PRODUCTION PLANNING THROUGH LEAN MANUFACTURING AND MIXED INTEGER LINEAR PROGRAMMING

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ABSTRACT. Production planning is one of the most important administrative decisions a company can make, as it involves achieving the lead times set by the customers while taking advantage of the resources the organization has. Over time, different strategies using mathematical models have been implemented in production planning, aimed at finding the best solution for optimizing the available resources. In recent years companies throughout the world have successfullly implemented Lean Manufacturing, aimed at improving their production processes and eliminating everything that does not add value to the product. This article exemplifies a new strategy for production planning, using basic concepts from Lean Manufacturing and mixed integer linear programming models by stages. We took a women's footwear factory in the city of León, Guanajuato, México, as a case study. The results show that it is possible to get planning that optimizes the organization's resources and shortens the products' lead times by shrinking inventories, from a Lean Manufacturing perspective.

KEY WORDS: production planning, lean manufacturing, mixed integer linear programming, footwear factory

PLANIFICAREA PRODUCȚIEI PRIN ADOPTAREA PRODUCȚIEI DE TIP LEAN ȘI A PROGRAMĂRII LINIARE MIXTE ÎN NUMERE ÎNTREGI

REZUMAT. Planificarea producției este una dintre cele mai importante decizii administrative pe care o poate lua o companie, deoarece implică atingerea timpilor de livrare stabiliți de clienți, profitând în același timp de resursele pe care le are organizația. De-a lungul timpului, diferite strategii care utilizează modele matematice au fost implementate în planificarea producției, având ca scop găsirea celei mai bune soluții pentru optimizarea resurselor disponibile. În ultimii ani, companiile din întreaga lume au implementat cu succes producția de tip lean, având ca scop îmbunătățirea proceselor de producție și eliminarea a tot ceea ce nu adaugă valoare produsului. Acest articol exemplifică o nouă strategie pentru planificarea producției, utilizând concepte de bază din producția de tip lean și modele de programare liniară mixtă în numere întregi pe etape. S-a efectuat un studiu de caz implicând o fabrică de încălțăminte pentru femei din orașul León, Guanajuato, México. Rezultatele arată că se poate face o planificare care să optimizeze resursele organizației și să reducă termenele de livrare ale produselor prin reducerea stocurilor, din perspectiva producției de tip lean.

CUVINTE CHEIE: planificarea producției, producție de tip lean, programare liniară mixtă în numere întregi, fabrică de încălțăminte

PLANIFICATION DE LA PRODUCTION EN ADOPTANT LA PRODUCTION AU PLUS JUSTE ET LA PROGRAMMATION LINÉAIRE MIXTE EN NOMBRES ENTIERS

RÉSUMÉ. La planification de la production est l'une des décisions administratives les plus importantes qu'une entreprise puisse prendre car elle implique de respecter les délais de livraison fixés par les clients, tout en tirant parti des ressources dont dispose l'organisation. Au fil du temps, diverses stratégies utilisant des modèles mathématiques ont été mises en œuvre dans la planification de la production, dans le but de trouver la meilleure solution pour optimiser les ressources disponibles. Ces dernières années, des entreprises du monde entier ont mis en œuvre avec succès une production au plus juste, visant à améliorer les processus de production et à éliminer tout ce qui n'ajoute pas de valeur au produit. Cet article illustre une nouvelle stratégie de planification de la production, utilisant des concepts de production au plus juste et des modèles de programmation linéaire mixte en nombres entiers par étapes. Une étude de cas a été menée sur une fabrique de chaussures pour femmes à León, Guanajuato, Mexique. Les résultats montrent que la planification peut être effectuée pour optimiser les ressources de l'organisation et réduire les délais de livraison des produits en réduisant les stocks, du point de vue de la production au plus juste.

MOTS CLÉS : planification de la production, production au plus juste, programmation linéaire mixte en nombres entiers, fabrique de chaussures

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INTRODUCTION

Production planning is a problem that manufacturing companies worldwide have. Its purpose is to choose the best alternative for attending to customers' orders, while considering the resources available within the organization.

Over time, different strategies using mathematical models have been implemented in production planning, aimed at finding the best solution for optimizing the available resources. These types of problems are classified as NP-Hard [1] because of their computational complexity.

The first studies used deterministic linear programming models [2-7]. However recent authors have developed mixed integer linear programming models for solve this problem [8-11].

In another vein, some authors have opted for hybrid algorithms, that combine linear programming and simulation models in the search for the best solution [12-22].

Another approach is the use of stochastic models that consider event probabilities in planning [23-29].

Robust optimization models have also been developed that consider uncertain parameters for the problem [30-36].

Over the last few years, a significant number of companies have opted for the implementation of the Lean Manufacturing approach, to improve their production processes and generate higher profits, by eliminating or reducing everything that, without adding any value to the products, adds cost and work [37]. This has made it necessary to consider planning with a different approach, such as product families in work cells or production lines, creating flexible processes with continuous operations.

The main contribution of this study is a new strategy that permits production to be planned over three stages, with it distinguishing itself from the aforementioned papers by the combination of mixed integer linear programming models with the basic concepts of Lean Manufacturing. We considered a women's footwear factory for a case study. The document is limited to the analysis of the problems faced by footwear companies in the city of León Guanajuato, Mexico. The analysis consider restrictions on demand, time, budget, machinery, personnel and available space for inventory.

The implementation of Lean Manufacturing in footwear manufacturing companies has been documented in different studies reported in the literature [38-43]. However unlike these, in this article we detail the production planning.

The rest of this document is organized as follows: First we describe the case study. Then we give a step-by-step breakdown of the proposed strategy in the search for a solution and the mathematical models developed in each stage appear. Next we show the experimentation as well as the results achieved in the fulfillment of objectives. Lastly, we give the conclusions of our research.

CASE STUDY

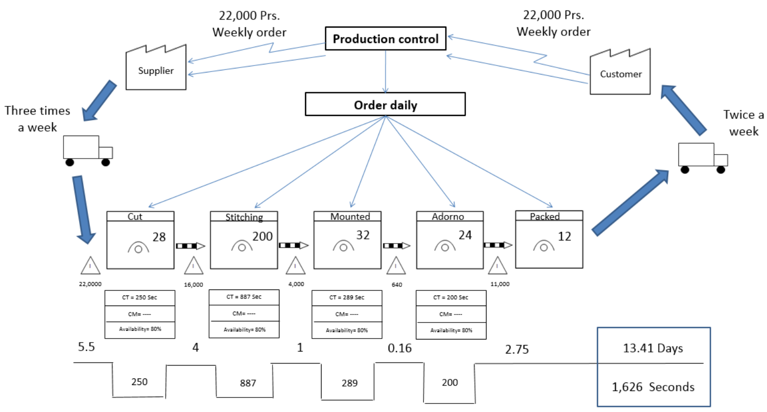
The leather Industry is the main economic motor of the city of León, Guanajuato, México. The quality of the products largely depends on the qualified personnel that organizations have in the production area. The constant changes of product with each new season (Spring-Summer and Fall-Winter) together with customer demand require frequent adjustments to the operations personnel, which in turn makes it hard to plan production in these companies.

The most complex process in footwear manufacturing is in the stitching (or seam) department because of the variation to be found in the assembly of the products and the different jobs involved. This department is considered to be the bottleneck of the manufacturing process. Large batches are commonly handled and the operations of the different work stations are isolated, without following a continuous flow. A lot of the companies use outside manufacturers, known as maquiladoras, in order to be able to produce the customers' orders on time.

We took as a case study a women's footwear factory that is just starting to implement Lean Manufacturing concepts. It normally works an eight-hour day from Monday to Friday with half-days on Saturday, producing an average of 22,000 pairs of shoes a week for customers in México and abroad.

Figure 1 details the initial value stream mapping drawn up before starting the planning strategy. As can be observed the stitching department in production has the biggest inventory, increasing the lead time of the products.

Production planning in this company, as in the majority of the footwear factories in the region, focuses on what the stitching department can do. A large part of the inventory generated therein corresponds to the poor planning of workloads on the part of the management, who do the planning empirically from week-to-week, investing a lot of time and effort without getting any efficient results.



Weekly demand	22,000
Working days	5.5
Daily demand	4,000
Working hours	8
Tack time (seconds)	7.2

Time adding value in seconds	1,626
Time adding value in days	0.056458
Time that doesn't add value in days	13.410
Lead Time in days	**13.466**
% Time adding value	**0.419%**
% Time that doesn't add value	**99.581%**

Figure 1. Value stream mapping of the company

STAGED STRATEGY FOR PRODUCTION PLANNING

The production planning proposed in this study is done in stages. It starts by defining the workers that need to be hired every month to meet the customers' demand, considering the company's resources. Then we proceed to assign the products to be manufactured on the production lines, taking into account their export quality and construction family. Lastly, the day and quantity in which each of them will be manufactured is established in accordance with the personnel's historical performance in the company (see Figure 2).

Mixed integer linear programming mathematical models are established in every stage and solved sequentially. The described strategy was applied to the stitching department of the case study.

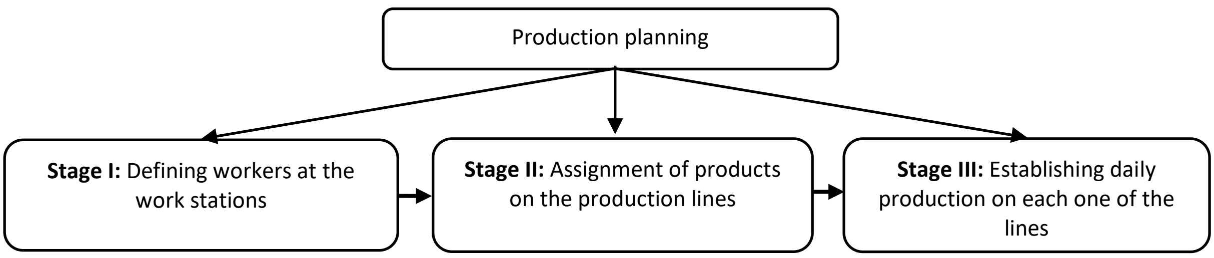


Figure 2. Three-stage production planning

Notation Employed in the Development of the Mathematical Models

Sets

I Work stations $I=\{work\ station_1, work\ station_2, \ldots, work\ station_{|I|}\}$.

J Products $j=\{Product_1, Product_2, \ldots, Product_{|J|}\}$.

K Production lines $k=\{Line_1, Line_2, \ldots, Line_{|k|}\}$.

D Days D={Monday, Tuesday, Wednesday, Thursday, Friday, Saturday}.

Indexes

i Work station $i \in I$.

j Product $j \in J$.

k Production line $k \in K$.

d Day $d \in D$.

Subsets

$I_1 \subset I$ *Work stations with sewing machines*

$I_1=\{work\ station1, work\ station_2, \ldots, work\ station_{|c|}\}$.

$I_2 \subset I$ *Work stations without sewing machines*

$I_2=\{work\ station_{c+1}, \ldots, work\ station_{|I|}\}$.

$I= I_1 \cup I_2$

Integer variables

x_i = *Number of workers to hire per work station i.*

y_{jk}= *Number of pairs of product j to be manufactured on the production line k.*

z_{jd}= *Number of pairs of product j to be manufactured on day d.*

Binary variables

W_{jk}= Auxiliary binary variable to establish product j to be manufactured on production line *k*.

W_{jd}= Auxiliary binary variable to establish product j to be manufactured on day d.

Coefficients of the objective function

α_i = Rating work station i.

β_{jk}= Compatibility of product j with the production line k.

δ_j= Product quality j.

λ_d= Performance rating for the workers on each day d of the week.

Parameters

Available machinery$_i$ = Machinery available for each work station *i*.

a_i= Weekly base salary at each work station i.

Workers required by work station$_i$= Workers needed in each work station *i* to manufacture the products demanded by customers.

Minimum of Workers per work station$_i$= Minimum number of workers to be hired at each work station *i*.

Budget = Economic resource available for the payment of weekly wages.

Demand$_j$= Number of pairs to produce of product j required by customers.

Manufacturing time$_{ij}$= Standard operating times of work station i by product *j*.

Weekly minutes of the work *station*$_i$= Minutes available to manufacture products per work station *i* in the company weekly.

$$Weekly\ minutes\ of\ the\ work\ station_i = Number\ of\ workers_i * Working\ day\ minutes * Manufacturing\ days * OEE \quad (1)$$

Daily minutes of the work station$_i$ = Minutes available to manufacture products per work station *i* in the company daily.

$$Daily\ minutes\ of\ the\ work\ station_i = Number\ of\ workers_i * Working\ day\ minutes * OEE \quad (2)$$

Space sewing machines$_{ik}$= Space available for the installation of sewing machines per work station *i* in each production line *k*.

Space machines$_{ik}$= Space available for the installation of machinery or equipment per work station *i* in each production line *k*.

Weekly schedule$_j$ = Weekly programming of products to be manufactured *j*.

STAGE I: DEFINING WORKERS AT THE WORK STATIONS

In this first stage we define the workers that need to be hired every month (or four weeks) to meet customer demand.

The process starts by estimating the workers needed at each work station every week. For this we use equation (3), that considers the total minutes needed for the manufacture of the different products, as well as the OEE (Overall Equipment Effectiveness) indicator for the total effectiveness of the equipment, used in Lean Manufacturing [37].

$$\forall\, i \in I \quad Estimated\ workers\ per\ week\ at\ each\ work\ station_i = \frac{\sum_{j=1}^{J} Demand_j * Manufacturing\ time_{ij}}{Manufacturing\ days * Working\ day\ minutes\ * OEE} \quad (3)$$

Each week, every station has different personnel requirements, so we propose to find the weighted average of these results through equation (4), seeking a balance during the month. The biggest values shall have the highest weighting.

$$\forall\, i \in I\ Weighted\ average_i = (workers\ 1 * 0.4) + (workers\ 2 * 0.4) + (workers\ \ 3 * 0.1) + (workers\ \ 4 * 0.1) \quad (4)$$

The decision-maker determines the number workers required by each work station by rounding up or down the value obtained in equation (4). The decision-maker is also responsible for rating work stations α_i in the order of their importance in the manufacture of the products using a range of values going from five as the most important to three as the least critical for the process. Once defined, they are substituted in the mathematical model of the first stage. Said model prioritizes hiring workers for work stations that are critical for the manufacture of the products.

Mathematical Model 1- Production Workers

$$Maximize\ \ F = \sum_{i=1}^{I} \alpha_i\, x_i \quad (5)$$

Subject to: (6)

$$x_i\ \leq\ Available\ machinery_i \quad \forall\, i \in I \quad (7)$$

$$x_i\ \leq\ Workers\ required\ by\ work\ station_i \quad \forall\, i \in I$$

$$x_i\ \geq\ Minimum\ of\ workers\ per\ work\ station_i \quad \forall\, i \in I \quad (8)$$

$$\sum_{i=1}^{I} a_i\, x_i \leq Budget \quad (9)$$

$$x_i \in \mathbb{R}^+ \quad (10)$$

Objective function (5) seeks to maximize the hiring of personnel at work stations that are critical for the manufacture of the products.

The constraints, for their part, are:

(6) The personnel hired should not exceed the available machinery.

(7) No more personnel should be hired than are required to meet customer demand.

(8) The minimum number of personnel per work station, as established by the decision-maker, should be hired.

(9) The weekly wages budget should not be exceeded.

STAGE II: ASSIGNMENT OF PRODUCTS ON THE PRODUCTION LINES

Before starting this stage, the production lines that will work in a continuous flow per product family will have to have been designed, in accordance with the operations and work stations involved.

This stage is divided into two parts. First the products to be manufactured every week on each production line are established, considering their export quality and construction family with the use of a mathematical model. Then the operations personnel are distributed on each line.

The aim of the mathematical model is to assign the products that are more compatible with the production line according to their construction family (see Figure 3), with the aim of reducing the variability of the process (Mura), considered to be one of the limitations of Lean Manufacturing production [37]. This also prioritizes the manufacture of export quality products in the company and considers the maquila of products for domestic consumption when so required.

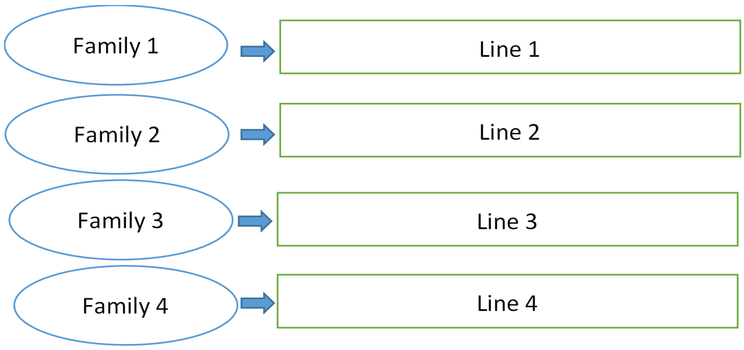


Figure 3. Construction family-production line

Coefficients β_{jk} weight the degree of compatibility of each product *j* with production line *k*, in accordance with their construction family, considering the value of five as high, the value of four as medium, the value of three as low and minus one for when it is not compatible. Values δ_j define the quality of the product, considering the value of two for export and one for national customers. Coefficients β_{jk} and the values of δ_j are established by the decision-maker. The mathematical model used in this stage is detailed below:

Mathematical Model 2- Product - Production Line

$$Maximize\ F = \sum_{j=1}^{J}\sum_{k=1}^{K} \beta_{jk}\ y_{jk}\ w_{jk} + \sum_{j=1}^{J}\sum_{k=1}^{K} \delta_j\ y_{jk}\ w_{jk} - \sum_{j=1}^{J}\sum_{k=1}^{K} 3\ w_{jk} \quad (11)$$

Subject to:

$$\sum_{k=1}^{K} y_{jk} \leq Demand_j \quad \forall\ j \in J \quad (12)$$

$$\sum_{j=1}^{J}\sum_{K=1}^{K} Manufacturing\ time_{ij}\ y_{jk} \leq Weekly\ minutes\ of\ the\ work\ station_i \quad \forall\ i \in I \quad (13)$$

$$\frac{\sum_{j=1}^{J} Manufacturing\ time_{ij} * y_{jk}}{Manufacturing\ days * Working\ day\ minutes\ * OEE} \leq Space\ sewing\ machines_{ik} \quad \forall\ i \in I_1, \forall\ k \in K \quad (14)$$

$$\frac{\sum_{j=1}^{J} Manufacturing\ time_{ij} * y_{jk}}{Manufacturing\ days * Working\ day\ minutes\ * OEE} \leq Space\ machines_{ik} \quad \forall\ i \in I_2, \forall\ k \in K \quad (15)$$

$$y_{jk} \in \mathbb{R}^+ \quad (16)$$

$$w_{jk} \in \{0,1\} \quad (17)$$

Objective function (11) seeks to maximize the compatibility of each product with the production line as well as prioritizing the manufacture of export quality products within the company. It also penalizes the scheduling of different products on each line.

The constraints, for their part, are:

- (12) No more products should be produced than those needed to meet customer demand.
- (13) No more products are scheduled than the company can produce with the personnel hired in the jobs (defined in stage I).
- (14) Avoid scheduling more products per line than the space available for sewing machines required at the work stations.
- (15) Avoid scheduling more products per line than the space available for other equipment or machines required at the work stations.

Distribution of the Workers on Each Line

Once it has been established which products are to be manufactured every week, the number of workers to work on each one of the lines is determined with the help of equation (18):

$$\forall\, i \in I, \forall\, k \in K \quad Workers_{ik} = \frac{\sum_{j=1}^{J} Manufacturing\ time_{ij} * y_{jk}}{Manufacturing\ days * Working\ day\ minutes * OEE} \qquad (18)$$

Lastly, the decision-maker makes adjustment to the personnel according to their criterion and experience.

STAGE III: ESTABLISHING DAILY PRODUCTION ON EACH ONE OF THE LINES

During this last stage, we establish the order and quantity of products to be manufactured on each day of the week, per production line.

The aim of the mathematical model is to distribute workloads to days of the week, in accordance with the historical performance of the workers in the company. This avoids the existence of an overburden of work (*Muri*) at each work station that, in Lean Manufacturing, is considered to be another one of the limitations on productivity [37]. It also seeks to lower the number of different products to be manufactured per day, simplifying variability (*Mura*) in the process.

Coefficients λ_d of the model establish a performance rating for the workers on each day of the week. For the case study, the value of six is assigned to Tuesdays and Wednesdays as the most productive days, five to Mondays and Thursdays, four to Fridays and three to Saturdays as the least productive. Coefficients λ_d, help to assign the heaviest workloads to the most productive days of the week, leaving the remaining days for closing the production schedule. The mathematical model employed in this stage is given below:

Mathematical Model 3- Daily Production on the Line

$$Maximize\ F = \sum_{j=1}^{J}\sum_{d=1}^{D} \lambda_d\, z_{jd}\, w_{jd} - \sum_{j=1}^{J}\sum_{d=1}^{D} 3\, w_{jd} \qquad (19)$$

Subject to:

$$\sum_{d=1}^{D} z_{jd} \le Weekly\ schedule_j \quad \forall\, j \in J \qquad (20)$$

$$\sum_{j=1}^{J} Manufacturing\ time_{ij}\ z_{jd} \le Daily\ minutes\ of\ the\ work\ station_i \quad \forall\, i \in I,\ \forall\, d \in D \qquad (21)$$

$$z_{jd} \in \mathbb{R}^+ \qquad (22)$$

$$w_{jd} \in \{0,1\} \qquad (23)$$

The objective function (19) seeks to maximizes the workload on the production line on each day of the week as per the historical performance, while also penalizing the scheduling of different products per day.

The constraints, for their part, are:

- (20) The weekly schedule on the production line, generated in stage II, should not be exceeded.
- (21) No more products should be scheduled then the production line can produce with the workers available at the work stations.

EXPERIMENTATION

For the experiment, we considered for the case study the planning for four weeks of the spring-summer season, which is characterized by the production of two types of footwear; flats and sandals. The factory has planned to produce 42 different products during this season.

Four production lines were created in the stitching department. Each one of these was designed based on a construction family for the different products to be manufactured in the season. Table 1 shows the lines and construction families, as well as the products according to each family.

Table 1: Product families by production line

Line-Family	Line 1 Flats	Line 2 Sandal 1	Line 3 Sandal 2	Line 4 Sandal 3
Products	P-01	S1-01	S2-01	S3-01
	P-02	S1-02	S2-02	S3-02
	V-01	S1-03	S2-03	S3-03
	V-02	S1-04	S2-04	S3-04
	V-03	S1-05	S2-05	S3-05
	V-04	S1-06	S2-06	S3-06
	V-05	S1-07	S2-07	S3-07
	V-06	S1-08	S2-08	S3-08
	V-07	S1-09	S2-09	
	V-08	S1-10	S2-10	
		S1-11	S2-11	
		S1-12		
		S1-13		

Customer demand (in pairs of shoes) is broken down in Table 2, where the level of quality required in the products can be appreciated; the value of two for export and one for the domestic market. 21 Different products are demanded during this month.

Table 2: Demand of the month

Nº	Product	Quality	Week 1	Quality	Week 2	Quality	Week 3	Quality	Week 4
1	P-01	1	1,500	2	2,500	1	1,250	1	3,200
2	P-02	1	500					1	1,000
3	S1-01	1	1,500	1	1,000			1	1,200
4	S1-02	2	3,000			1	1,500	1	3,000
5	S1-03	1	2,000	1	3,600				
6	S1-08	1	1,000			1	2,500		
7	S2-01	2	2,000	1	1,000			1	1,000
8	S2-04	1	1,200	1	1,000	1	2,800	2	1,200
9	S2-05	2	1,000	1	1,500	1	3,000	1	1,200
10	S2-06							1	4,000
11	S2-07	1	1,800	1	1,100	2	1,600		
12	S3-01	1	2,000	1	1,200	1	1,000	2	1,000
13	S3-02	1	550			1	2,500	1	800
14	S3-03			2	1,000	1	2,500	1	1,800
15	S3-04	1	1,000	1	2,000	1	1,280	1	250
16	S3-07			1	1,000				
17	S3-08							1	1,000
18	V-01	1	2,000	1	2,000	2	1,000	2	1,000
19	V-05			2	500	1	500		
20	V-06					1	500	1	1,000
21	V-08			1	1,650	2	1,500		
Total pairs			21,050		21,050		23,430		22,650

The company has a weekly payroll of \$350,000 pesos. Salaries and the machinery or equipment limitations are given in Table 3. A total effectiveness of the equipment or OEE of 60% for production planning was also considered.

The standard operating times in minutes per pair for each work station in the manufacture of the different products are given in Table 4.

Table 3: Weekly salaries and machinery available per workstation

Work station	Weekly salary per worker	Machinery or equipment available
1	\$2,200	74
2	\$2,200	6
3	\$1,400	90
4	\$1,500	2
5	\$1,400	16
6	\$1,700	16
7	\$1,500	6
8	\$1,400	2
9	\$1,700	3

Table 4: Standard operating times in minutes per pair of products

Nº	Product	Work station								
		1	2	3	4	5	6	7	8	9
1	P-01	1.80		3.15	0.43	0.42	0.50			
2	P-02	4.27	1.71	5.04	0.90	1.54			0.23	1.49
3	S1-01	5.07		7.42		1.33	1.00	0.52		
4	S1-02	4.58		3.73		1.75	1.38	0.25		
5	S1-03	6.33		8.73		2.00	1.42	1.60		
6	S1-08	3.83		1.88		1.07	1.00			
7	S2-01	4.08		4.73		0.67	0.67	0.27		
8	S2-04	4.25		4.53		0.92	1.08	0.25		
9	S2-05	3.30		4.35		0.42	0.92	0.25		
10	S2-06	3.38		2.90		0.42	0.92	0.25		
11	S2-07	4.33		3.83		0.83	0.75	0.25		
12	S3-01	8.62		23.05		4.63	0.97		0.23	
13	S3-02	4.62		4.77		0.67	1.52	0.33		
14	S3-03	9.28		11.48		1.92	2.17	1.40		
15	S3-04	13.43		8.38		1.50	4.08	1.58	0.23	
16	S3-07	7.63		9.22		2.58	2.33	1.75		
17	S3-08	3.85		3.95		1.47	1.55	0.27		
18	V-01	2.88		2.11					0.26	0.63
19	V-05	5.18	1.03	3.63		0.70	0.73	0.28	0.23	
20	V-06	6.15	2.82	3.33		0.75	0.93	0.28	0.23	
21	V-08	6.27	2.17	3.38		0.75	1.02	0.28	0.23	

We used a computer with an Intel Celeron processor of 2.16-GHz N2840 CPU and 4 GB of RAM, together with the Windows 10 Home operating system for the generation going to the solutions in each stage. The data matrices were programmed in Excel, which was linked to LINGO 17 software where we captured the mathematical models and solved them using the exact branch and bound technique. The runtime is reasonable and was not a variable to be considered in our case.

RESULTS AND DISCUSSIONS

Table 5 shows the estimated workers per work station required to satisfy the weekly demand, as well as the result obtained in stage I. It must be pointed out that personnel requirements often change, with it being unsuitable for the company to be constantly hiring and firing workers. The strategy being proposed in this study tries to generate a balanced solution for the operations personnel to be employed each month, considering the company's limitations. With the solution we obtained, we get a weekly payroll worth $349,500 pesos, within the budget limit.

Table 5: Estimated operators vs Workers to hire (Stage I)

Work station	Estimated workers per week				Stage I workers to hire
	1	2	3	4	
1	66.93	77.80	79.52	64.27	71
2	0.54	2.58	3.27	2.86	3
3	86.11	90.59	82.83	76.54	87
4	0.69	0.68	0.34	1.44	1
5	18.43	17.26	16.30	15.70	16
6	13.88	17.15	18.90	14.69	16
7	5.07	9.07	5.87	4.40	6
8	0.85	1.12	0.87	0.64	1
9	1.26	0.79	0.39	1.34	2
Total	193.76	217.05	208.29	181.87	203

The results of stage II are given in Table 6 and Figure 4.

Table 6 illustrates the assignment of products to be manufactured on each production line. Because of the conditions of the problem, it is impossible to plan the manufacture of all the products of the stitching department within the company, so some of them are outsourced to maquiladoras.

Most of the products to be manufactured were highly compatible with the production line, as per their construction family (see Figure 4), thus fulfilling one of the most important objectives of stage II.

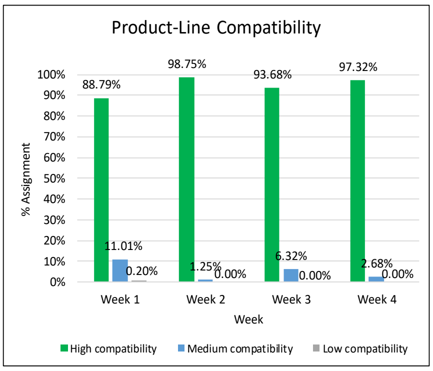


Figure 4. Product-Line Compatibility

The results of stage III in the daily production planning on each line are summarized in the graphs of Figure 5-9.

More pairs were scheduled for the most productive days (Mondays to Thursdays) of each week, as can be appreciated in the graphs of Figure 5-8, leaving Fridays and Saturdays for closing the production schedules.

The average number of different products to be produced on each line every day during the month is given in Figure 9. With the strategy implemented, there are few product changes and small production batches of 12 pairs were handled.

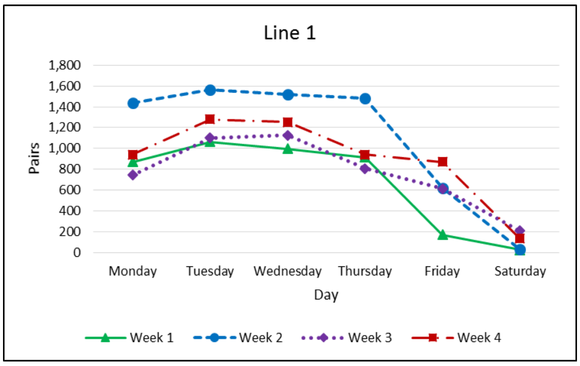


Figure 5. Pairs - Day line 1

Table 6: Stage II Results: Product-Production Line

Nº	Product	Week 1				Week 2				Week 3				Week 4			
		Line 1	Line 2	Line 3	Line 4	Line 1	Line 2	Line 3	Line 4	Line 1	Line 2	Line 3	Line 4	Line 1	Line 2	Line 3	Line 4
1	P-01	1,500				2,500				1,250				3,200			
2	P-02	500												219			
3	S1-01		1,500				1,000								1,200		
4	S1-02		2,773	227							1,500				3,000		
5	S1-03			1,586	413		2,646										
6	S1-08		1,000								2,500						
7	S2-01			2,000				1,000								1,000	
8	S2-04			1,200				1,000				2,800				1,200	
9	S2-05			1,000				1,500				3,000				1,200	
10	S2-06															4,000	
11	S2-07			1,800				1,100				1,600					
12	S3-01	41			1,128			227	973		138	174	688		220	311	469
13	S3-02				550								2,500				800
14	S3-03								1,000		902		1,598				1,800
15	S3-04				1,000				996			188			33	21	196
16	S3-07																
17	S3-08																1,000
18	V-01	2,000				2,000				1,000				1,000			
19	V-05					500				500							
20	V-06									349				1,000			
21	V-08					1,650				1,500							
	Total pairs per line	4,041	5,273	7,813	3,091	6,650	3,646	4,827	2,969	4,599	5,040	7,762	4,786	5,419	4,453	7,732	4,265
	Total pairs per week	20,218				18,092				22,187				21,869			
	Unscheduled pairs (destined for maquila)	832				2,958				1,243				781			

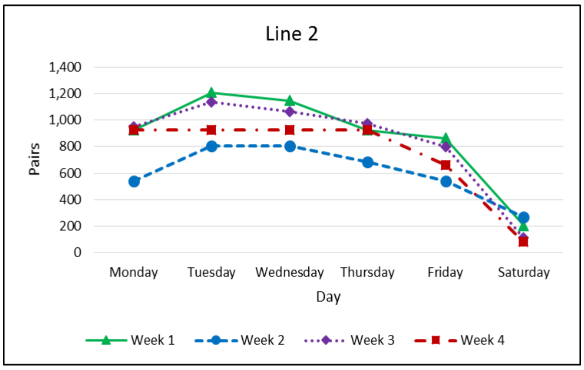


Figure 6. Pairs - Day line 2

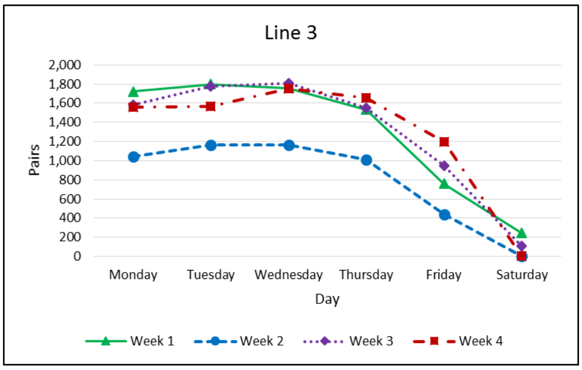


Figure 7. Pairs - Day line 3

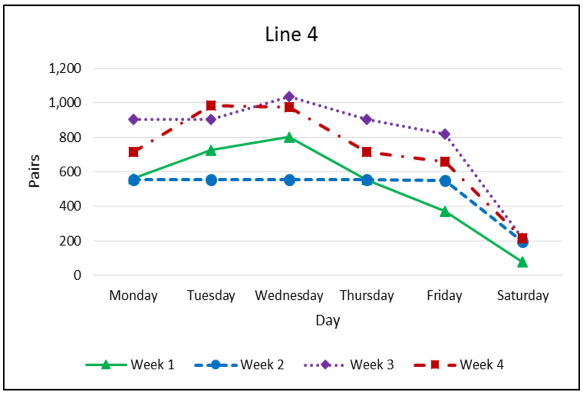


Figure 8. Pairs - Day line 4

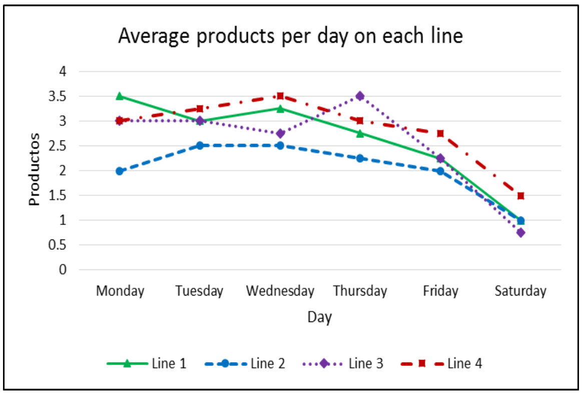
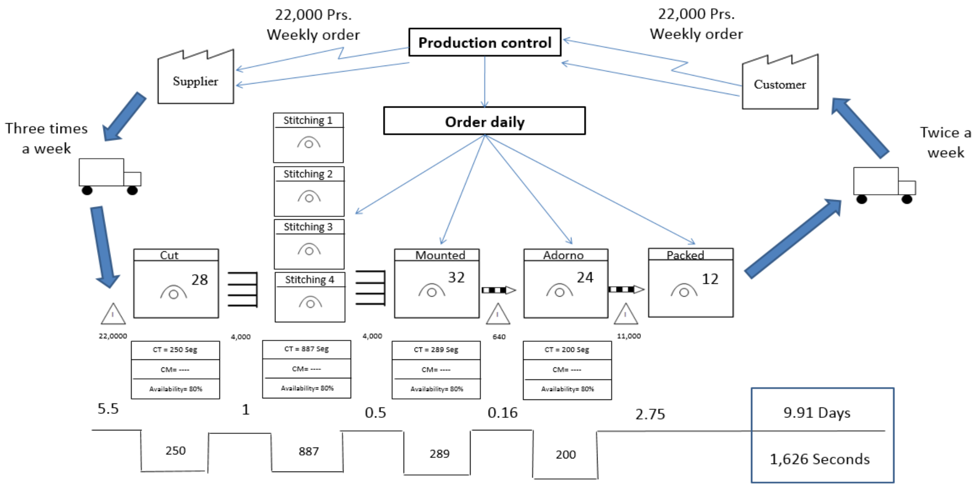


Figure 9. Average products per day on each line

Figure 10 shows the value map generated when the strategy described in this study is applied, considering four production lines in the stitching department.

The most important results include reductions in: 1) the size of the batch in production, 2) the number of defective pairs, 3) inventory in the stitching department, 4) the lead time and 5) the time that does not add value to the products (see Table 7), thus fighting waste (*Muda*), which is the last limitation on productivity considered in Lean Manufacturing [37].



Weekly demand	22,000
Working days	5.5
Daily demand	4,000
Working hours	8
Tack time (seconds)	7.2

Time adding value in seconds	1,626
Time adding value in days	0.056458
Time that doesn't add value in days	9.910
Lead Time in days	**9.966**
% Time adding value	**0.566%**
% Time that doesn't add value	**99.434%**

Figure 10. Value stream mapping of the company after the staged strategy

Table 7: Benefits generated by the staged strategy in production planning

Concept	Before the staged strategy	After the staged strategy	% Reduction
Size of the batch (Pairs)	60	12	80%
Number of defective pairs in the stitching daily	300	150	50%
inventory in the stitching department (days)	4	1	75.00%
Lead time (days)	13.466	9.966	25.99%
Time that does not add value (days)	13.41	9.91	26.10%

CONCLUSIONS

The fundamental contribution of this study is a new strategy for production planning, using basic concepts of Lean Manufacturing and mixed integer linear programming by stages.

This strategy primarily considered the definition of the workers per work station, followed by the assignment of products on production lines and lastly, the establishment of the daily workloads on each line.

We used a footwear factory in the city of León Guanajuato, México as a case of application to exemplify the process involved with the analysis, mathematical modeling and solution. This administrative problem is normally solved by trial and error, which takes up a great deal of the administrative personnel's time. However, the proposal developed in this study now makes it possible to standardize this process and facilitate the work involved in planning.

This study deals with a problem faced by most of the region's footwear companies. This demonstrated that it is possible to generate solutions where the company's resources are optimized, by decreasing the work-in-process inventory, defective products, the time that does not add value and, mainly, the lead time required to deliver the products to the customer by up to 25.99%, by dealing with the limitations on productivity (*Muri, Mura and Muda*) considered in Lean Manufacturing.

The proposal described in this article can be adopted by other companies that are starting to apply Lean Manufacturing, particularly if they form part of the footwear manufacturing industry. For future research it would by interesting to study the impact of this strategy on the analysis of other manufacturing industries. Stochastic programming or fuzzy programming could also be used with uncertain parameters of the problem.

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