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Linear Programming for Aggregate Production Planning in a Textile Company

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Abstract
This article aims to propose and implement an aggregated production planning model to provide optimal strategies in the medium term for a textile company, for which a linear programming model is proposed to minimise total costs associated with labour and inventory levels. The model proposed takes into account characteristics associated with fabric contraction, wastes in the process, the efficiency of new employees, and training requirements. The model is implemented and solved in GAMS, supported on an MSExcel interface, to find the optimal solution, which is to apply a hybrid strategy to the production plan, and also some strategies for improving the production process are generated.

Key words: *aggregate planning, linear programming, textiles, strategies, fabrics.*

Introduction

Nowadays the textile industry faces a competitive manufacturing environment that has led manufacturers to implement planning strategies that guarantee operational effectiveness, motivating the redesign of organisational and productive structures, to reach satisfactory levels of competitiveness [1]. These conditions force global textile and clothing supply chains to optimise their production planning in order to face the challenges demanded by market dynamics [2]. For the long or medium-term, aggregate production planning is considered as a tool that takes into account the constraints of existing capacity [3], providing guidance to the manufacturer regarding efficient production and supply strategies [4]. In this sense, aggregate production planning determines the manufacturing capacity of products to satisfy the demand in a time horizon, for which it evaluates design configurations and manufacturing scenarios that maximise benefits and/or minimise costs through optimal production quantities, capacity, subcontracting, inventory and shortages [5, 6].

For its operation, aggregate planning is based on demand forecasts and customer orders that must be met [7], taking into account constraints related to production capacity, available materials, equipment, labour and other necessary resources for the production system. Once the production strategy is obtained, the master production schedule (MPS) is built, decomposing temporally and spatially the goals of the aggregate planning and forecasting into the manufacturing requirements of specific products, thus being a guide for the acquisition of resources and materials [8, 9]. To solve the aggregate production planning problems, level, chase, and hybrid strategies are often used. The level strategy maintains a steady quantity of labour and production rate, and for cases in which variations in demand occur, the strategy increases or decreases the inventory levels, creates a portfolio of products with complementary demands, and influences the increase in demand and pending orders. Chase strategies equalise the production rate with the demand rate in each period through hiring and firing labour, using overtime and part-time workers and subcontracting production, among others. Hybrid strategies combine the options proposed by the level and chase strategies in order to provide an optimal production plan that satisfies demand and other business policies at the lowest cost [9-11].

The complexity associated with the formulation of mixed strategies suggests the use of optimisation models based on mathematical programming, which according to the specific conditions of the problem to be solved, can generate transport models of linear programming [12], mixed-integer linear programming (MILP) [13, 14], multi-criteria mixed-integer linear programming (MCMILP) [15], and non-linear programming (NLP) [16], among others. These mathematical models provide a solution to the specific requirements of each problem, offering a wide range of possibilities in modeling, which allows to pose a great diversity and quantity of linear and non-linear constraints, integer and continuous variables, and one or multiple objective functions, as in the case of goal programming [6, 17]. In order to find a solution for mathematical programming models of aggregate planning, several alternatives can be found, ranging from spreadsheets and solvers [11, 18, 19] to specialised mathematical programming software such as CPLEX [20] and GAMS [21].

In literature related to the modelling of aggregate production problems, some studies propose objective functions related to total costs, labour fluctuations, late orders, benefits and utilities, equipment use, service level, and quality, among others [6, 13-15, 18, 21]. Likewise these studies take into account parameters, variables and constraints related to the size of labour, hiring and firing, labour learning rates, working hours and legal restrictions, production capacity, subcontracting of production, multiple production factories, storage capacity, inventory levels, machine maintenance, setup and assembly times, customer demand, and cash management.

However, to the best of our knowledge, in the literature, there are currently no aggregate planning models for companies in the textile industry that addresses variables related to fabric waste and shrinkage by line and by process, training days needed for new employees in each process, and the efficiency of new employees in each process. Therefore this article aims to design and implement

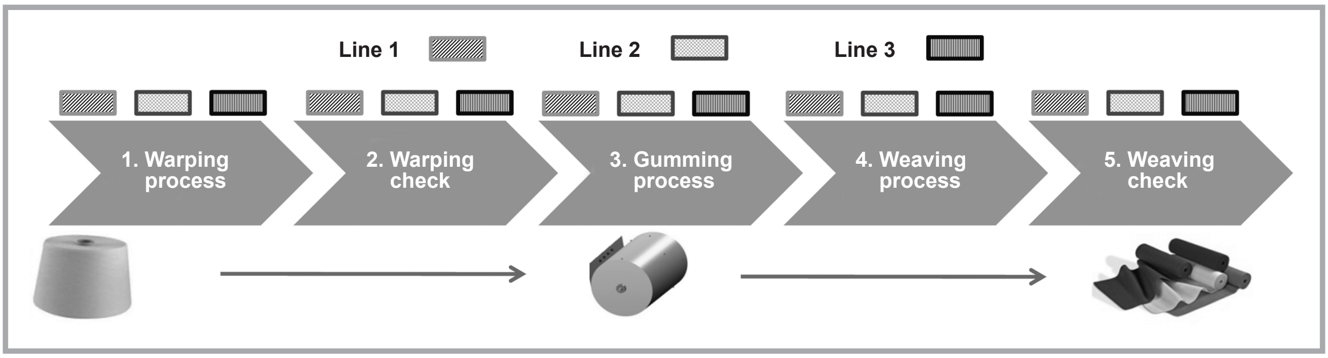

Figure 1. Textile manufacturing processes for the product lines.

an aggregate production planning model to provide optimal production strategies in the medium term that suit the needs of companies in the textile industry. For this, we propose an algebraic formulation for the aggregate planning model, which is then validated with an experimental development to analyse output variables such as production rates, inventory levels, labour level, hiring, and firing. Finally we present the main conclusions and contributions of this study.

Formulation of the aggregate production planning model

The company selected for this study manufactures pre-dyed and one-colour fabrics suitable for dyeing which have high turnover rates. The company has 3 product lines, which are permanently in use due to customer demand, called Line 1 – Simple Pocket (one-colour fabrics weighing less than 130 gr/m^2), Line 2 – Double Pocket (one-colour fabrics weighing over or equal to 130 gr/m^2), and Line 3 – Staffing (pre-dyed fabrics weighing over or equal to 120 gr/m^2). ***Figure 1*** shows the transformation processes for each product line.

The company needs to determine its annual aggregate production plan to minimise the total costs represented by labor costs and inventory management,, and ensure compliance of constraints related to each product line demand, production capacity expressed in meters (m), work in process storage, and operational efficiency. In addition, the company is required to take into account the efficiency of hired employees because the initial part of the work contract is dedicated to receiving training, and they also have a lower performance in their work due to their little experience in the tasks assigned. The waste and contractions of the fabric must also be included in the production plan.

Due to the policies established by the company, the use of overtime or production subcontracting is not considered, because these decisions can significantly affect the quality of the product and put industrial secrets at risk. In the same way, since it is a medium-term production plan based on 12 month's horizon planning, operational details related to the setup time, assembly and maintenance of machines are not considered directly; however, these factors are included proportionally to the operating times of each product line based on time and motion studies in each process mentioned in ***Figure 1***. Therefore we propose the use of mathematical programming to create a linear programming model, which will be referred to as the LIPROTEX model. The use of a linear programming model is justified due to the complexity of the model related to the number of parameters and variables taken into account in a medium-term planning horizon, and to the constraints of resources, capacities, inventories, demand, labour and product lines, which guarantee the feasibility and optimisation of the aggregate production plan.

Table 1. Indices, parameters, coefficients and variables for the LIPROTEX model.

Indices	Definition
I	Number of processes (i = 1, … , I)
T	Number of months (t = 1, … , T)
L	Number of product lines (l = 1, … , L)
Parameters and coefficients	Definition
CE_i	Monthly cost per employee in process i, $
$CA_{i,t}$	Cost of inventory management in process i in month t, $/m
A_i	Storage capacity in process i
PM_i	Maximum production capacity for process i, m
$DT_{l,i}$	Waste and shrinkage of product line l in process i
$D_{l,t}$	Expected fabric demand of line l in month t, m
DE_i	Required training days for new employee in process i
E_i	New employee efficiency in process i
$MH_{l,i}$	Production of meters per hour of product line l in process i
HD_t	Real available hours per employee in month t
CAC	Administrative cost of hiring employee, $
CAD	Administrative cost of firing employee, $
Output variables	Definition
$H_{l,i,t}$	Production hours dedicated to line l in process i in month t
$S_{l,i,t}$	Final inventory of product line l in process i in month t, m
$X_{i,t}$	Number of employees in process i in month t
$XD_{i,t}$	Number of employees fired in process i in month t
$XN_{i,t}$	Number of employees hired in process i in month t
Decision variables	Definition
$P_{l,i,t}$	Fabric production of product line l in process i in month t, m

Variables for the LIPROTEX model

This study identifies variables that have not been taken into account in previous models of aggregate programming which influence the total cost of a production plan and generate a great impact on decision-making processes in the textile industry. Among these variables, fabric waste by product line and by process is highlighted due to the nature of fabric processing, which commonly generates contractions and losses; the training days needed for new employees in each process is also included, since a new employee must be trained before starting a job, and a salary must be paid equally while this training is being provided. Proportionally the efficiency of new employees in each process is taken into account, since this varies according to the employees' expertise and adaptation to the job. ***Table 1*** presents the indices, parameters, coefficients, and variables of the LIPROTEX model.

Table 2. *Monthly demand for one year for the product lines (thousands of meters).*

Month, *t*		Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Demand forecast ($D_{l,t}$)	*Line 1*	60	70	70	85	80	60	70	90	110	80	75	70
	Line 2	64	71	139	115	133	80	123	99	163	135	104	84
	Line 3	100	105	166	123	177	124	172	194	206	219	140	149

Table 3. *Production capacity and production per process.*

Process (*i*)	Production capacity, m/month (PM_i)	Production, m/hour ($MH_{l,i}$)			Shrinkage percentage ($DT_{l,i}$)		
		Product line 1	*Product line 2*	*Product line 3*	*Product line 1*	*Product line 2*	*Product line 3*
Warping	425.000	120	120	115	0%	0%	0%
Warping check	420.000	390	390	350	0%	0%	0%
Gumming	570.000	219	219	240	3%	3%	2%
Weaving	490.000	157	120	125	10%	12%	7%
Weaving check	410.000	318	318	280	2%	2%	3%

Objective function and constraints

The objective function and constraints of the mathematical model for the production programming of companies in the textile industry (LIPROTEX) are presented in ***Equations (1)-(9)***.

The objective function represented in ***Equation (1)*** minimises the total costs of the production plan in terms of the labour and inventory management costs. Labor costs are represented by the monthly cost of employees per process in a month, the training time of employees, and the administrative cost of hiring and firing employees. The inventory management costs are proportional to the monthly inventory level in each process. ***Equation (2)*** guarantees fulfillment of the finished product demand for each product line. ***Equation (3)*** represents the constraints for the final inventory by period, process and product line. The storage capacity constraints in ***Equation (4)*** ensure that the final inventory of a process does not exceed the maximum storage capacity of the process. ***Equation (5)*** represents labour balance equations for hiring and firing. The production of meters of fabric in a period, process, and product line is represented in ***Equation (6)***. ***Equation (7)*** presents the number of monthly hours available in the production plant, which results from multiplying the available hours per employee in a month by the number of employees available per process and month. The constraints of the maximum production capacity are found in ***Equation (8)***. ***Equation (9)*** represents non-negativity restrictions for the variables of the model related to production hours, final inventory, hiring, firing, and production level.

Once the aggregate production planning problem has been modelled, it is identified as a linear programming model that does not require entire variables, due to the nature of the production process, which produces fabric continuously and not in discrete units. Likewise, for labour-related variables, the company's management decides that it does not require entire variables of workers, and according to the results, it decides to hire part-time staff, redistribute operators with idle capacity, take advantage of high-skilled employees, and assign employees with idle time to other processes, among others. In addition, the mathematical programming model proposed handles deterministic

$$Min\ Z = \sum_{t=1}^{T}\sum_{i=1}^{I}\left[CE_i \times \left(X_{i,t} + XN_{i,t} \times \frac{DE_i}{30}\right) + CAC \times XN_{i,t} + CAD \times XD_{i,t}\right] + \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{l=1}^{L}\left(CA_{i,t} \times S_{l,i,t}\right) \quad (1)$$

$$S_{l,I,t} = S_{l,I,t-1} + P_{l,I,t} - D_{l,t} \quad \text{for} \quad l = 1, \dots, L \quad t = 1, \dots, T \quad (2)$$

$$S_{l,i,t} = S_{l,i,t-1} + P_{l,i,t} - \frac{P_{l,i+1,t}}{1-DT_{l,i}} \quad \text{for} \quad l = 1, \dots, L \quad i = 1, \dots, I\text{-}1 \quad t = 1, \dots, T \quad (3)$$

$$\sum_{l=1}^{L} S_{l,i,t} \leq A_i \quad \text{for} \quad i = 1, \dots, I \quad t = 1, \dots, T \quad (4)$$

$$X_{i,t} = X_{i,t-1} + XN_{i,t} - XD_{i,t} \quad \text{for} \quad i = 1, \dots, I \quad t = 1, \dots, T \quad (5)$$

$$P_{l,i,t} = H_{l,i,t} \times MH_{l,i} \quad \text{for} \quad l = 1, \dots, L \quad i = 1, \dots, I\text{-}1 \quad t = 1, \dots, T \quad (6)$$

$$\sum_{l=1}^{L} H_{l,i,t} = HD_t \times \left(X_{i,t-1} + XN_{i,t} \times E_i - XD_{i,t}\right) \quad \text{for} \quad i = 1, \dots, I \quad t = 1, \dots, T \quad (7)$$

$$\sum_{l=1}^{L} P_{l,i,t} \leq PM_i \quad \text{for} \quad i = 1, \dots, I \quad t = 1, \dots, T \quad (8)$$

$$H_{l,i,t} \geq 0, S_{l,i,t} \geq 0, X_{l,i,t} \geq 0, XD_{l,i,t} \geq 0, XN_{l,i,t} \geq 0, P_{l,i,t} \geq 0 \text{ for } l = 1,\dots, L \quad i = 1,\dots, I\text{-}1 \quad t = 1,\dots, T \quad (9)$$

Equations (1), (2), (3), (4), (5), (6), (7), (8) and (9).

Table 4. Estimated waste by process, costs and inventory levels.

Process (*i*)	Storage capacity. m/month (A_i)	Monthly inventory cost per. $USD/m ($CA_{i,t}$)	Initial inventory (m) ($S_{l,i,0}$)		
			Product line 1	*Product line 2*	*Product line 3*
Warping	170.000	$ 0.013	20.000	10.000	15.000
Warping check	120.000	$ 0.013	10.000	5.000	7.500
Gumming	30.000	$ 0.021	30.000	15.000	22.500
Weaving	350.000	$ 0.025	40.000	20.000	30.000
Weaving check	150.000	$ 0.025	20.000	10.000	15.000

Table 5. Labour costs, efficiencies and training requirements.

Process (*i*)	Cost of employee per process, $USD/month ($CE_i$)	Initial employees ($X_{i,0}$)	New employee efficiency (E_i)	Training requirements for new employees, days (DE_i)
Warping	$ 696.7	13	70%	5
Warping check	$ 443.3	3	80%	12
Gumming	$ 696.7	4	70%	5
Weaving	$ 823.3	11	60%	5
Weaving check	$ 443.3	3	80%	12

Table 6. Available hours per employee per month.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec
Working hours per employee (HD_t)	208	184	200	208	200	200	216	200	208	208	192	208

variables, and in the case of integrating uncertainty with some parameters and/or variables, the model must be adjusted by implementing techniques such as fuzzy logic [22, 23].

Experimental development

According to the demand forecasts and negotiations carried out with the company's customers, ***Table 2*** presents the monthly demands for each of the product lines for a planning horizon equivalent to one year.

Table 3 presents the production capacity by process per month, a breakdown of the production capacity per hour for each of the product lines, and estimated fabric waste due to contractions between processes in each product line.

Regarding inventories, ***Table 4*** shows the storage capacity per process per month,

Table 7. Fabric production per product line, process and month $P_{l,i,t}$ (m x 1000).

Product line, *l*	Process, *i*	Month, *m*											
		1	2	3	4	5	6	7	8	9	10	11	12
1	1	–	24.8	125.4	52.2	91.6	148.9	0.0	182.2	79.1	59.5	85.9	80.2
	2	–	44.8	125.4	52.2	91.6	148.9	0.0	182.2	79.1	59.5	85.9	80.2
	3	–	54.8	86.3	91.2	91.6	72.3	76.6	103.1	126.0	91.6	85.9	80.2
	4	22.8	59.4	77.8	94.4	88.9	70.1	74.3	100.0	122.2	88.9	83.3	77.8
	5	40.0	70.0	70.0	85.0	80.0	63.1	66.9	90.0	110.0	80.0	75.0	70.0
2	1	130.6	53.2	74.9	158.4	195.8	147.8	70.1	186.1	111.4	123.8	121.8	98.4
	2	140.6	53.2	74.9	158.4	195.8	147.8	70.1	186.1	111.4	123.8	121.8	98.4
	3	145.6	53.2	74.9	158.4	132.1	186.6	95.0	186.1	111.4	123.8	121.8	98.4
	4	155.8	51.6	72.7	153.7	128.1	181.0	92.2	180.5	108.0	120.1	118.2	95.5
	5	134.0	66.0	63.9	135.3	112.7	159.3	81.1	158.8	89.7	111.0	104.0	84.0
3	1	71.8	99.5	143.7	212.5	129.4	123.3	354.9	46.7	229.7	236.6	153.6	163.5
	2	86.2	100.0	143.7	209.4	132.5	123.3	349.9	51.7	229.6	236.8	153.6	163.5
	3	40.2	115.2	182.1	154.5	174.6	136.1	265.3	136.3	226.0	240.3	153.6	163.5
	4	61.4	112.9	178.5	151.4	171.2	133.3	258.0	135.5	221.5	235.5	150.5	160.2
	5	85.0	105.0	166.0	140.8	159.2	124.0	238.4	127.6	206.0	219.0	140.0	149.0

Table 8. Final inventory per product line, process, and month $S_{l,i,t}$ (m x 1000).

Product line, *l*	Process, *i*	Month, *m*											
		1	2	3	4	5	6	7	8	9	10	11	12
1	1	20.0	–	–	–	–	–	–	–	–	–	–	–
	2	10.0	–	39.0	–	–	76.6	–	79.1	32.2	–	–	–
	3	6.5	–	6.2	–	–	–	–	–	–	–	–	–
	4	18.4	–	–	–	–	–	–	–	–	–	–	–
	5	–	–	–	–	–	3.1	–	–	–	–	–	–
2	1	–	–	–	–	–	–	–	–	–	–	–	–
	2	–	–	–	–	63.8	24.9	–	–	–	–	–	–
	3	23.5	–	–	–	–	–	–	–	6.1	–	–	–
	4	–	–	–	–	–	–	–	–	–	–	–	–
	5	80.0	75.1	–	20.3	–	79.3	37.4	97.3	24.0	–	–	–
3	1	0.5	–	–	3.1	–	–	5.0	–	0.1	–	–	–
	2	53.6	38.4	–	54.9	12.7	–	84.6	–	3.5	–	–	–
	3	–	–	–	–	–	–	2.0	–	–	–	–	–
	4	–	–	–	–	–	–	1.7	–	–	–	–	–
	5	–	–	–	17.8	–	–	66.4	–	–	–	–	–

the cost of inventory management, and the initial level of inventories for the period to be planned.

When a new employee is integrated into a production process, they require training that takes a certain amount of time according to the characteristics and specific standards of each process. During the training time employees do not produce, only accompany processes, thus it is important to consider these factors to calculate real production. This explains, to a large extent, why the production efficiency of new employees is lower than that of those who have been working in the company for more than a month in a certain process. ***Table 5*** shows the monthly labour costs, as well as the average efficiency in the first month of the work of new employees and the training days they require.

In addition, ***Table 6*** shows the stipulated working hours per employee in a month, completing the essential information for calculation of the production capacity by process and the allocation of employees to these processes.

Results and discussion

To execute the mathematical programming model LIPROTEX, GAMS optimization software was used, which is a robust computer package with a high capacity for processing problems with a significant number of variables and constraints. To facilitate the input of the model's input data in GAMS, a link was made with MSExcel spreadsheets coded in Visual Basic Applications, and similarly an interface was created to facilitate extraction, reading and analysis of the output data of the model executed.

Consequently when executing the LIPROTEX model, a minimum cost of $ 424.074 USD is found for the aggregate planning program in the planning horizon established. It should be clarified that for this solution, approximately 95% of the total cost is due to the payment of labour, personnel training and administrative costs of hiring and firing. ***Tables 7*** and ***8*** show values of the production variables by product line and inventory levels for the optimal solution to the problem of aggregate planning.

In this way, it is observed that in product line 2 in each month the production plan suggests producing a similar amount in each manufacturing process, while in product line 3 the production level is stable for the manufacturing processes during the last four periods. For product line 1, stabilisation between processes is observed for the last two planning periods. This implies that in the first planning periods in each of the product lines, the storage and use of work in process inventories are suggested.
The results of the model suggest maintaining a low level of work in process and finished product inventory throughout the planning horizon. Processes such as warping, gumming, and weaving are characterised by a low level of inventories, which in certain product lines becomes zero. The warping check process presents high levels of inventory for product lines 1 and 3, as does the weaving check process for product line 2. In addition, it is clear that the optimal aggregate production plan does not generate final inventories of the product in the process and finished product in the last three months of the planning horizon. On the other hand, ***Table 9*** shows results of the number of employees and hiring and firing per month which allow to achieve an optimal solution to the problem of aggregate planning.

Thus the results obtained by the LIPROTEX model guarantee continuity of the workforce in production, mitigating operational inefficiencies caused by the lack of motivation, fear, and instability of the workforce. For processes 2, 3 and 5 (warping check, gumming, fabric check) at least ten periods of work continuity are guaranteed without firing employees. Similarly process 4 (weaving) guarantees 9 periods of work continuity for labour, and process 1 (warping) only generates firing during a period of 9 months. The greatest amount of firing is generated in the last two months of production, due to the decrease in production rates and increase in inventories, which are because of compliance to the demand forecast for the planning horizon.

Interpretation of the optimal solution
To meet the demand for fabric in the three product lines, the result of the linear programming model proposed shows different strategies for each product line in ***Figures 2***, ***3*** & ***Figure 4***. For production line 1, the result of the linear programming model proposes a chase strategy to match demand with production, where at the end of June, only 3.128 m is stored. It is also observed that in the first month of the time horizon, production is less than the demand due to the initial inventory,

Table 9. *Level of labour, hiring and firing by product line and month* $X_{i,t}$, $XN_{i,t}$, $XD_{i,t}$

	Process, *i*	Month, *m*											
		1	2	3	4	5	6	7	8	9	10	11	12
Employees ($X_{i.t}$)	1	8	8	17	17	18	18	17	18	17	17	16	14
	2	3	3	5	6	6	6	5	5	6	6	5	4
	3	4	6	8	9	9	9	9	10	10	10	8	7
	4	9	9	15	15	15	15	15	17	17	17	14	12
	5	4	4	5	6	6	6	6	6	7	7	6	5
Hiring ($XN_{i.t}$)	1	–	–	9	–	–	–	–	1	–	–	–	–
	2	–	–	2	1	–	–	–	–	–	–	–	–
	3	–	2	2	1	–	–	–	1	–	–	–	–
	4	–	–	6	–	–	–	–	1	–	–	–	–
	5	1	–	1	1	–	–	–	–	–	–	–	–
Firing ($XD_{i.t}$)	1	5	–	–	–	–	–	1	–	–	–	1	2
	2	–	–	–	–	–	–	–	–	–	–	–	1
	3	–	–	–	–	–	–	–	–	–	–	1	1
	4	2	–	–	–	–	–	–	–	–	–	2	2
	5	–	–	–	–	–	–	–	–	–	–	1	1

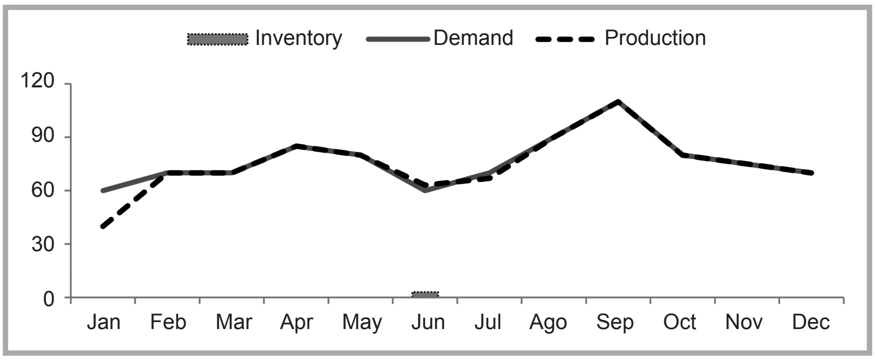

***Figure 2.** Demand, production, and inventory level for production line 1 (m x 1000).*

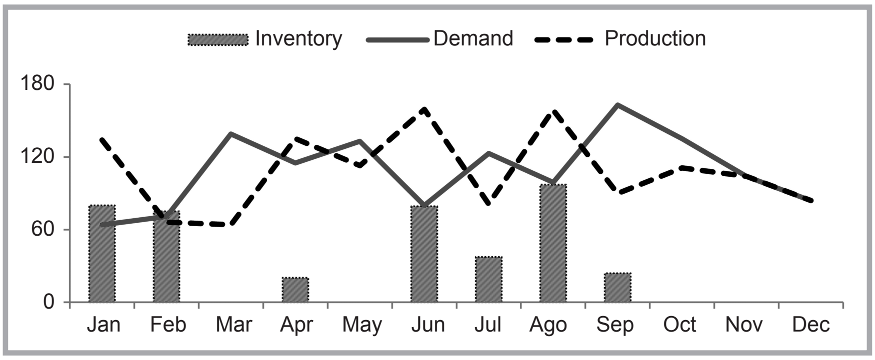

***Figure 3.** Demand, production, and inventory level for production line 2 (m x 1000).*

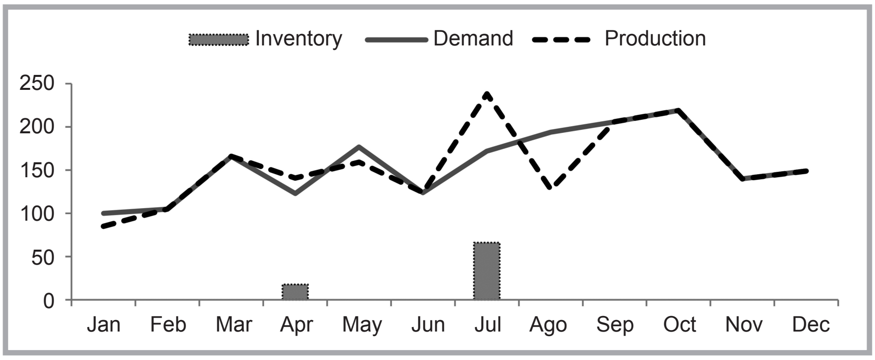

***Figure 4.** Demand, production, and inventory level for production line 3 (m x 1000).*

which counts on this line, equivalent to 20.000 m.

For line 2, finished product inventory is stored to meet demand peaks, because this product line has a greater amount of waste and lower efficiency level within all processes. The accumulation of inventories facilitates an efficient response to the needs of customers in high demand periods. Thus inventory is accumulated in January and February to face the demand increase in March. In June, July and August inventory is accumulated to meet the demand of the last months of the production plan and to reduce labour in these months, thereby significantly reducing total costs.

For product line 3, as for product line 1, a chase strategy is presented. However, the storage of finished products occurs in months prior to demand increases, which are generated by a high volume of orders. This strategy reduces the high costs of hiring, training, and firing, which would imply having variable production levels.

In summary, the plan created by the LIPROTEX model reduces work-in-process inventories and finished product inventories, in addition implying minimum hiring and firing due to the high costs related to these decisions. Therefore the production plan does not cause large differences between the accumulated demand and production, suggesting the use of low inventory levels in periods where production exceeds demand, and minimizing the use of pending orders where demand exceeds production. These decisions are reinforced based on an analysis of reduced costs (opportunity costs) for non-basic inventory variables, finding that when a meter of fabric is stored for a month, the total cost per meter increases by $ 0.15 USD. Similarly the cost of hiring an additional employee in the optimal solution may increase the total cost of the production plan by up to $654 USD. Consequently in order to obtain the lowest cost and satisfy the constraints of the model, in the last months of the planning horizon, final inventories and hiring of employees are avoided, and firings occur.

Analysis of slacks and dual prices

Analysing the results of the optimal solution of the LIPROTEX model, an analysis of slacks is performed which finds three production processes using their maximum capacity in some planning periods, allowing to identify dual prices. The most limited process in terms of production capacity is process 2 (warping check), because if the production capacity increases by 1 meter between months 4 and 10, the total cost of the production plan decreases by $ 0.29 USD. Similarly if the production capacity of process 1 (warping) increases by 1 meter in the seventh period, the total cost of the production plan decreases by $ 0.05 USD.

Sensitivity analysis

When analysing the constraints related to storage capacity and production capacity per process, it is identified that the optimal solution is very sensitive to changes in production capacity in process 2 (warping check) and process 5 (weaving check). Therefore the solution found remains the optimal if the production capacity in processes 2 and 5 belongs to intervals [420,000; 420,000] and [409,300; 412,800], respectively. This means that the warping check process is the limiting factor of the production plan and represents a bottleneck when trying to increase production. In order to improve the current solution, it is necessary to change or improve the technology, working methods, and increase production by outsourcing, among other decisions concerning the warping check process. Regarding the other manufacturing processes, they present intervals with an infinite upper limit. Thus making improvements in those processes, without improving process 2 or process 5, will not change the optimal solution. Finally regarding the storage capacity for the manufacturing processes, no interval has an upper limit, and therefore any increase in storage capacity will not change the optimal solution.

Conclusions

The development of mathematical programming models for aggregate planning of production is not only limited to providing an optimal solution for executing a production plan, but it also allows the identification of improvement strategies, such as the increase of production and storage capacity to reduce total costs. Through linear programming models such as LIPROTEX, it is possible to represent real and particular conditions of a manufacturing process in the textile industry, allowing operation managers to easily modify the parameters. Likewise it is possible to support the decision-making process through quantitative results to satisfy business objectives and comply with intrinsic constraints of the processes of the textile industry.

The LIPROTEX model contributes to the creation of models that fit business reality, because it takes into account variables that significantly affect the performance of a production plan in the textile industry, such as the efficiency of new employees, training requirements, fabric shrinkage and fabric waste in manufacturing processes.

In the company case discussed in this article, the optimal production strategy provided by the LIPROTEX model is a hybrid one, which in some production lines suggests the implementation of level and chase strategies based on inventory accumulation and hiring and firing of labour. Similarly to decrease costs and achieve production goals, the model suggests increasing the production capacity of process 2 (warping check) because this reduces inventory levels and increases the total capacity of the production process, resulting in a considerable reduction in total costs. In addition to the benefits related to the reduction of production and inventory costs obtained with implementation of the LIPROTEX model, the demand compliance is also increased, and short-term improvement plans are identified allowing the company to fulfill the strategies proposed according to internal and external variations of the company. Finally we recommend increasing the planning horizon in the execution of the LIPROTEX model to avoid the effects of labor firing at the end of a year. In the case where the labour requirements at the beginning of the next year are the same or higher than at the end of the current year, firing costs can be saved. Finally the LIPROTEX model can be adapted to handle uncertainty in some parameters using techniques such as fuzzy logic.

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