Cellular Manufacturing System Selection with Multi-lean Criteria, Optimization and Simulation[1]

Selección de sistemas de manufactura celular con múltiples criterios lean, optimización y simulación[2]

Claudia C. Bocanegra-Herrera[3]
Juan Pablo Orejuela-Cabrera[4]

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[3] Chemical engineer, Universidad del Valle. Master in engineering with emphasis in Industrial Engineering, Universidad del Valle, Cali, Colombia. Faculty at Universidad Santiago de Cali. E-mail: claudia.bocanegra00@usc.edu.co

[4] Industrial engineer, Universidad del Valle. Master in Engineering with emphasis in Industrial Engineering, Universidad del Valle, Cali, Colombia. Faculty at Universidad del Valle. E-mail: juan.orejuela@correounivalle.edu.co

Abstract

Introduction: this study proposes a method to design and balance a cellular manufacturing system of a typical industrial company to obtain an optimal configuration in terms of the process, total cost, idle time and reliability criteria. **Methods**: the developed method has three phases. The first phase obtains candidate solutions using optimization models to minimize the cycle time and total cost. In the second phase, the performance measures for the remaining criteria of each candidate solution are found using discrete-event simulation. In the last phase, the optimal configuration is selected using the analytic network process (ANP). **Results**: the proposed method was validated with a practical case, where the optimal configuration had the best reliability with a zero-smoothness index, which minimized the wasted time and excess inventory. However, it was not the configuration with the lowest cost. **Conclusions**: This method has two contributing elements: multiple lean criteria and the approach, which combines different solution strategies to select the best configuration in an integral manner.

Keywords

cellular manufacturing; optimization; discrete-event simulation; analytic network process-ANP

Resumen

Introducción: esta investigación propone una metodología para diseñar y balancear un sistema de manufactura celular de una empresa industrial típica con el propósito de obtener una configuración óptima bajo los criterios de, proceso, costo total, tiempo ocioso y confiabilidad. **Métodos**: la metodología desarrollada tiene tres fases. La primera fase consiste en obtener soluciones candidatas usando modelos de optimización para minimizar tiempo de ciclo y costo total. En la segunda fase se encuentran las medidas de desempeño de los demás criterios para cada solución candidata utilizando simulación de eventos discretos. En la última fase se escoge la configuración óptima utilizando el análisis de decisión multicriterio. **Resultados**: la metodología propuesta fue validada en un caso práctico donde la mejor configuración encontrada tiene la mayor confiabilidad, un índice de suavidad de cero que minimiza el desperdicio de tiempo y el exceso de inventario, aunque no fue la configuración con menor costo. **Conclusiones**: esta metodología tiene dos elementos de contribución: el primero, que involucra múltiples criterios *lean*, y el segundo, el enfoque que combina diferentes estrategias de solución para la selección de la mejor configuración de una manera integral.

Palabras clave

manufactura celular; optimización; simulación de eventos discretos; proceso de redes jerárquico

Introduction

Lean manufacturing (LM) is a production philosophy that aims to reduce waste in a continuous improvement process, which involves principles, techniques, tools and measures [1]. Waste is an activity that does not aggregate value from the customer perspective [2]–[4]. The design of a cellular manufacturing system is notably important to LM because it increases the process flexibility and decreases the work in-process inventory (WIP) and flow time [5].

Cellular manufacturing is a system of different processes and resources that respond to a grouping principle. When a group of cells produces the same subproduct and it is delivered to another process, the resulting configuration can be considered an assembly line (AL) with parallel cells.

An assembly line is a manufacturing process, where the total amount of work is divided into tasks. The task area is organized into stations, which are usually arranged along a conveyor belt to form a line. Jobs are consecutively sent and moved from one station to another. At each station, the tasks are repeatedly performed [6]. Assembly lines are typically used in industrial companies with standardized customized products. One of the problems in this context is the assembly line balancing (ALBP), which consists of assigning tasks to an ordered sequence of stations so that the precedence relations of the tasks are satisfied and optimized under any performance measure [7], [8].

The ALBP can have different objective criteria. Ghosg and Gagnon [9] classified the objective criteria into two main categories: technical and economical. In the technical category, minimizing the number of stations for a required cycle time has been the most popular criterion. For the economical category, minimizing the labor cost or idleness cost has been the most selected criterion [10]. Most studies have focused on a solo criterion [11].

The ALBP with multiple objectives is called the MOALBP [12]. The objectives to balance a manufacturing system are frequently in conflict among themselves when different user requirements are considered [13]. Bukchin and Masin [14] designed a multi-objective assembly system using a Branch and Bound algorithm. Esmaeilbeigi *et al.* [15] formulated a mixed integer linear program for a simple ALBP to minimize different objectives. These studies [16]–[18] considered worker allocation with the balancing problem in their multi-objective model. Other techniques have been used for MOALBP, such as fuzzy programming [19], [20], evolutionary models [21]–[23], neural networks [24] and different metaheuristics [25]–[28].

The research works [29]–[32] used different lean measures to design manufacturing systems. Deif [33] developed a dynamic model for a lean manufacturing cell to study the leveled production performance. The authors [34] state that the flow time, cycle time, and work-in-process inventory level (WIP) are important measures. Their relationship in a production line is captured by Little's Law.

The simulation technique enables one to capture the complexity of an actual system; thus, it is combined with optimization techniques to complement the analysis. Kabir and Tabucanon [35] used an analytic hierarchy process (AHP) and simulation to determine a specific configuration for a batch-model assembly system. Studies such as [36]–[39] used discrete-event simulation to analyze the scenarios of a manufacturing system and select a specific solution. Tiacci [40] developed an event simulator for different assembly line configurations. Mendes *et al.* [41] presented a mixed-model of an ALB case study using simulation models and heuristic procedures. Cappanera *et al.* [42] developed a mixed-integer programming model for surgical scheduling with respect to three performance criteria; then, its strength was evaluated with a discrete-event simulation model.

Both authors [43], [44] agree that the NP-Hard complexity of the parallel assembly line balancing problem makes its solution almost impossible using traditional techniques and if another criterion is considered. In this sense, this paper focuses on developing a method to design a cellular manufacturing system with parallel cells considering multi-lean measures, i.e., it is framed into an MOALBP. This approach is based on the optimization, simulation and multi-criteria decision analysis. Therefore, the method can be used in assembly industries to obtain an optimal configuration in an integral manner.

1. Proposed methodology approach

This study focuses on developing a methodology for a cellular manufacturing system with parallel cells, where the best configuration is selected among different types of cells and system balancing. The study focuses on an arrangement where there are a specific number of tasks with trained workers who accomplish the tasks in a required cycle time, which is set according to demand. It is desirable to know how to set each cell and how many cells for each type to use. The cycle time is the time between product outputs from two consecutive production lines, which represents the maximum amount of work processed by each station.

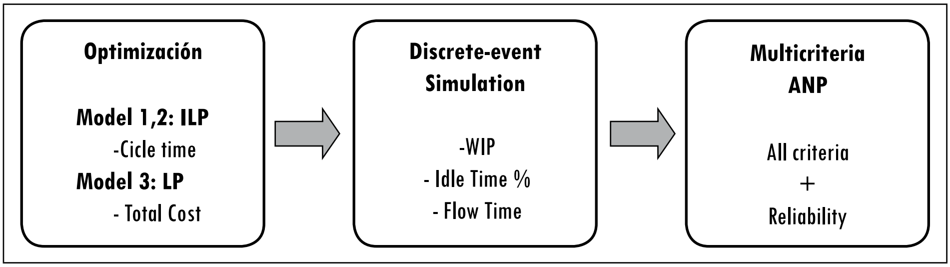
This approach must considers multiple objectives, which become the total cost. The total cost is defined as the cost of all workers and cells (See Equation 1)

$$Total\ Cost = Cc = \sum_{c=1}^{L} C^{Cell} \cdot Number\_Cells_c + C^{Worker} \cdot Number\_Workers_c \qquad (1)$$

The multi-lean measures enable one to quantify the LM impact and guide the development of lean systems [45]. They are the process, idle time percentage and reliability. For the process, Little's Law measures were selected (WIP, flow time and cycle time) because they enable an analysis of the process performance. The idle time percentage was used as a criterion because it is a measure of waste time. The reliability criterion was selected because having more cells mitigates the risk created by damages in a cell or defects in the materials and increases the process flexibility [46]. The reliability was measured as the number of cells, where 1 is the lower value, and the total number of cells is the maximum value.

The methodological formulation consists of three phases (See Figure 1). The first phase is made of two integer linear programming models and one linear programming model to obtain candidate solutions to satisfy the required cycle time and minimize the total cost. In the second phase, a discrete-event simulation model is developed for each candidate solution, where the WIP, flow time and idle time percentage of each candidate solution are found. In the third and last phase, the multi-criteria decision analysis called Analytic Network Process (ANP) is applied to select the optimal solution. The phases are explained in detail below.

Figure 1. Criteria in the methodological phases



Source: authors' own elaboration

1.1. Phase 1. Mathematical optimization

In this phase, three mixed integer linear programming models were developed based on [47]-[49] and written in AMPL. The assumptions of the models are as follows:

- The workers are multi-functional.
- The demand is known and constant over time.
- The task process times are known and constant over time for every worker.
- The movement times are known and constant over time.

Table 1 shows each model formulation. The first two models minimize the cycle time, and the third aims to minimize the cost. The first model considers fewer or equal number of workers than tasks to determine the task set for each worker to do to minimize the cycle time, assuming that there is at most one worker per task. For *n* tasks, the model is run for 1 to *n* workers to obtain *n* candidate solutions.

The second model eliminates the assumption of the first model to assign parallel workers to each task. This model is run for a different number of workers from *n* to *nw* and obtains *nw-n+1* candidate solutions. The third model takes the candidate solutions from the first two models, which provide the possible types of cells. This model combines different cell types to minimize the total cost and ensure the required cycle time.

1.2. Phase 2. Discrete-event simulation

A discrete-event simulation model was developed to estimate the other performance measures: WIP, Flow Time and Idle time percentage. The production plant is assumed to be continuously working during the shift. The Microsoft Excel® spreadsheet application was used. Figure 2 shows the flow diagram of the assembly process, where TM is the clock time of the simulation, AT is the scheduled time of the next arrival, DT is the scheduled time of the next departure, WLi is the length of the ith task waiting in line, IT is the inter-arrival time, and MX is the required demand. There are two types of events: arrival and departure; a departure is also the arrival for the next task until the process is finished, and a final product (FP) with a flow time (FTFP) is obtained.

Table 1. Formulations for each model

1. Cell Balancing: Fewer or equal workers than tasks	2. Cell Balancing: More workers than tasks	3. Numbers of cells for each type
Sets: OPE (*i*) EST (*j*) PRE within {OPE, OPE}	**Sets:** OPE (*i*) EST (*j*) MAX within {OPE, EST}	**Sets:** CEL (*c*)
Decision variables: X_{ij} = Binary variable indicating whether task i is made by worker *j* TW_j = Time of worker *j* CTS = Cycle time	**Decision variables:** Y_{ij} = Binary variable indicating whether task *i* has *j* workers FCT_i = Final time for task *i* CTS = Cycle time	**Decision variables:** Y_c = Number of cells of type *c*
Objective function: $Min\ z$: CTS (2)	**Objective function:** $Min\ z$: CTS (9)	**Objective function:** $Min\ z : \sum_{c=1}^{L} Y_c * C_c$ (16)
Subject to: $\sum_{j=1}^{M} X_{ij} = 1\ \forall i$ (3) $\sum_{i=1}^{N} X_{ij} * tpt_i = TW_j$ $\forall j$ (4) $TW_j \leq CTS\ \forall j$ (5) $\sum_{i=1}^{N} \sum_{j=1}^{M} X_{ak} \geq X_{bj}$ $\forall$ (a, b) *in PRE* (6) TWj, CTS ≥ 0 (7) $X_{ij} \in \{0,1\}$ (8)	**Subject to:** $\sum_{j=1}^{M} Y_{ij} = 1\ \forall\ i$ (10) $\sum_{j=1}^{M} Y_{ij} tpt_{ij} = FTC_i$ $\forall_i$ (11) $FCT_i \leq CTS\ \forall\ i$ (12) $\sum_{i=1}^{N} \sum_{j=1}^{M} Y_{ij} * j \geq mw$ (13) TCF_j, $CTS \geq 0$ (14) $Y_{ij} \in \{0,1\}$ (15)	**Subject to:** $\sum_{c=1}^{L} \frac{Y_c}{fct_c} \leq \frac{1}{dCT}$ $Y_c \geq = \forall_c$ (18) $Y_c \in integer$ (19)
Objective: Minimizes Cycle Time	**Objective:** Minimizes Cycle Time	**Objective:** Minimizes Total Cost

1. Cell Balancing: Fewer or equal workers than tasks	2. Cell Balancing: More workers than tasks	3. Numbers of cells for each type
Constraints: (3) Ensure that each task is performed only once. (4) Determine the worker times. (5) Ensure that TCS will be the maximum time of worker. (6) Ensure precedence relations between tasks. (7) Sign restrictions. (8) Binary values.	**Constraints:** (10) Ensure that each task is executed at least by one worker. (11) Determine the resulting final time for task. (12) Ensure that TCS will be the maximum task time. (13) Ensure the number of workers do not exceed the maximum number of workers. (14) Sign restrictions. (15) Binary values.	**Constraints:** (17) Determine the resulting cycle time will be the required value. (18) Sign restrictions. (19) Integer values.

Source: authors' own elaboration

1.3. Phase 3. Multi-criteria decision analysis

The multi-criteria decision analysis is a theory and a set of techniques to choose alternatives according to attributes and criteria. ANP is one of those multi-criteria techniques, which captures the dependence among different elements [50]. The paired comparison scale is 1-9, where 1 is equal to the importance, and 9 is the extreme importance [51]. The paired comparisons are used to derive the priority function of the network criteria.

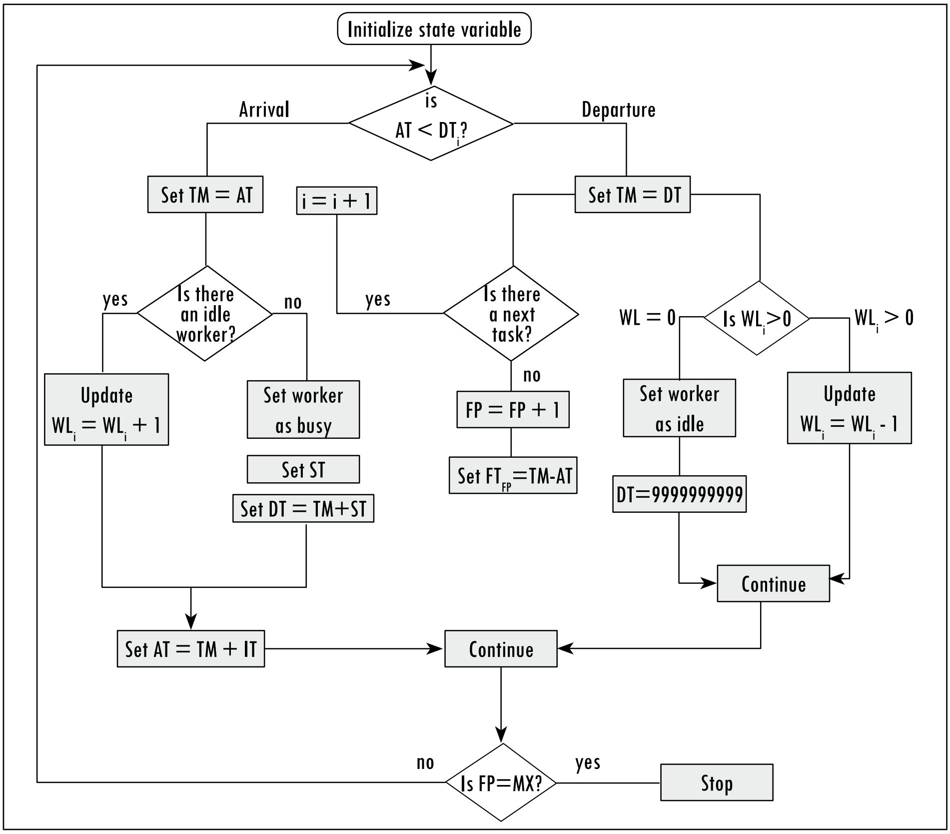
2. Application Case

There is an analysis of an application to demonstrate the use of the developed methodology. This application case was obtained from Sempere *et al.* [52]. A company produces an assembly product with a daily demand of 7,000 units. The shop works 7 hours daily. The assembly consists of 8 tasks as shown in Figure 3. A worker can move from one workbench to another with a transportation time of 0.05 min, and many workers can work in the same task. Annually, the cost of every single installed cell is three times the worker cost.

2.1. Computational results of phase 1

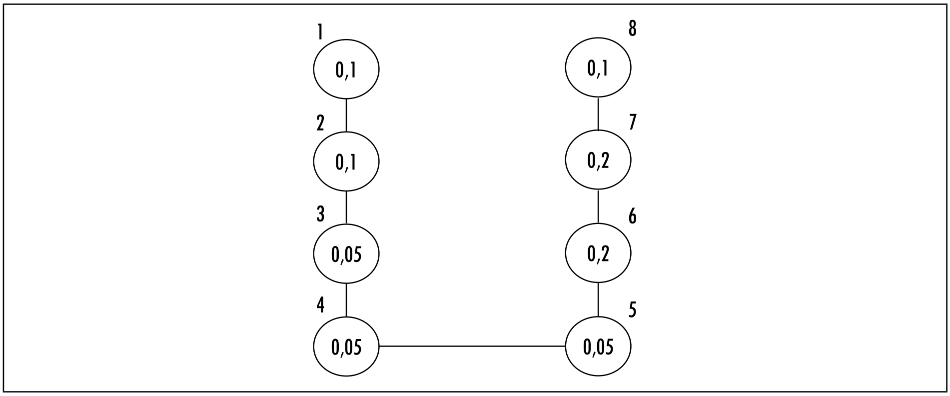
Model 1 shows 8 optimal solutions; however, the cases with 7 and 8 workers have the identical maximum cycle time as the case with 6 workers but at a higher cost; thus, they were not selected as candidate solutions. In the set of candidate solutions, the minimum cost (40) is found when there are five cells with five workers in each cell. For model 2, the necessary maximum number of workers

Figure 2. Flow diagram of the discrete-event simulation



Source: authors' own elaboration

Figure 3. Task times of the case

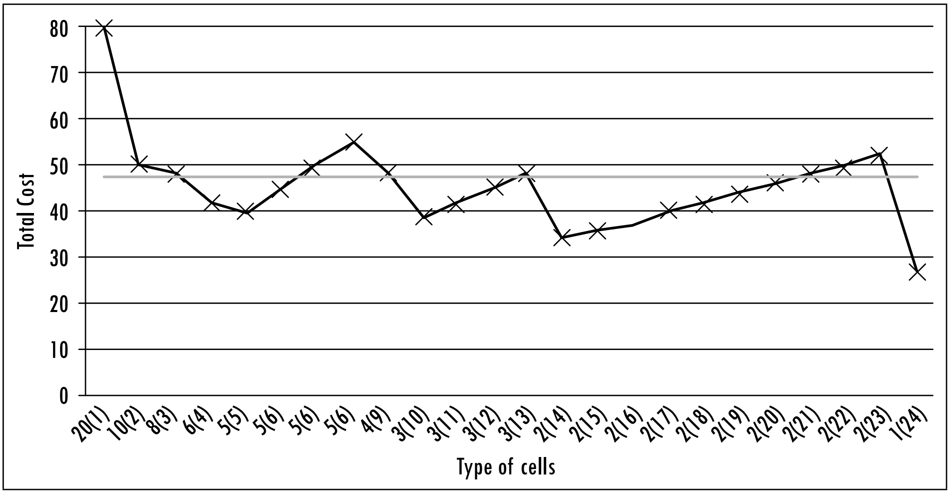


Source: modified from Sempere *et al.* (2008).

was calculated to obtain the required cycle time with one cell. The new processing times for different numbers of workers who are in one parallel task were previously found. The results were 17 possible solutions, where a cell type with a single cell and 24 workers has a minimum cost of 27 and a cycle time of 0.05 min. However, model 3 enables one to mix different cell types in models 1 and 2. Model 3 provided the same optimal solution as model 2.

Figure 4 shows the cost behavior for each cell type. The number outside the parentheses is the number of cells, and the number inside the parentheses is the number of workers. The idle time percentage depends on the bottleneck position and whether the calculated number of cells is an exact integer value. For identical numbers of cells, there are multiple configurations with different numbers of workers, where the total cost linearly increases with the number of workers. The total cost behavior is oscillatory. The flat line shows that for a total cost, there are different cell types. If the reliability criterion is added, it is better to have 8 cells with three workers than the remaining options. Therefore, other criteria must be analyzed to select the best solution.

Figure 4. Total cost for each type of cell

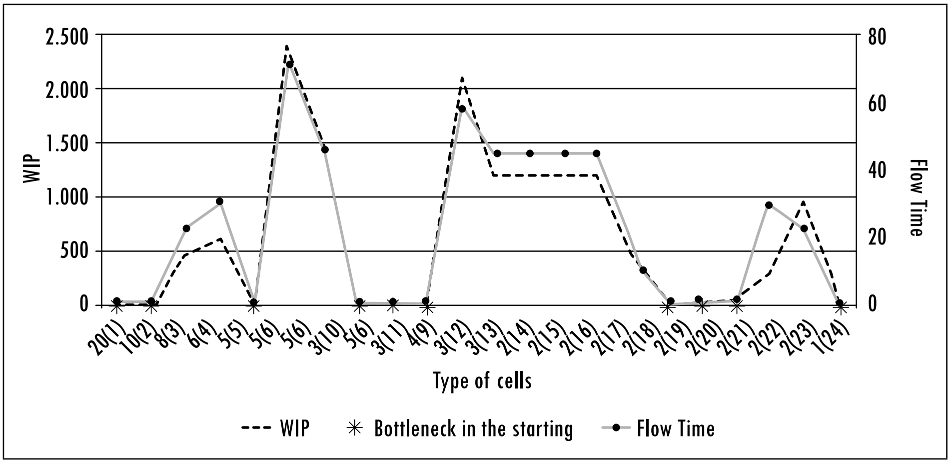


Source: authors' own elaboration

2.2. Computational results of phase 2

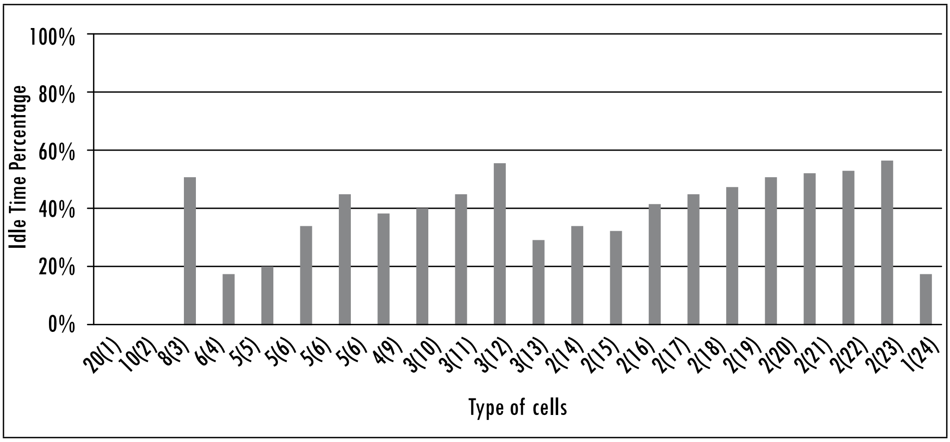
To validate the simulation model, the WIP and flow time were compared to the theoretical values obtained with Little's Law, which show that the results were similar. Figure 5 shows that the WIP and flow time results are classified into two categories. The first category occurs when the cell has the bottleneck in the first task, and the second category includes other cases. The first category has less WIP and a shorter flow time than the second one.

Figure 5. Summary of WIP and flow time results with the simulations



Source: authors' own elaboration

Figure 6. Idle time percentage for different types of cells



Source: authors' own elaboration

The idle time percentage mainly depends on the position of the bottleneck, and the number of cells was rounded up. Figure 6 shows the average Idle time percentage for different types of cells. 20(1) and 10(2) have an idle time percentage of 0%.

2.3. Computational results of phase 3

The criteria pairwise comparison for the ANP technique according to a previous analysis is shown in Tables 2 and 3. The ranking of the alternatives for each criterion is provided for the identical simulation results. The consistency indices of the matrices [53] offer an acceptable estimation.

Table 2. Criteria paired comparison

Criteria	Cost	Idle Time %	Reliability	Process
Cost	1	4	2	1
Idle Time %		1	1/4	1/4
Reliability			1	1/2
System				1

Source: authors' own elaboration

Table 3. Process sub-criteria paired comparison

Sub-criteria	Cycle time	WIP	Flow time
Cycle time	1	4	2
WIP	-	1	1/2
Flow Time	-	-	1

Source: authors' own elaboration

New constraints were added to optimization model 3 to find additional solutions between cells two and five for the multi-criteria decision analysis. These solutions are more expensive but may be better for all combined criteria. The new solutions were analyzed with the existing solutions for the ANP. Furthermore, ANP results were compared to a non-compensating analysis (NCA). Table 4 has two parts: NCA ranking and ANP ranking. In relation to NCA, the scoring of the alternative cell configurations was measured for each criterion, and the scores were normalized by criteria. When only the process criterion was considered, all best solution configurations had the bottleneck at the beginning. The 20-cell configuration with one worker 20(1) is the best for both analyses. The configuration of one cell with 24 workers 1(24) shows the lowest cost but is not reliable, so it was discarded. It is important to highlight that changing the criteria weights will change the score of each configuration and consequently its ranking in the results.

To analyze the results, the smoothness index is measured to know the process synchronization (See Equation 2), i.e., the load leveling among the workers. The perfect balance is indicated by a zero (0) value [54][55]. The k station time (ST_k) is identical in TW_j for model 1 and FCT_i for model 2. The best two alternatives have zero (0) smoothness indices.

$$Smoothness\ Index\ \left(SX\right) = \sqrt{\sum_{k=1}\left(CY - ST_k\right)^2} \qquad (2)$$

A zero (0) smoothness index implies a perfect synchronization among the tasks, which is notably important for the process because it decreases the wasted time and excess WIP.

Table 4. NCA and ANP results

NCA						ANP	
Cell Configurations	Scoring					Scoring	Cell Configurations
	Total Cost	Idle Time %	Reliability	Process	Total		
20Cell(1)	0.056	1.000	1.000	1.000	3.056	0.057	20Cell(1)
10Cell(2)	0.063	1.000	0.500	1.000	2.563	0.041	10Cell(2)
1Cell(24)	1.000	0.250	0.111	0.333	1.694	0.031	5Cell(5)
3Cell(2,2,19)	0.333	0.333	0.143	0.500	1.310	0.031	3Cell(2,2,19)
2Cell(5,19)	0.500	0.091	0.125	0.333	1.049	0.030	1Cell(24)
5Cell(2,2,2,2,14)	0.143	0.500	0.200	0.071	0.914	0.030	8Cell(3)
2Cell(1,23)	0.500	0.143	0.125	0.077	0.845	0.029	2Cell(5,19)
5Cell(5)	0.100	0.200	0.200	0.250	0.750	0.029	5Cell(2,2,2,2,14)
6Cell(4)	0.091	0.250	0.250	0.071	0.662	0.028	6Cell(4)
4Cell(2,3,4,14)	0.200	0.167	0.167	0.067	0.600	0.027	4Cell(2,3,4,14)
2Cell(14)	0.250	0.125	0.125	0.059	0.559	0.026	3Cell(10)
8Cell(3)	0.067	0.063	0.333	0.077	0.539	0.025	2Cell(1,23)
3Cell(10)	0.111	0.083	0.143	0.200	0.537	0.025	5Cell(6)
3Cell(11)	0.091	0.077	0.143	0.167	0.477	0.025	3Cell(11)

NCA						ANP	
Cell Configurations	Scoring					Scoring	Cell Configurations
	Total Cost	Idle Time %	Reliability	Process	Total		
2Cell(15)	0.167	0.100	0.125	0.059	0.450	0.023	3Cell(12)
3Cell(12)	0.077	0.071	0.143	0.143	0.434	0.023	2Cell(14)
5Cell(6)	0.077	0.100	0.200	0.050	0.427	0.022	2Cell(15)
2Cell(16)	0.125	0.111	0.125	0.059	0.420	0.022	4Cell(9)
2Cell(19)	0.083	0.067	0.125	0.125	0.400	0.021	2Cell(19)
2Cell(18)	0.091	0.071	0.125	0.083	0.371	0.021	2Cell(16)
2Cell(20)	0.071	0.063	0.125	0.111	0.370	0.021	2Cell(20)
2Cell(17)	0.100	0.077	0.125	0.059	0.361	0.020	2Cell(17)
4Cell(9)	0.067	0.071	0.167	0.056	0.360	0.020	2Cell(21)
2Cell(21)	0.067	0.059	0.125	0.100	0.350	0.019	2Cell(18)
2Cell(22)	0.063	0.056	0.125	0.091	0.334	0.019	3Cell(13)
3Cell(13)	0.067	0.053	0.143	0.053	0.315	0.017	2Cell(22)
2Cell(23)	0.059	0.050	0.125	0.063	0.296	0.016	2Cell(23)

Source: authors' own elaboration

3. Conclusions

The methodology developed for the MOALBP enables us to select the best configuration of parallel cells in a cellular manufacturing system, which involves the multi-criteria selection to enrich the problem solution. The method considers the economic criteria, total cost, multi-lean measures, cycle time, WIP, flow time and reliability to make decisions in an integral manner.

Furthermore, the method combines different solution strategies when the solution is broken down into several phases and sub-models, which handle the procedure in a simple manner without advance tools or long computing processing time.

The optimization models enable us to find the best solution, but simplifying the actual system and the simulation do not optimize. However, it considers the interrelations and complexity, so it is important to combine them. In addition, the ANP selects the best alternative among multiple possible solutions.

The presented method is notably different than those in the literature. The method is useful in practical cases. The multi-lean criteria focus on eliminating idle time and excess inventory and synchronizing the manufacturing system.

In the best configuration, there is a bottleneck at the beginning of the process with a zero-smoothness index, which generates a perfect load balancing; thus, there is no idle time. Although this configuration is optimal under multiple criteria, it is not the configuration with the lowest cost, which would be selected in a traditional approach.

For future study, a larger application should be considered because this problem is a combinatorial problem to analyze the use of metaheuristics to solve optimization models.

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Nomenclature

Set
OPE = Set of task
EST = Set of workers
PRE = Set of precedence tasks
MAX = Set of maximum quantity workers in each task
CEL = Set of cell's type

Index
L = Maximum number of cells
N = Number of total tasks
M = Number of total workers
i = Index of task $i = 1, 2, \ldots N$
j = Index of worker $j = 1, 2, \ldots M$
c = Index of type of cells $c = 1, 2, \ldots L$

Parameters
C^{Cell} = Cell cost in a year
C^{Worker} = Cell cost in a year
tpt_i = Process time of tasks i
tpt_{ij} = Process time of tasks i with j workers
mw = Maximun number of workers
fct_c = Final cycle time of cell type c
dCT = Required cycle time