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Mathematical Models for the Formation and Evaluation of Manufacturing Cells in A Textile Company. A Case Study

Israel Naranjo, María Porras, Daysi Ortiz, Franklin Tigre, Carlos Sánchez, Edith Tubón, Sandra Carrillo, Christian Mariño, Jéssica López, Freddy Lema, César Rosero

Universidad Técnica de Ambato (Ecuador)

ie.naranjo@uta.edu.ec, mporras6560@uta.edu.ec, dm.ortiz@uta.edu.ec, fg.tigre@uta.edu.ec, carloshsanchez@uta.edu.ec, ee.tubon@uta.edu.ec, sandralcarrillor@uta.edu.ec, christianjmarino@uta.edu.ec, jp.lopez@uta.edu.ec, fr.lema@uta.edu.ec, cesararosero@uta.edu.ec

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Abstract:

Purpose: Mathematical models of Mixed Integer Linear Programming oriented to cellular manufacturing and aggregate production planning to form the appropriate product family in each cell and minimize production and material handling costs through the appropriate allocation of productive resources.

Design/methodology/approach: This article develops two mathematical models in LINGO 18.0 software, performing the computational calculation to obtain the best efficiency in cell formation at minimum production cost.

Findings: The mathematical model oriented to the formation of manufacturing cells allows a grouping of products and machines with 82.5% group efficiency. By reallocating machines to each cell and redistributing facilities, the cost of material handling is reduced by 35.1%, and the distance traveled in product manufacturing is reduced by 26.6%. The mathematical model of aggregated planning provides information on production resource requirements such as personnel, machinery, distances traveled, as well as the cost generated by the need to outsource part of the production, inventory maintenance and overtime work.

Research limitations/implications: It is necessary to clearly define the capacity variables. The model does not take into account the cost of mobilizing machines and readjusting facilities.

Practical implications: The case study company can adequately plan production and efficiently manage its resources.

Social implications: The study can be applied to other textile SMEs.

Originality/value: The aggregate production planning model requires the assignment of the mathematical model of manufacturing cell formation in order to calculate the resource requirements needed to meet a demand.

Keywords: mixed integer linear programming, cellular manufacturing, product families, aggregate planning, plant layout

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1. Introduction

In a globalized environment, it is necessary for companies to adopt strategies that allow them to be competitive and remain in force in the market, thus producing what the market demands, aligning processes and resources to the company's strategy (Monge, 2010).

At present, SMEs in the textile industry are characterized by large production volumes and weak competitiveness, since vertical integration strategies are scarce. The textile industry presents structural and technological equipment problems, generating the need to improve productivity, production processes, and quality (Zorrilla-Navarrete, 2015).

Textile production in small companies presents problems such as deficiency in production and operation, scarce or outdated technological use, high production costs, inefficient computer systems, inadequate time management, among others. To address the aforementioned problems, lean manufacturing tools provide options such as cellular manufacturing based on a production system where workstations are organized allowing a regular flow of materials and components, and the minimization of transports and delays (Niño-Gaona & Baeza-Serrato, 2017).

Cellular Manufacturing (CM) systems are alternatives that benefit the flexibility of workshops and production lines through a series of machine cells where each cell is capable of processing similar families of parts. In this sense, Cellular Manufacturing (CM) addresses shorter product life cycles, time to market, changing demand, as well as product mixes in terms of average volume and variety of models (Shiyas & Pillai, 2014).

Singh (1993) analyzed the aspects of cell formation in cellular manufacturing design, identifying the utility and limitations, by classifying cell formation approaches into: classification and coding systems for families of pie-zas, cluster analysis of machine component groups, similarity coefficient-based clustering methods, mathematical and heuristic methods, knowledge and pattern recognition-based methods, fuzzy focus clustering, neural network-based approaches, and heuristics.

The design of a CM must solve two problems, (1) constructing product families, taking into account physical characteristics such as similar sizes, shapes, weights or process requirements, (2) forming machine families (cells) for the creation of machine groups for the manufacture of conforming product families, breaking down a complex manufacturing system into smaller subsystems, which must serve the operations of entire product families (Wang & Roze, 1997). Studies such as that of (Ayough & Khorshidvand, 2019) can be used to plan labor allocation in manufacturing cells with the goal of reducing total cost in many industries, considering the uncertain demands of the real world.

In the review of papers, the analysis of cellular manufacturing independently of production planning is observed. Das and Abdul-Kader (2011) presented a mathematical model to counter dynamic changes in part demand and ensure machine reliability in a manufacturing cell design. The model considered alternative processing routes for part types and evaluated machine reliability along those routes to maximize the overall system output. Another approach studied is the pursuit of downtime cost reduction using simulation models to maximize the availability of machines in a system (Madu & Kuei, 1992). In a study by Djassemi and Seifoddini (2019), the effect of critical improvement of machine reliability on production capacity and production time in manufacturing cells was analyzed. Machine criticality policies were established and the labor resource, particularly maintenance technicians were coded in the model, reflecting real manufacturing operating environments and allowing to focus on maintaining resources on the most critical machines.

Other studies expose the formation of groups of machines by calculating a coefficient of similarity between pairs of machines, as well as the construction of an algorithm to find the various manufacturing cells that can be formed by analyzing the product-machine matrix and how to find the best design, based on the calculation of the cost for intracellular and intercellular movements (Córdova, 2007). On the other hand, a process was generated through studied methodologies as a general guide to obtain a physical model of a manufacturing cell leading to the implementation of various scenarios for a case study applied in the production of luminaire chassis (García, 2016). Other authors present a methodology for the distribution of plants in flexible manufacturing systems, based on quantitative methods for grouping families, formation of manufacturing cells and the use of multi-criteria techniques, such application was executed through a real case in a Colombian company of the metal-mechanical sector (Contreras, 2011).

2. Problem Statement

The study analyzes a model for the redistribution of facilities under a productive and biosafety approach for a textile manufacturing SME in the province of Tungurahua, where an analysis of the company's productive processes is carried out, in addition to determining the biosafety parameters, costs and production times, through the development of a mathematical model for the redistribution of facilities. The analysis is not only focused on the formation of manufacturing cells but also on production planning considering the changes to be made. The use of mathematical models that work together for the formation of manufacturing cells and the determination of the productive resources such as labor, machinery, time and money needed to meet the demand, is the scenario that is intended to be addressed in this research.

Plant layout planning is a powerful tool for companies to improve a process in terms of productivity and efficiency. Several studies and proposals have generated beneficial results and have also highlighted situations to be considered for future studies (Lascano-Martínez, 2019).

The case study dedicates its textile activity to the manufacture of slippers, being a company that has grown in recent years; however, it was developed without a strategic vision. Currently the company has a type of plant distribution by processes, which has resulted from the adaptation as demand and production increased, i.e., a distribution without proper planning, which leads to deficiencies in the use of space, long distances between workstations, among other problems.4.

This document is an analysis of a model for the redistribution of facilities under a productive and biosafety approach for a textile manufacturing SME in the province of Tungurahua, where an analysis of the company's productive processes is carried out, in addition to determining the biosafety parameters, costs and production times to be considered in the project.

3. Methodology

The proposed case study handles a distribution by processes; therefore, an analysis was performed using the method of weighted factors to determine the appropriate type of distribution, considering an alternative that ensures social distancing (as a preventive measure against Covid-19), in addition to responding to the characteristics of production, generation of improvement value and feasibility of implementation, resulting in a distribution by manufacturing cells.

3.1. Mathematical Model 1

Mathematical Model 1 corresponds to a Mixed Integer Linear Programming problem and its objective is to find the appropriate product family for each manufacturing cell considering information regarding machines and products of the case study. The model shown below has been analyzed and proposed based on the research conducted by Delgado-Carpintero (2017) changing the objective function approach to an alternative one for the evaluation of the goodness of heuristic solutions, thus finding the effectiveness of the achieved clustering, a method proposed by Suresh-Kumar and Chandrasekharan (1990).

Indexes

C Number of cells to evaluate.
P Number of products.
M Number of machines.
c Manufacturing cell index ($c = 1, 2, \dots, C$).
p Product index ($p = 1, 2, \dots, P$).
m Machine index ($m = 1, 2, \dots, M$).

Parameters

Ma_m Number of machines type m.
Am_p Product p processed by machine m.

Decision Variables

H_{mcp} 1, if the *p-th* product does not require machine *m* inside cell *c*, otherwise 0.
E_{mcp} 1, if the *p-th* product requires machine *m* out of cell *c*, otherwise 0.
X_{mc} Variable for the assignment of machine *m* in cell *c*.
Y_{pc} Variable for product assignment *p* in the cell *c*.

$$Max = \frac{1-(exceptional/operations)}{1+(empty\ elements/operations)} * 100 \tag{1}$$

Subject to:

$$\sum_{c}^{C} X_{mc} <= Ma_m,\ \forall m; \tag{2}$$

$$\sum_{c}^{C} Y_{pc} = 1,\ \forall p; \tag{3}$$

$$\sum_{m}^{M} X_{mc} \leq M,\ \forall c; \tag{4}$$

$$\sum_{m}^{M} X_{mc} \geq 0,\ \forall c; \tag{5}$$

$$KX_{mc} - \sum_{p}^{P} A_{mp}Y_{pc} \geq 0,\ \forall c, \forall m; \tag{6}$$

$$K(1-X_{mc}) - \sum_{p}^{P}(1-A_{mp})Y_{pc} + \sum_{p\in(A_{mp}=0)}^{P} H_{mcp} \geq 0,\ \forall c, \forall m; \tag{7}$$

$$\sum_{m}^{M}\sum_{c}^{C}\sum_{p\in(A_{mp}=1)}^{P} E_{mcp} = 0; \tag{8}$$

$$\sum_{m}^{M}\sum_{c}^{C}\sum_{p\in(A_{mp}=0)}^{P} H_{mcp} = Empty\ elements; \tag{9}$$

$$\sum_{m}^{M}\sum_{p}^{P} A_{mp} = Operations; \tag{10}$$

$$H_{mcp},\ Y_{pc},\ E_{mcp},\ \in (0,1). \tag{11}$$

The objective function shown in Equation (1) allows the formation of product families and assignment of machines to the different cells maximizing group efficiency. The description of the constraints is detailed in Table 1:

Equation	Restriction
(2)	One machine can be assigned to several cells depending on the quantity available.
(3)	A product must not be assigned to more than one cell.
(4), (5)	Limits the minimum and maximum number of machines within each cell.
(6)	The number of times a machine is required to produce a product must be greater than or equal to the number of operations required by that machine on all products assigned to the cell.
(7)	The number of empty elements must be greater than or equal to the number of operations assigned to the cell that does not use that type of machine.
(8)	No intercellular movements.
(9)	Allows counting empty elements.
(10)	Allows to count all the operations performed.
(11)	Variables take values of 0 o 1

Table 1. Description of restrictions Model 1.

3.2. Mathematical Model 2

Mathematical Model 2 also corresponds to a Mixed Integer Linear Programming problem and focuses on an aggregated production planning, determining the quantity of units to be manufactured with normal time, overtime, subcontracting and for inventory, as well as transforming the demand into resources needed within each manufacturing cell (labor and machinery), also obtaining a manufacturing and material handling cost using the allocation of machines and products as a result of Model 1. Model 2 is based on the aggregate planning alternatives proposed by several authors, among them Render and Heizer (2009) and Chase and Robert (2014), the combination of these alternatives can be achieved with the support of linear programming.

Indexes

I	Periods of demand.
C	Number of cells to evaluate.
P	Number of products.
M	Number of machines.
i	Demand period index ($i = 1, 2, \ldots, I$).
c	Manufacturing cell index ($c = 1, 2, \ldots, C$).
p	Product index ($p = 1, 2, \ldots, P$).
m	Machine index ($m = 1, 2, \ldots, M$).

Parameters

Tn_p	Unit cost to manufacture the product p.
$CTES_p$	Unit cost of manufacturing product p in supplementary time.
$CTEE_p$	Unit cost to manufacture product p in extraordinary time.
CS_p	Unit cost of subcontracting the product p.
CSO_p	Unit cost of outsourcing product specific operations p.
CI_p	Unit cost of maintaining product inventory p.
CDR_p	Unit cost per distance traveled by product p in normal time.
$CDRTES_p$	Unit cost per distance traveled by product p in additional time.
$CDRTEE_p$	Unit cost per distance traveled by product p in extraordinary time.
DR_p	Quantity traveled by product p for its assembly.
t_p	Assembly time of product p.
tm_{pm}	Operation time of product p in machine m.
X_{pc}	Product p manufactured in cell c.
M_{mc}	Machine m assigned to cell c.

D_{pi}	Demand for product *p* in period *i*.
$CAPS_i$	Subcontracting capacity in period *i*.
TND_i	Normal time available per period *i*.
$TESD_i$	Supplementary time available per period *i*.
$TEED_i$	Extraordinary time available per period *i*.

Decision Variables

N_{pci}	Number of products *p* produced in normal time in cell *c* in period *i*.
Es_{pci}	Number of products *p* produced in Supplementary time in cell *c* in period *i*.
EE_{pci}	Quantity of products *p* manufactured in Extraordinary time in cell *c* in period *i*.
S_{pi}	Quantity of products to be subcontracted of product *p* in period *i*.
In_{pi}	Quantity of inventory of product *p* in period *i*.
KMa_{mc}	Number of machines *m* in cell *c*.
KMO_{ci}	Number of personnel required in cell *c* in period *i*.

$$\begin{aligned} Min = {} & \sum_{i=1}^{Pe}\sum_{c=1}^{C}\sum_{p=1}^{P} Tn_p N_{pci} + \sum_{i=1}^{Pe}\sum_{c=1}^{C}\sum_{p=1}^{P} CTES_p ES_{pci} + \sum_{i=1}^{Pe}\sum_{c=1}^{C}\sum_{p=1}^{P} CTEE_p EE_{pci} \\ & + \sum_{i=1}^{Pe}\sum_{p=1}^{P} CS_p S_{pi} + \sum_{i=1}^{Pe}\sum_{p=1}^{P} CI_p In_{pi} \\ & + \sum_{i=1}^{Pe}\sum_{c=1}^{C}\sum_{p=1}^{P} CSO_p (N_{pci} + ES_{pci} + EE_{pci}) + \sum_{i=1}^{Pe}\sum_{c=1}^{C}\sum_{p=1}^{P} DR_p N_{pci}\, CDR_p \\ & + \sum_{i=1}^{Pe}\sum_{c=1}^{C}\sum_{p=1}^{P} DR_p ES_{pci}\, CDRTES_p + \sum_{i=1}^{Pe}\sum_{c=1}^{C}\sum_{p=1}^{P} DR_p EE_{pci}\, CDRTEE_p \end{aligned} \tag{12}$$

Subject to:

$$X_{pc} In_{pi} = (In_{pi-1} + N_{pci} + ES_{pci} + EE_{pci} + S_{pi} - D_{pi}) X_{pc} \quad \forall i, \forall c, \forall p; \tag{13}$$

$$X_{pc}(In_{pi-1} + N_{pci} + ES_{pci} + EE_{pci} + S_{pi}) \geq D_{pi} X_{pc} \quad \forall i, \forall c, \forall p; \tag{14}$$

$$\sum_{i=1}^{Pe}\sum_{p=1}^{P} S_{pi} \leq CAPS_i; \tag{15}$$

$$\sum_{p=1}^{P} N_{pci}\, tm_{pm} X_{pc} = KMa_{mci} \times TND_i \quad \forall i, \forall c, \forall m; \tag{16}$$

$$\sum_{c}^{C} KMa_{mci} <= Ma_m \quad \forall m, i; \tag{17}$$

$$\sum_{p=1}^{P} N_{pci}\, t_p X_{pc} = KMO_{ci} \times TND_i \quad \forall i, \forall c; \tag{18}$$

$$\sum_{c=1}^{C} KMO_{ci} \leq TMO \quad \forall i; \tag{19}$$

$$\sum_{p=1}^{P} ES_{pci} t_p X_{pc} <= KMO_{ci} \times TESD_i \quad \forall i, \forall c; \tag{20}$$

$$\sum_{p=1}^{P} ES_{pci} tm_{pm} X_{pc} <= KMa_{mci} \times TESD_i \quad \forall i, \forall c, \forall m; \tag{21}$$

$$\sum_{p=1}^{P} EE_{pci} t_p X_{pc} <= KMO_{ci} \times TEED_i \quad \forall i, \forall c; \tag{22}$$

$$\sum_{p=1}^{P} EE_{pci} tm_{pm} X_{pc} <= KMa_{mci} \times TEED_i \quad \forall i, \forall c, \forall m; \tag{23}$$

$$KMa_{mc}, KMO_{ci}, In_i, S_{pi}, N_{pci}, ES_{pci}, \ EE_{pci} \geq 0. \tag{24}$$

Taking into account the parameters and variables to be analyzed, the objective function is constructed, which is the quantitative measure that we wish to optimize through its minimization, this is shown in Equation (12), which contains seven general terms: cost of manufacturing in ordinary, supplementary and extraordinary time, cost of subcontracting final product, cost of maintaining inventory, cost of subcontracting specific manufacturing operations, cost of handling materials in ordinary, supplementary and extraordinary time respectively. The description of the constraints of the second model is detailed in Table 2:

Equation	Restriction
(13)	Balance of inventories.
(14)	Fulfillment of demand.
(15)	Limits subcontracting capacity.
(16)	Calculation of required machines.
(17)	Control of the number of machines required in relation to the quantity available.
(18)	Calculation of required workers.
(19)	Control of the number of workers required in relation to the number available.
(20), (21)	Determines the number of units to be manufactured in additional time with respect to the labor and machinery required.
(22), (23)	Determines the number of units to be manufactured in extraordinary time with respect to labor and machinery.
(24)	Non-negativity

Table 2. Description of restrictions Model 2.

3.3. Proposed Plant Layout

The Systematic Layout Planning (SLP) method was used for the redesign of the plant, taking into account the degree of importance of each of the work centers being located next to each of the others. For the table of relationships shown in Figure 1, all the production processes necessary for the manufacture of the products have been considered, as well as the areas for quality control and storage of raw materials and finished product. The proximity codes are specific to the SLP and the reasons considered for proximity or remoteness were: process sequence, material flow, noise generation, use of the same equipment/machines. Additionally, Guerchet's method was used to determine the areas to be considered for machines, equipment and operating personnel. This total area is the sum of the static, gravitation and evolution surfaces calculated for each of the work areas. This dimensioning generates suitable working spaces with respect to spacing as a biosafety factor. A U-shaped flow has been used in each cell, always seeking communication between personnel and compliance with distribution principles such as: integration as a whole, minimum distance traveled, circulation and satisfaction and safety (Muther, 1981).

4. Results and Discussion

To illustrate the validity of the mathematical models based on mixed integer linear programming (Mixed Inter-ger Programming), the LINGO 18.0 software is used. The information on the products and the machines used to make them is shown in Table 3. The processing time in each of the machines, as well as the assembly time is shown in Table 4. Table 5 contains the cost information related to each product and the distance traveled in the current distribution. Table 6 shows the demand data for the next six periods, while Table 7 shows the normal, supplementary and extraordinary time available in each period.

Machines	Type	P1	P2	P3	P4	P5
M1	Laser Cutter 01	0	0	1	0	0
M2	Laser Cutter 02	1	0	0	0	0
M3	Four-head embroidery machine	1	1	1	0	0
M4	Sublimator 02	0	0	0	1	1
M5	Bagging machine	1	0	0	1	1
M6	Gumming machine	1	1	1	1	1
M7	Sewing Machine	1	1	1	1	1
M8	Side Sewing Machine	0	1	1	0	0
M9	Sewing Machine Bagging	1	0	0	1	1
M10	Roughing machine	1	0	0	1	1

Table 3. Machine - product information.

Machines	P1	P2	P3	P4	P5
M1	0	0	54.95	0	0
M2	54.95	0	0	0	0
M3	458.53	350.1	436.68	0	0
M4	0	0	0	29.77	29.85
M5	40.93	0	0	40.93	40.93
M6	45.73	43.79	43.79	45.73	45.73
M7	511.98	385.08	385.08	511.98	511.98
M8	0	45.46	45.46	0	0
M9	94.61	0	0	94.61	94.61
M10	11.15	0	0	11.15	11.15
Tp	1435.60	1054.21	1195.74	951.89	951.97

Table 4. Processing time in seconds per machine (tmp).

	Tnp	CSp	CIp	CDRp	CDRTESp	CDRTEEp	CTESp	CTEEp	DRp
P1	$8.87	$9.75	$1.77	$0.05	$0.08	$0.10	$10.80	$12.73	236.28
P2	$8.98	$9.88	$1.80	$0.05	$0.08	$0.11	$10.91	$12.84	171.41
P3	$8.64	$9.50	$1.73	$0.07	$0.10	$0.13	$10.57	$12.50	197.96
P4	$9.31	$10.24	$1.86	$0.04	$0.06	$0.09	$11.24	$13.17	220.78
P5	$10.22	$11.24	$2.04	$0.04	$0.06	$0.09	$12.15	$14.08	220.78

Table 5. Costs and distances related to each product.

Productos	Mes 1	Mes 2	Mes 3	Mes 4	Mes 5	Mes 6
P1	2087	2485	2500	2651	3000	3100
P2	1558	2015	2500	2379	2200	2250
P3	874	1007	1100	900	1000	1150
P4	802	545	1618	595	2200	1091
P5	709	260	506	614	502	810

Table 6. Product demand.

Detail	Mes 1	Mes 2	Mes 3	Mes 4	Mes 5	Mes 6
Days per month	21	20	22	22	21	22
Saturdays and Sundays	10	8	8	8	10	8
Hr normal time	8	8	8	8	8	8
Hr supplementary time	2	2	2	2	2	2
Hr extraordinary time	4	4	4	4	4	4
TND (seg)	604800	576000	633600	633600	604800	633600
TESD (seg)	151200	144000	158400	158400	151200	158400
TEED (seg)	144000	115200	115200	115200	144000	115200

Table 7. Time available for each demand period.

4.1. Results Model 1

Three different configurations representing possible scenarios for the selection of product families to be assigned to each cell are analyzed; the group efficiency for each configuration is shown in Table 8.

Configuration	Group efficiency	Machine groups	Products
1 celdas	62.22%	(M2, M3, M4, M5, M6, M7, M8, M9, M10)	(P1, P2, P3, P4, P5)
2 y celdas	70.00%	(M2, M3, M4, M5, M6, M7, M8, M9, M10) (M3, M6, M7, M8)	(P1, P3, P4, P5) (P2)
2 y 3 celdas utilizando M1*	82.50%	(M2, M3, M4, M5, M6, M7, M9, M10) (M1, M3, M6, M7, M8)	(P1, P4, P5) (P2, P3)

*M1: It is rarely used because its capacity is lower than M2.

Table 8. Assignment of machines and products to cells and product families

In the third configuration, the group efficiency is higher than the other two options, being 82.50%. Therefore, two manufacturing cells are assigned: the first one with products P1, P4 and P5, while the second one with products P2 and P3.

4.2. Results of Model 2 with Current Distribution

Model 2 uses the machine and product allocation obtained in Model 1, using information from the current plant layout. The case study company has a subcontracting capacity of 200 units per month. Model 2 determines the production costs in normal, supplementary and extraordinary time, cost for subcontracting and inventory maintenance, as well as the amount of resources such as labor and machinery necessary to meet the expected demand in the analysis periods. The resources to be used to meet the demand in each of the cells are shown in Tables 9 and 10, while the total costs are shown in Table 11.

CELL 1		Month 1	Month 2	Month 3	Month 4	Month 5	Month 6
Normal Time	Cost of production TN	$32,745.09	$23,984.85	$37,744.48	$31,816.54	$45,341.25	$38,330.15
	Material handling cost	$379.26	$289.50	$429.69	$373.84	$508.42	$439.57
	Distance covered	8080.69m	6060.33m	9284.36m	7912.08m	11069.17m	9421.91m
	Product 1	1878 u	1724 u	1780 u	1994 u	1882 u	2025 u
	Product 4	850 u	550 u	1700 u	750 u	2200 u	1200 u
	Product 5	800 u	350 u	600 u	700 u	800 u	900 u
Supplementary Time	Cost of production	$1,801.21	$4,653.79	$4,805.88	$5,382.10	$5,079.33	$5,467.51
	Material handling cost	$19.71	$50.92	$52.58	$58.88	$55.57	$59.82
	Distance covered	394.14m	1018.43m	1051.61m	1177.69m	1111.44m	1196.38m
	Hours required	33.26	85.94	88.74	99.38	93.79	100.96
	Days required	4.71	14.86	11.85	14.84	10.21	13.04
	Product 1	167 u	431 u	445 u	498 u	470 u	506 u
Extraordinary Time	Cost of production	0	0	$949.80	$99.29	$5,702.10	$4,687.10
	Material handling cost	0	0	$8.82	$0.92	$52.93	$43.50
	Distance covered	0	0	176.32m	18.43m	1058.52m	870.10m
	Hours required	0	0	14.88	1.56	89.33	73.43
	Days required	0	0	1.99	0.23	9.72	9.48
	Product 1	0	0	75 u	8 u	448 u	368 u
Resources Required	Workforce	7.00	6.00	7.00	7.00	9.0	8.0
	Machine 2	0.2	0.2	0.2	0.2	0.2	0.2
	Machine 3	1.4	1.4	1.3	1.4	1.4	1.5
	Machine 4	0.1	0.1	0.1	0.1	0.1	0.1
	Machine 5	0.2	0.2	0.3	0.2	0.3	0.3
	Machine 6	0.3	0.2	0.3	0.2	0.4	0.3
	Machine 7	3.0	2.3	3.3	2.8	4.1	3.4
	Machine 9	0.6	0.4	0.6	0.5	0.8	0.6
	Machine 10	0.1	0.1	0.1	0.1	0.1	0.1
CSp	Subcontracting cost	$1,950.92	$1,950.92	$1,950.92	$1,950.92	$1,950.92	$1,950.92
	Product 1	200 u	200 u	200 u	200 u	200 u	200 u
CIp	Inventory cost	$257.26	0	0	0	0	0
	Product 1	145 u	0	0	0	0	0

Table 9. Resources required to meet demand. Cell 1

CELL 2		Month 1	Month 2	Month 3	Month 4	Month 5	Month 6
Normal Time	Cost of production TN	$22,140.91	$21,995.31	$25,559.66	$23,459.16	$22,438.87	$22,874.14
	Material handling cost	$266.23	$260.60	$300.78	$272.45	$263.88	$268.82
	Distance covered	4524.17m	4463.34m	5170.22m	4716.36m	4537.51m	4632.16m
	Product 2	1600 u	1680 u	2000 u	1920 u	1760 u	1775 u
	Product 3	900 u	800 u	880 u	720 u	768 u	803 u
Supplementary Time	Cost of production	0	$6,695.44	$7,779.51	$7,138.59	$6,829.57	$6,962.42
	Material handling cost	0	$65.14	$75.20	$68.11	$65.97	$67.46
	Distance covered	0	1115.74m	1292.56m	1179.09m	1134.38m	1158.04m
	Hours required	0	94.71	109.75	100.17	96.32	98.31
	Days required	0	20.00	22.00	22.00	21.00	22.0
	Product 2	0	420 u	500 u	480 u	440 u	444 u
	Product 3	0	200 u	220 u	180 u	192 u	201 u
Extraordinary Time	Cost of production	0	0	0	0	$496.96	$2,229.32
	Material handling cost	0	0	0	0	$5.19	$22.00
	Distance covered	0	0	0	0	78.71m	343.03m
	Hours required	0	0	0	0	6.60	28.86
	Days required	0	0	0	0	1.44	6.46
	Product 2	0	0	0	0	0 u	31 u
	Product 3	0	0	0	0	40 u	146 u
Resources Required	Workforce	5	5	5	5	4	4
	Machine 1	0.1	0.1	0.1	0.1	0.1	0.1
	Machine 3	1.6	1.6	1.7	1.6	1.6	1.5
	Machine 6	0.2	0.2	0.2	0.2	0.2	0.2
	Machine 7	1.6	1.7	1.8	1.6	1.6	1.6
	Machine 8	0.2	0.2	0.2	0.2	0.2	0.2

Table 10. Resources required to meet demand. Cell 2

Detail	Plan cost
Cost of production in ordinary time	$348,430.44
Cost of production in supplementary time	$62,595.35
Cost of production in extraordinary time	$14.164.57
Cost of subcontracting	$11,705.52
Cost to maintain inventory	$257.26
Cost of product movement	$5,279.58

Table 11. Costs generated to meet demand

4.3. Layout with SLP

In addition to the favorable results through the two mathematical models, the SLP methodology is applied to obtain a new plant layout proposal. The following is a table of relationships that organizes the importance of the relationship between the activities according to: 1. Process Sequence, 2. Material Flow, 3. Noise Generation, 4. Use of the same equipment/machines.

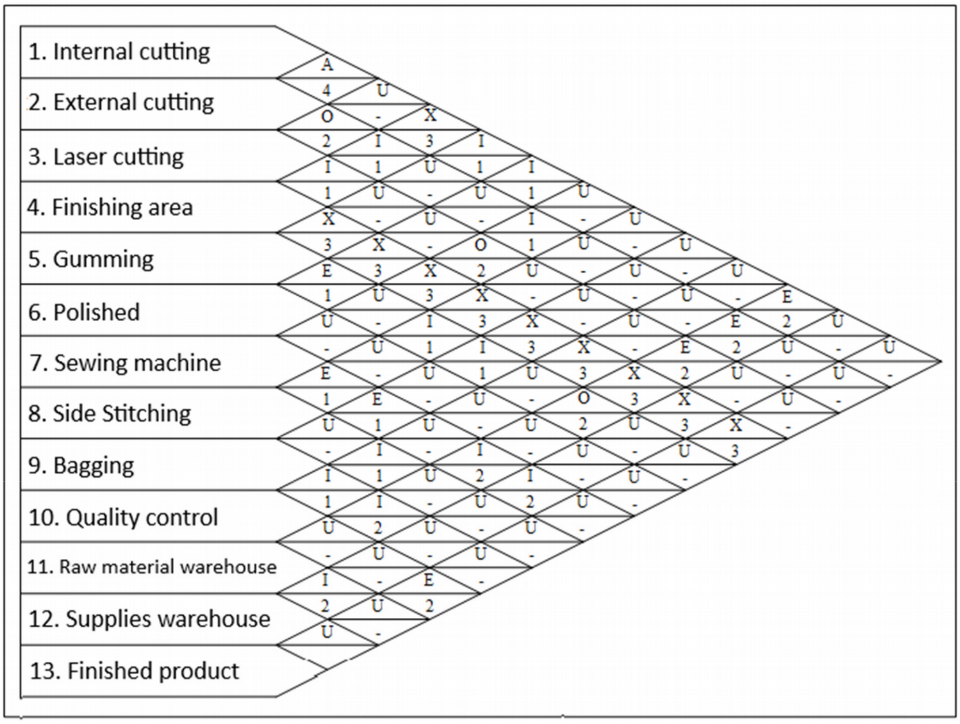

Figure 1. Relationships between manufacturing processes

These proximity values can be visually represented by a relational diagram of activities, using the symbology established by the SLP for the connections with respect to the proximity value. The current and proposed distribution are shown in Figures 2 and 4 respectively.

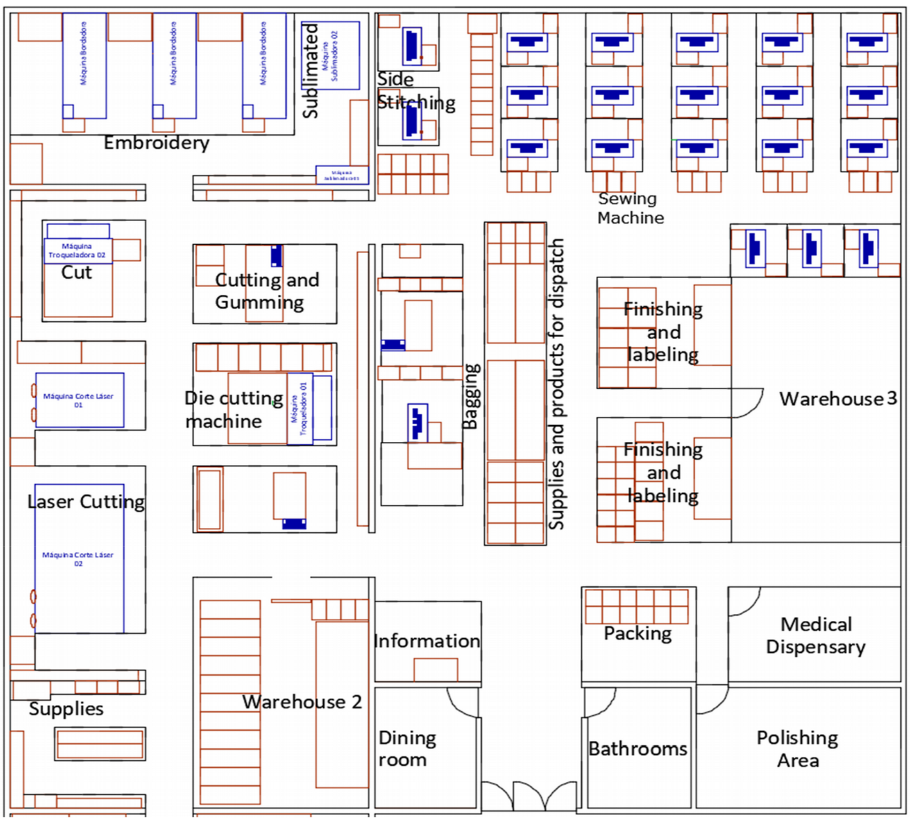

Figure 2. Actual layout

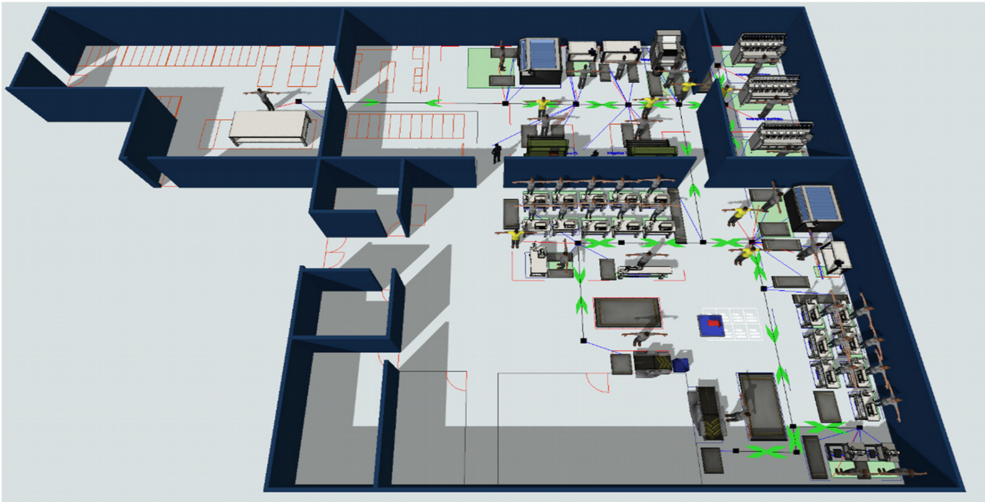

Figure 3. Proposed layout. Simulation in FlexSim

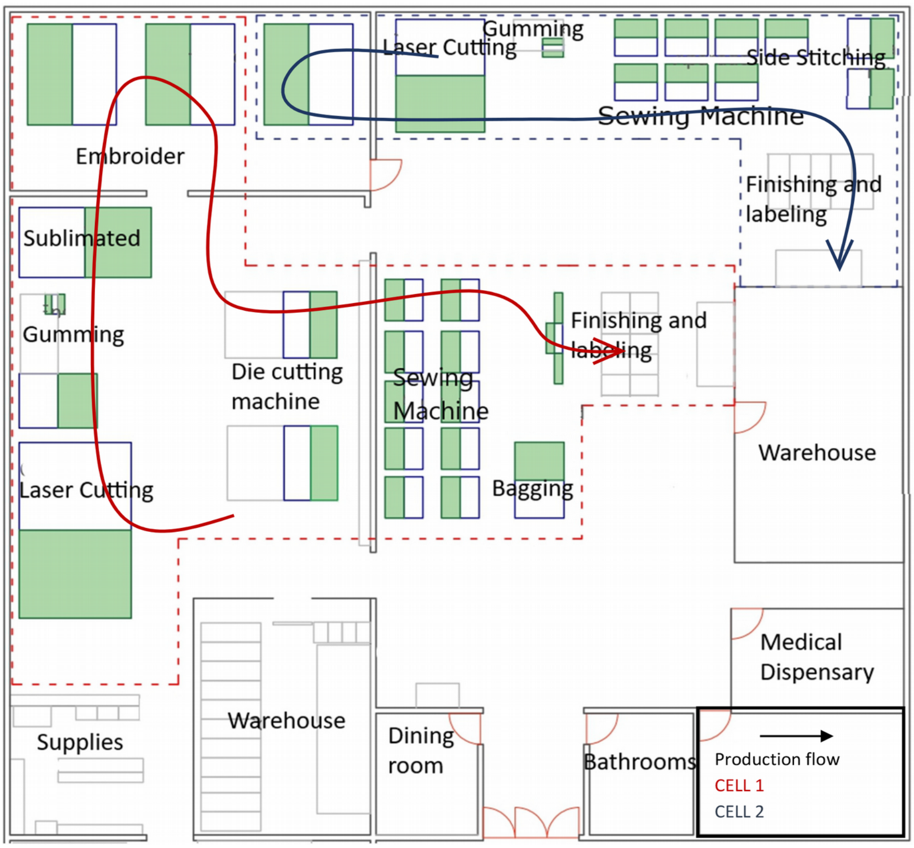

Figure 4. Proposed layout

Additionally, the Guerchet method determines a static surface area of 27.86 m2 required for machines and equipment; the gravity surface area is 30.60 m2 where the materials and workers involved in the process are located; and an evolution surface area of 8.77 m2. Thus. the total area required is 109.56 m2, which is possible given that there is an available area of 491.31 m2.

These data allow us to obtain a redistribution in which products are assigned to the machines and the distance traveled to manufacture the product is reduced. When contrasting both scenarios. using the total distance traveled to manufacture the five products, there is an improvement of 26.6%.

With the proposed distribution, we proceed to solve Model 2 again, observing a variation only in the cost for material movement from $5,279.58 to $4,031.01 with the proposal, $1.248,57 less, representing a reduction of 23.65% of this cost.

Once the results of the simulated scenarios are observed, the major finding is the proper functioning between mathematical models with approaches that at first glance are different (family formation - aggregate planning), but working together allow to have a clear picture regarding the products to be manufactured in each manufacturing cell with a functional plant layout in compliance with basic principles of distribution and with the productive resources required to meet the demand.

Products	Actual distance (m)	Proposed distance (m)	% improvement
P1	236.28	149.87	36.57%
P2	171.41	162.49	5.20%
P3	197.96	197.68	0.14%
P4	220.79	129.35	41.41%
P5	220.79	129.35	41.41%
Total	1,047.22	768.74	26.59%

Table 12. Comparison of distances traveled for product packaging in current and proposed distribution

4.4. Advantages of the Proposed Mathematical Models

Some of the studies shown in the literature review focus only on the formation of manufacturing cells, minimizing the cost of intracellular and intercellular movements and even considering the cost of using or not using a machine. Other studies analyze the best route for manufacturing products within the cells and include variables such as the level of utilization of machinery and personnel.

Improvements in production processes should not be implemented in isolation from each other. With this premise, the mathematical models of Mixed Integer Linear Programming proposed in the document seek to align to the objectives of a lean distribution (work cells - product families) and to the objectives of production planning. In the first theme, we seek to identify a product family, form teams, cross-train team members, where the location of machinery and equipment should focus on the production of a single product or a group of related products and align to the second theme, an aggregate plan that meets forecasted demand by adjusting production rates, labor levels, quantity of machinery, inventory levels, overtime, subcontracting rates, and other controllable variables within each manufacturing cell (Heizer & Render, 2014).

5. Conclusions

The paper presents two mathematical models using mixed integer linear programming. The first model proposes a matrix of machines and products to be processed in them, with the objective of finding the appropriate product family for each manufacturing cell. The second model is oriented to aggregate planning with the purpose of minimizing production and material handling costs, as well as determining labor and machinery requirements; for its construction, several parameterization characteristics were taken into account, including demand, times, machines and products grouped previously and certain costs involved in production.

By applying the first model in the case study, a configuration of two manufacturing cells with a group efficiency of 82.5% was determined. With the second model, a comparison was made between the results of the current and proposed scenarios, showing that the annual cost of material handling is reduced by 35.1% with the proposed alternative plant layout.

The results obtained in the simulated scenarios demonstrate the proper functioning between mathematical models with approaches that at first glance are different but allow us to have a clear picture regarding the products to be manufactured in each manufacturing cell and the production resources required to meet the demand. The mathematical models presented in the paper seek to align with the objectives of cellular distribution and production planning, identifying a family of products where the location of machinery and equipment should focus on the production of a single product or a group of related products supported by an aggregated plan, seeking to meet the forecasted demand by adjusting production rates, labor levels, the quantity of machinery, inventory levels, overtime, subcontracting rates and other controllable variables within each manufacturing cell.

To fulfill this task, it is necessary to clearly and adequately define and collect the information of the variables used in the models, thus guaranteeing the veracity and usefulness of the results. This work does not take into account the cost of mobilization of machines and readjustment of facilities, i.e. reconfigurable cells, so this paper leaves open the experimentation with more variables in similar application.

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