1.40	0.17	29.84	10080	34272
X5	4000	4000	5000	185	1.20	0.04	2.65	10080	34272
	12000	8000	10000	−11	1.20	0.03	1.30	10080	34272
X6	5000	750	938	0	1.20	0.23	20.96	4320	10080
X7	12500	12500	15625	−139	1.34	0.22	15.24	10080	34272
X8	167	167	208	235	1.39	0.25	24.60	4320	10080
	500	500	625	192	1.39	0.05	6.72	4320	10080
X9	375	375	469	1294	1.50	0.43	65.00	4320	10080
X10	625	625	781	2051	1.50	0.45	131.52	4320	10080
X11	500	500	625	2663	1.50	0.17	26.68	4320	10080
	500	500	625	4788	1.50	0.12	16.20	4320	10080
	200	200	250	4896	1.50	0.14	18.54	4320	10080
X12	500	500	625	0	1.35	0.05	13.44	4320	10080
	833	833	1042	1475	1.35	0.20	40.24	4320	10080
X13	2500	2500	3125	5	1.50	0.15	31.28	7200	20160
X14	6250	6250	7813	−1	1.50	0.27	111.28	10080	34272
X15	1250	1250	1563	465	2.00	0.45	114.32	7200	20160
X16	1250	1250	1563	4220	2.20	0.38	46.00	4320	10080
X17	10000	10000	12500	3669	2.00	0.88	72.48	10080	34272
X18	2000	2000	2500	2	1.50	0.22	14.00	7200	20160
X19	0	5000	10000	2320	1.01	0.15	6.24	7200	20160
	0	500	500	7084	1.01	0.15	4.92	7200	20160
X20	0	5000	10000	61	1.10	0.21	13.44	7200	20160
	0	500	500	4657	1.10	0.22	12.84	7200	20160
X21	0	500	500	11747	1.20	0.23	13.70	4320	10080
	0	500	500	3102	1.20	0.29	10.24	4320	10080
X22	0	500	500	6269	1.30	0.30	9.92	4320	10080
	0	500	500	3485	1.30	0.32	12.38	4320	10080
X23	1500	1500	1875	3255	1.80	0.47	107.28	7200	20160
X24	1400	1400	1750	3066	1.80	0.42	132.72	7200	20160
X25	133	133	167	1196	1.80	0.38	35.00	4320	10080
X26	167	83	104	0	1.60	0.40	32.00	4320	10080
X27	417	417	521	3283	2.00	0.52	67.84	4320	10080
X28	17	133	167	−3	2.00	0.62	26.00	4320	10080
X29	1750	1750	2188	7514	1.60	0.43	212.00	4320	10080
X30	4000	4000	5000	1650	1.60	0.13	93.92	7200	20160
	2250	2250	2813	3905	1.60	0.15	89.52	7200	20160
X31	750	250	313	0	1.60	0.30	40.00	4320	10080
X32	800	800	1000	1968	1.70	0.17	36.76	4320	10080
	1000	1000	1250	2980	1.70	0.17	35.68	4320	10080
X33	7500	7500	9375	−37	1.50	0.37	94.00	10080	34272
X34	250	250	313	142	1.60	0.47	22.00	4320	10080
X35	175	175	219	16	1.50	0.82	28.00	4320	10080
X36	10000	7000	8750	30	1.50	2.00	40.76	10080	34272
X37	2500	2500	3125	971	1.60	0.35	79.92	7200	20160
X38	417	417	521	2	2.20	0.40	32.00	4320	10080
X39	875	875	1094	479	2.00	0.38	44.80	4320	10080
X40	5000	2500	3125	9268	1.50	0.32	97.80	7200	20160

a policy, to give appropriate strategic weights to each class of products with respect to the production loss due to setup times. The bounds control the size of any production lot that is produced in a given time period.

4.8. Setup cost (S_i)

This cost depends on mould characteristics and can be calculated for each mould separately, based on historical data. In the production planning model, the setup cost is not explicitly used but is indirectly controlled by the bounds on production times. It is however, computed for comparing the total costs of the existing and the proposed procedures.

Table 3
Availability of productive time

	Productive time available (min)		
	July	August	September
Subproblem 1	137 088	137 088	171 360
Subproblem 2	181 440	181 440	226 800
Subproblem 3	181 440	181 440	226 800

Table 4
Example of setup cost computation

Action	Time (h)	Cost (Baht)
1. Mould change[a]	2.5	750
2. Preparation of injection machine[a]	1	300
3. Test run and adjustment[a]	0.5	150
4. Raw materials for test run	—	2520
5. Waiting time machine (lost contribution)	4	2958
6. Energy loss	—	205
Total		6883

[a] Highly skilled people.

5. Results and discussion

The results of the goal programming model for the production planning, and of the heuristic for scheduling are analyzed for their efficiency. These results are then compared with those of the current procedure.

5.1. Production planning

The proposed model is tested using as the inputs, the company's data for a specific three month period. An example of the input data is given in Tables 2–4, for the subproblem #2. The output of the linear mixed-integer goal programming model yields the desired production plan for the planning horizon, from which the plan for the first period is taken for implementation. The output is shown for the subproblem #2, in Table 5.

The results of the proposed procedure are compared with the actual planning for the same planning period. The factors of interest are: the number of production lots in planning period, sizes of production lots, number of setups, number of products that are in surplus, and number of products that are in shortage in each period.

The comparison shows that the current procedure tends to produce larger lots, but smaller in number. This is due to the practice of running a product lot for a whole week. The shortages and excess inventories are more in the current plans.

The effects of the above factors are translated into different categories of costs, and on these bases, further comparisons are made between the two procedures. The categories of costs that are of interest for the present study are inventory carrying cost, backorder cost, setup cost, profit contribution loss, total weighted cost, and total cost. The total weighted cost is the sum of inventory carrying cost, backorder cost, and the setup cost. The total cost is same as the total weighted cost, except the backorder cost which is replaced by the contribution loss. The cost comparisons are summarized in Table 6.

It can be seen from the results that the backorder cost decreases substantially for the proposed procedure, thus, satisfying the main objective of this study. However, the setup cost increases because

Table 5
Output of linear mixed-integer goal programming model for subproblem 2

Mould	Io (shot)	July				August				September			
		DI (shot)	Plan (shot)	Inven. (shot)	B.Order (shot)	DI (shot)	Plan (shot)	Inven. (shot)	B.Order (shot)	DI (shot)	Plan (shot)	Inven. (shot)	B.Order (shot)
X1	3224	1250	4044	6018	0	1250		4768	0	1563		3205	0
	4230	625	4044	7649	0	625		7024	0	781		6243	0
X2	1452	700	2666	3418	0	700		2718	0	875		1843	0
X3	20 785	2000		18 785	0	2000		16 785	0	2500		14 285	0
X4	9168	7500		1668	0	7500	10 218	4386	0	9375	11 073	6084	0
X5	185	4000	8400	4585	0	4000	17 311	17 896	0	5000	8400	21 296	0
	− 11	12 000	8400	0	3611	8000	17 311	5700	0	10 000	8400	4100	0
X6	0	5000	8360	3360	0	750		2610	0	938		1673	0
X7	− 139	12 500	15 773	3134	0	12 500	15 634	6268	0	15 625	19 543	10 186	0
X8	235	167	3107	3175	0	167		3008	0	208		2800	0
	192	500	3107	2799	0	500		2299	0	625		1674	0
X9	1294	375		919	0	375		544	0	469		76	0
X10	2051	625		1426	0	625		801	0	781	2880	2900	0
X11	2663	500		2163	0	500		1663	0	625		1038	0
	4788	500		4288	0	500		3788	0	625		3163	0
	4896	200		4696	0	200		4496	0	250		4246	0
X12	0	500	3200	2700	0	500		2200	0	625		1575	0
	1475	833	3200	3841	0	833		3008	0	1042		1966	0
X13	5	2500	6246	3751	0	2500		1251	0	3125	4800	2926	0
X14	− 1	6250	7813	1562	0	6250	7813	3125	0	7813	9766	5079	0
X15	465	1250	4613	3828	0	1250		2578	0	1563		1016	0
X16	4220	1250		2970	0	1250	1963	3683	0	1563		2120	0
X17	3669	10 000	16 878	10 547	0	10 000	17 136	17 683	0	12 500	21 420	26 603	0
X18	2	2000	4994	2996	0	2000		996	0	2500	4800	3296	0
X19	2320	0		2320	0	5000	7128	4448	0	10 000	9302	3750	0
	7084	0		7084	0	500	7128	13 712	0	500	9302	22 514	0
X20	61	0		61	0	5000	6545	1606	0	10 000	12 143	3749	0
	4657	0		4657	0	500	6545	10 702	0	500	12 143	22 345	0
X21	11 747	0		11 747	0	500		11 247	0	500		10 747	0
	3102	0		3102	0	500		2602	0	500		2102	0
X22	6269	0		6269	0	500		5769	0	500		5269	0
	3485	0		3485	0	500		2985	0	500		2485	0
X23	3255	1500		1755	0	1500	4000	4255	0	1875	4000	6380	0
X24	3066	1400		1666	0	1400		266	0	1750	4000	2516	0
X25	1196	133		1063	0	133		929	0	167		763	0
X26	0	167		0	166	83		0	250	104		0	354
X27	3283	417		2866	0	417		2449	0	521		1929	0
X28	− 3	17		0	19	133		0	153	167		0	319
X29	7514	1750		5764	0	1750		4014	0	2188		1827	0
X30	1650	4000	4500	2150	0	4000	4500	2650	0	5000	5601	3251	0
	3905	2250	4500	6155	0	2250	4500	8405	0	2813	5601	11 193	0
X31	0	750	2700	1950	0	250		1700	0	313		1388	0
X32	1968	800		1168	0	800		368	0	1000	2541	1909	0
	2980	1000		1980	0	1000		980	0	1250	2541	2271	0
X33	− 37	7500	9412	1875	0	7500	9375	3750	0	9375	11 719	6094	0
X34	142	250		0	108	250		0	358	313		0	670
X35	16	175		0	160	175		0	335	219		0	553
X36	30	10 000	12 470	2500	0	7000	8750	4250	0	8750	10 938	6438	0
X37	971	2500	5279	3750	0	2500		1250	0	3125	4500	2625	0
X38	2	417		0	415	417	1963	1131	0	521		610	0
X39	479	875		0	396	875	3076	1805	0	1094		711	0
X40	9268	5000		4268	0	2500		1768	0	3125	4800	3443	0

Table 6
Comparison of the results between the existing procedure and proposed procedure (July–September)

		Existing Procedure [A]	Proposed Procedure [B]	Difference [C] = [B] – (A)	% Difference [C]/[A]* 100
Inv. carrying cost	Baht	703 465.00	668 373.00	– 35092.00	– 4.99
Backorder cost	Baht	3 470 651.00	1 008 129.00	– 2462522.00	– 70.95
Contribution loss	Baht	1 188 182.00	392 035.00	– 796147.00	– 67.01
Setup cost	Baht	180 773.00	230 141.00	49368.00	27.31
Total weighted cost	Baht	4 354 889.00	1 906 643.00	– 2448246.00	– 56.22
Total cost Baht	Baht	2 072 420.00	1 290 549.00	– 781871.00	– 37.73
No. of moulds	Moulds	118	153	35	29.66
No. of Backorders	Items	100	51	– 49	– 49.00

the product is changed more frequently to satisfy the demands of various products. Although setup cost is increasing, the overall improvement largely outweighs the disadvantage of an increasing setup cost, as can be seen by the substantial decrease in total weighted cost and in total cost. The total weighted cost and the total cost are decreasing by about 56% and 38%, respectively. Even more important than savings in costs is the increase in customers' satisfaction, which is a key policy of the company in running its business in a sustainable manner.

5.2. Production scheduling

The results from the production planning are used as inputs for the production scheduling. This step tries to balance the utilization of each machine in the subproblems and to satisfy the solution from the production planning model. The parallel machine scheduling problem with the objective of minimizing makespan is solved by a heuristic method as given in Section 3.3. The scheduling is done for period by period on a rolling basis. An example of a schedule is given for subproblem #2, in Table 7.

From the results of the production scheduling heuristic, it can be seen that the heuristic performs well in distributing load among the machines. There are some instances when the load cannot be scheduled properly, resulting in the work load overflowing into the next period. But these instances are found to be rare, and at the most extend by only 2 days. These overflows are not serious as, in anyway, the planning is on a rolling basis.

6. Conclusions

The main objective of this study is to develop a model of production planning and scheduling for a PVC pipe fitting company. Management was actively involved in the development of the model, and in supplying subjective weights where necessary. The proposed model seems promising in substantially reducing the overall costs. This would be possible by the reductions in backorder and inventory costs. Extensive sensitivity analysis, which is not shown here, also indicates that the proposed procedure would be consistently better than the current one.

The strength of the suggested model stems from its ability to use forecast data in a formalized manner which will be an improvement over a completely intuitive procedure for a complex but routine problem, and from its greater speed in finalizing the plans. Above all, it would score in customer satisfaction, by supplying the right quantities at right times.

Table 7
Production scheduling for subproblem 2 (July)

Mould No.	Ti (Min)	Fi	Machine no. 2		Machine no. 11		Machine no. 14		Machine no. 3		Machine no. 10	
			Allocated Time (min)	Available Time (min) 605	Allocated Time (min)	Available Time (min) 605	Allocated Time (min)	Available Time (min) 605	Allocated Time (min)	Available Time (min) 605	Allocated Time (min)	Available Time (min) 605
X17	563	3	563	42	0	605	0	605	0	605	0	605
X36	312	3	0	42	312	293	0	605	0	605	0	605
X33	235	3	0	42	0	293	235	370	0	605	0	605
X14	195	3	0	42	0	293	195	175	0	605	0	605
X6	167	3	0	42	167	126	0	175	0	605	0	605
X1	120	3	0	42	0	126	120	55	0	605	0	605
X7	352	4	0	– 42	0	126	0	55	352	253	0	605
X15	154	4	0	42	0	126	0	55	154	99	0	605
X5	168	5	0	42	0	126	0	55	0	99	168	437
X13	156	5	0	42	0	126	0	55	0	99	158	281
X37	141	5	0	42	0	126	0	55	0	99	141	140
X18	125	5	0	42	0	126	0	55	0	99	125	15
X30	120	5	0	42	120	6	0	55	0	99	0	15
X12	72	5	0	42	0	6	0	55	72	27	0	15
X31	72	5	0	42	0	6	72	– 17	0	27	0	15
X8	72	5	72	– 30	0	6	0	– 17	0	27	0	15

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