Arango-Marín, Jaime Antero; Giraldo-García, Jaime Alberto; Castrillón-Gómez, Omar Danilo
Applying TOC Heuristics to Job Scheduling in a Hybrid Flexible Flow Shop

Applying TOC Heuristics to Job Scheduling in a Hybrid Flexible Flow Shop

Jaime Antero Arango-Marín [a], Jaime Alberto Giraldo-García [b] & Omar Danilo Castrillón-Gómez [c]

[a] Facultad de Ingeniería y Arquitectura, Universidad Nacional de Colombia; Universidad Católica de Manizales, Colombia. jaarangom@unal.edu.co
[b] Facultad de Ingeniería y Arquitectura, Universidad Nacional de Colombia, Colombia. jaiagiraldog@unal.edu.co
[c] Facultad de Ingeniería y Arquitectura, Universidad Nacional de Colombia, Colombia.odcastrillong@unal.edu.co

Abstract

This paper introduces an application of the Theory of Constraints product mix heuristic to job scheduling in a Hybrid Flexible Flow Shop. The general heuristic is adapted for unrelated parallel machines and the algorithm is implemented as a job detailed scheduling tool based on the principle of the Theory of Constraints to schedule the production based in the bottleneck resource. The adaptation of the methodology to a flexible hybrid context, where there is parallelism in the bottleneck stage, and its application in a textile plant, helps to assign capacity based on the contribution margin. The result is a viable job scheduling focused on the profitability unit. Although the results do not reach the global optimum of this type of problems, they represent a fast and effective job scheduling alternative in the contexts under study.

Keywords: Theory of Constraints; Flow Shop; job scheduling; heuristics

Aplicando la Heurística TOC a la Secuenciación de Trabajos en un Flow Shop Híbrido Flexible

Resumen

Este artículo presenta una aplicación de la heurística para la mezcla de productos de la Teoría de Restricciones, a la planificación de tareas en un Flow Shop híbrido flexible. La heurística general se adapta para el caso de máquinas paralelas no relacionadas y el algoritmo se implementa como una herramienta de programación detallada de trabajos, basada en el principio de la Teoría de Restricciones de subordinar toda la programación al recurso cuello de botella. La adaptación de la metodología a un contexto híbrido flexible, donde hay paralelismo en la etapa cuello de botella y su aplicación en una planta textil contribuye a asignar la capacidad con base en el margen de contribución. El resultado es una programación de trabajos viable enfocada en la utilidad unitaria. Aunque los resultados no alcanzan el óptimo global para este tipo de problemas, sí representan una alternativa de programación de trabajos rápida y eficaz en los contextos estudiados.

Palabras clave: Teoría de Restricciones; flow shop; secuenciación de trabajos; heurística.

1. Introduction

Production scheduling is the stage that defines the assigning of specific jobs on a machine or set of machines and the sequence or order in which the pending jobs will be processed. Efficient production programs can lead to substantial improvements in productivity and cost reduction. [1]

Each production environment has its own restrictions and particularities that require the application of appropriate techniques to ensure efficient scheduling.

The hybrid Flow Shop is a production line process in which at least one of the stages includes parallel machines. In a flexible Hybrid Flow Shop, some products might be processed without going through one or more of the stages. [2] A classic example of such a process is in the textile industry.

The Scheduling in the Hybrid Flow Shop has been approached by dozens of researchers using different techniques. Some of the more recent contributions are those of Qiao and Sun, [3](2011), Yue-Wen et al. [4](2011) and Yalaoui et al. [5](2011) who applied intelligent particles, and Hidri and Haouari [6] (2011) who applied limitation strategies.

One of the main features in the flexible hybrid Flow Shop is parallelism in at least one stage of the production process. The most general and most common case in the

real world [7][8] is that of unrelated parallel machines These are, machines with different production rates and different job scheduling possibilities. Some recent work on parallel machines scheduling includes: Zhank and Van de Velde [9](2012) who proposed an approximation algorithm, Driessel and Monch [10](2011) and James and Almada-Lobo [11](2011) with Variable neighborhood search, Lin et al. [12](2011) who applied a greedy algorithm, while Chang and Chen [13](2011) and Arango et al. [14](2013) adapted genetic algorithms.

It is common to find the use of heuristics. In the most general sense heuristics refer to those smart technical methods or procedures required to perform a task. Heuristics is the result of the knowledge of an expert and does not come from a rigorous formal analysis.

The optimal "product-mix" of the Theory of Constraints is obtained using a heuristic known as TOC, which was developed based on the five steps proposed by Goldratt [16] (1984). (Find the constraint, exploit the constraint, subordinate the system to the constraint, elevate the constraint and when the constraint is overcome, find a new one and repeat the process).[16]

Several researchers have taken into consideration this algorithm: (Fredendall and Lea [17] 1997; Lee and Plenert [18], 1993), who discussed the capacity of TOC compared to LP or ILP models (Lea and Fredendall [19] 2002; Mabin and Davies [20], 2003; Aryanezhad and Komijan [21], 2004; Souren, Ahn and Schmitz [22](2005).

Metaheuristics have also been applied to the problem of the optimal mix under study using the Theory of Constraints: Onwubolu [23](2001) proposed an algorithm based on tabu search; Mishra, Prakash, Tiwari, Shankar, and Chan [24] (2005) presented a hybrid algorithm of tabu search and simulated annealing; and Onwubolu and Mutingi [25] (2001) developed a genetic algorithm.

The aim of this paper is to present an adaptation of the optimal product mix of the Theory of Constraints in the case where parallelism takes place in the bottleneck of the process and use it as a scheduling tool in production in this kind of environments.

Different from most papers that address problems using this approach, this paper will take into account the capacity constraints and also the constraints in market size and the availability of the supplies. The test data are based on a producer of textiles for industrial use. The model is solved using a heuristic adapted from the original TOC proposal which provides load assignation and a sequencing of jobs on the machines. The results obtained will be compared to those obtained using the optimal mix according to the classical view of integer linear programming.

The heuristic is proposed as a viable solution, due to the combinatorial nature of the problem, and the long computational time of exact methods, not appropriated for the habitual use in real production environments.

2. Methodology

Linares (2009) [26] summarizes the first two steps of the TOC heuristic corresponding to the quantitative part:

Step 1: Identify the system constraints:
Calculate the required load on each resource to manufacture all the products. The constraint or bottleneck (BN) is the resource in which demand exceeds capacity.

Step 2: Decide how to exploit the system constraints:
(a) Calculate the contribution margin (CM) of each product such as the selling price minus costs of raw materials (RM).
(b) Calculate the relation between the contribution margin of the products and the processing time at the bottleneck resource (CM/BN).
(c) Reserve the capacity of the bottleneck resource, by sorting the products in descending order according to the relation CM/BN.

The classical approach of the Theory of Constraints assumes a sequential production line in which there is only one item of each resource type, and the products can have alternative process routes by varying the order on the same resources.

Industrial processes classified as "Hybrid Flexible Flow Shop", such as in the case of textile production, count on several similar resources in parallel with similar process routes for all the products regarding the order in which these go through the transformation processes. The issue is to find out how to distribute each job in the different resources with the aim to favor contribution to the business profits.

The following steps are proposed to determine the optimal product mix in a Flexible Hybrid Flow Shop according to the Theory of Constraints:

Step 1: Identify the system constraints:
Data Envelopment Analysis (DEA) is applied to determine the main constraint of the system. DEA is a mathematic technique that allow the construction of an efficient border, or empirical production function from data of a set of studied units, where the units which are into the border are called "efficient units" and the other are called "inefficient units". DEA allows one to evaluate the relative efficiency of each unit in the study. [27] Figure 1 shows the efficiency of the processes of the textile production plant evaluated by using DEA. The units in the figure are the ratio of efficiency of each process with respect to those belonging to the efficiency frontier (most efficient).
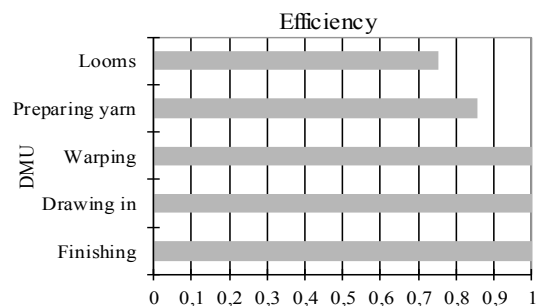

Figure 1. DEA analysis (Data Envelopment Analysis) Textile Process.
Source: Authors ´contribution

The figure shows that the process of looms, with an indicator of 0.754, is the least efficient of all and the furthest away from the efficiency frontier. Therefore, it is determined that the process of looms is the bottleneck of the system.

Step 2: Decide how to exploit the system constraints:

Calculate the contribution margin (CM) of each product, the selling price minus costs of raw materials (RM).

The throughput (contribution margin), as stated by the procedure, ignores the processing costs which can have, in many cases, a high impact on total cost. The difference in profitability of different products, depending on technical characteristics and the required processes, can also be established.

Therefore, it is proposed to calculate the contribution margin as the difference between the sales price and manufacturing costs with the objective to arrive at a model. This model might be considered when making scheduling and production decisions at the operational and strategic levels, and might also be used to obtain results comparable with the determination of the optimal product mix using the traditional methodology of operations research focused on the strategic level.

In this way:

$$CM_i = SP_i - UC_i \qquad (1)$$

Where:

CM_i = Contribution margin per kilogram of product i.
SP_i = Selling price per kilogram of product i.
UC_i = Manufacturing Unit Cost per kilogram of product i.

Calculate the relation between the contribution margins of the products per processing time at the bottleneck resource (CM/BN).

The formula below might be used to get the contribution margin per unit of time in the bottleneck resource, taking into account the description of the problem and using some of the considerations presented in [28] regarding the numerical relations to calculate the capacity of a weaving (the Looms process):

$$(CM/BN)_i = \frac{(SP_i - UC_i)gm_i rpm_i el_i lo_i}{100000 dw_i} \qquad (2)$$

Where:

$(CM/BN)_i$ = Contribution margin of product i per unit of time in the bottleneck resource.
gm_i = Weight in grams per meter of product i
rpm_i = Average speed in revolutions per minute of the looms on which product i is processed.
el_i = Efficiency in the loom of product i
lo_i = Loom simultaneous outputs when product i is processed.
dw_i = Density in wefts/centimeters in product i.

The constant 100000 corresponds to the conversion of units: 100 match centimeters of dw_i to the meters of gm_i and 1000 for the consistency between grams of gm_i and kilograms of $(SP_i - UC_i)$.

The the capacity of the bottleneck resource must be reserved sorting the products in descending order according to the relation CM/BN, until capacity is depleted.

In this step, a ranking of profitability per unit of time of the different products must be established until the capacity of the bottleneck resource is depleted, in descending order, starting with the product with the highest contribution margin.

The problem is compounded when, as happens in textile weaving, there are multiple parallel machines with different capacities, and product differentiation depends on the technical specifications of the loom on which textiles are weaved. It must then be considered that the parallel machines as unrelated.

The decision, therefore, is not only related to the distribution of productive capacity among a set of jobs waiting to be processed on a resource. An optimal distribution of work is required, that meets the criterion of maximizing total contribution margin, and the scheduling of resources according to technical features taking into account the limitations of the market and the availability of raw materials.

The optimization model is thus formulated:

$$\text{Maximize } z = \sum_{l=1}^{s}\sum_{i=1}^{n}(CM/BN)_i y_{il} \qquad (3)$$

Subject to:

Capacity constraints:

Assuming a month of thirty working days, 24 hours a day, 60 minutes per hour:

$$\sum_{i=1}^{n} y_{il} \le 60 \cdot 24 \cdot 30 \quad l = 1,2,...,s \qquad (4)$$

Market constraints:

$$\sum_{l=1}^{s} \frac{gm_i rpm_i el_i lo_i}{100000 dw_i sr_i} y_{il} \le U_i \qquad (5)$$

Raw material constraints:

$$\sum_{i=1}^{n}\sum_{l=1}^{s} \frac{gm_i rpm_i el_i lo_i}{100000 dw_i sr_i} r_{ik} y_{il} \le R_k \qquad (6)$$

Non-negativity condition:

$$y_{il} \ge 0 \quad i = 1,2,..., n \; l = 1,2,..., s \qquad (7)$$

Where:

z = Total contribution margin
$(CM/BN)_i$ = Contribution margin of product i per every minute of work in the loom.
y_{il} = Minutes for product i on loom l.

i = Product.

n = Total amount of products.

dw_i = Density in wefts/centimeters of product i.

sr_i = Size of roll of product i (kilograms).

gm_i = Linear weight of product i (grams/meters).

el_i = Efficiency in looms of product i (ratio of 0 (not efficient) and 1 (fully efficient)).

lo_i = Number of loom outputs used simultaneously on a loom to make product i.

rpm_l = Loom speed l (revolutions per minute).

l = Loom.

s = Total number of looms.

U_i = Maximum demand of product i. (rolls).

r_{ik} = Demand of raw material k in kilograms per roll of product i.

R_k = Available kilograms of raw material k.

k = Raw material.

q = Total amount of raw material.

This model, according to the initial philosophy of TOC heuristics, must be resolved by sorting products from the highest to the lowest contribution margin. The proposed algorithm includes a flexibility indicator of the loom as a criterion for job assignation. The total of minutes required by each process is distributed among the looms to complete the maximum rolls of each product, taking into account technical constraints:

Step 1: Sort products from the highest to the lowest value of CM / BN.

Step 2: Calculate the flexibility indicator in each loom. This is calculated as the result of dividing the number of groups in which the loom is scheduled by the lower number of looms among all the groups where the loom belongs. For example the flexibility indicator of a loom that belongs to a group of 6 looms and a group of 3, will be 2/3. And the flexibility indicator of another loom that belongs to two groups of 4 and a 5 looms, will be 3/4.

Step 3: Sort in ascending order the looms according to the flexibility indicator calculated in step 2. In the above example the first loom is better sorted (indicator = 2/3) than the second loom (indicator = 3/4). This rule favors products that can be manufactured in very few looms and these looms should be scheduled only as needed. Similarly, the looms with the highest flexibility are assigned at the end thereby facilitating the scheduling of more products.

Step 4: Assign the first product of the current list to the first of the available looms with capacity to manufacture. The assignment corresponds to the lower value in rolls equal to the available capacity on the loom, the maximum demand of the unscheduled product, and the availability of raw material for this product. Then subtract the assigned value from the available capacity of the loom, from the maximum product demand and from the availability of raw materials.

$$y_{il} = \min(cap_l, dem_i, rm_k) \qquad (8)$$

Where:

y_{il} = Job assignment i to loom l

cap_l = Available capacity in loom l

dem_i = Maximum demand of product i

rm_k = Raw materials k

Step 5: When maximum demand is not covered with one loom, continue to the next loom. When maximum demand is covered, the product should be removed from the list and return to step 4. Continue until the list of products is exhausted.

At the end, a detailed product assignation of each of the productive resources must be obtained considering market constraints, raw materials and machine capacities. The algorithm is based on the original TOC heuristics and tries to respect its main premises. A general integer optimization algorithm might be applied based on the model presented in expressions (3) a (7) (such as the hybrid genetic simplex introduced in [28]).

Thus, it is necessary to depart from the standard procedure of the Theory of Constraints to achieve the optimal product mix, following strategies such as those by different authors who have proposed modifications to the model and to the algorithm; among which are worth mentioning: Lee and Plenert (1993) [18], Hsu and Chung (1998) [29], Onwubolu (2001) [23], Onwubolu and Mutingi (2001) [25], Vasant (2004) [29], Mishra, Prakash, Tiwari, Shankar, and Chan (2005) [24], Bhattacharya and Vasant (2007) [30] and Linhares (2009) [26].

As noted at the beginning, works about the optimal product mix under the Theory of Constraints require different working conditions in the textile industry. So, an application of some of the findings made by the authors to the problem under study must be reviewed and adapted to the particularities of the production of textiles.

It is also worth noting that the theory of constraints in general and its method of determining the optimal product mix in particular are aimed at the operation of production rather than the strategic direction of the company. Thus, its philosophy, although it has been extended to the entire business context, does not correspond at all with the objective of directing the marketing policy, but to improve productivity in the operation plant.

3. Numerical Example

The following tables summarize an example of the application of the algorithm to a case in the textile industry.

Table 1.
Product information

Product	V	W	X	Y	Z
Looms group	B	A	C	E	D
Fill Yarns / cm.	10.4	24.4	15	15	5.83
Actual Efficiency (%)	40.9	48.3	57.1	57.1	45.7
Outputs	1	1	2	2	1
1st Raw Material (code)	1	3	4	4	2
x100 kg 1st Raw Material / roll	1.2	1	0.9	1	3.3
2nd Raw Material (code)			5	5	
x100 kg 2nd Raw Material / roll			0.4	0.5	
Max Sales (rolls)	8	89	18	25	59
Profit / roll	19.8	30.5	11	21.5	20.5
Roll length (mts)	200	300	300	700	1,025

Source: Authors' contribution

Table 2

Machines information

Looms Group	Looms in group	Production / month
A	1	11.23
B	1, 2, 4, 5, 6	56.16
C	1, 3, 8	34.13
D	3, 10	23.33
E	1, 3, 7, 8, 9	56.59
All	1,2,3,4,5,6,7,8,9,10	113.18

Source: Authors´ contribution

Table 3
Raw Material Information

Raw Material	Availability (ton)
1	20
2	20
3	20
4	20
5	20

Source: Authors ´contribution

Table 1 summarizes the technical information of the products, including the group of looms (to compare to Table 2), the density of the fabric in wefts per centimeter (important for speed), the actual efficiency of the product in the machines, the simultaneous product outputs on the looms, raw materials (to compare with Table 3), amount of raw material in a roll of fabric, market restrictions in rolls, the profit per unit and the length of the fabric roll in meters.

Table 2 describes the group of looms, identifying both the looms included in each group and its total production capacity in millions of wefts

Table 3 summarizes the availability of Raw Material. It is an important constraint in industries such as technical textiles where suppliers are in distant countries and immediate availability is required to improve response times.

The exact mathematical model would be as follows:

$$\text{Max } W = 0.024676(Y_{11}+Y_{12}+Y_{14}+Y_{15}+Y_{16}) + 0.010833(Y_{21}) + 0.006430(Y_{31}+Y_{33}+Y_{38}) + 0.005373(Y_{41}+Y_{43}+Y_{47}+Y_{48}+Y_{49}) + 0.009277(Y_{53}+Y_{510})$$

Subject to:

$Y_{11}+Y_{21}+Y_{31}+Y_{41}$	$\leq 43{,}200$
Y_{12}	$\leq 43{,}200$
$Y_{33}+Y_{43}+Y_{53}$	$\leq 43{,}200$
Y_{14}	$\leq 43{,}200$
Y_{15}	$\leq 43{,}200$
Y_{16}	$\leq 43{,}200$
Y_{47}	$\leq 43{,}200$
$Y_{38}+Y_{48}$	$\leq 43{,}200$
Y_{49}	$\leq 43{,}200$
Y_{510}	$\leq 43{,}200$
$0.000511(Y_{11}+Y_{12}+Y_{14}+Y_{15}+Y_{16})$	≤ 8
$0.000172(Y_{21})$	≤ 89
$0.000668(Y_{31}+Y_{33}+Y_{38})$	≤ 18
$0.000285(Y_{41}+Y_{43}+Y_{47}+Y_{48}+Y_{49})$	≤ 25
$0.009277(Y_{53}+Y_{510})$	≤ 59
$0.61306(Y_{11}+Y_{12}+Y_{14}+Y_{15}+Y_{16})$	$\leq 20{,}000$
$0.17153(Y_{21})$	$\leq 20{,}000$

$$0.068161(Y_{53}+Y_{510}) \leq 20{,}000$$
$$0.060157(Y_{31}+Y_{33}+Y_{38})+0{,}066842(Y_{41}+Y_{43}+Y_{47}+Y_{48}+Y_{49}) \leq 20{,}000$$
$$0.011400(Y_{31}+Y_{33}+Y_{38})+0{,}014249(Y_{41}+Y_{43}+Y_{47}+Y_{48}+Y_{49}) \leq 20{,}000$$

$Y_{11},Y_{12},Y_{14},Y_{15},Y_{16},Y_{21},Y_{31},Y_{33},Y_{38},Y_{41},Y_{43},Y_{47},Y_{48},Y_{49},Y_{53},Y_{510},$ ≥ 0 and integers

Following the procedure introduced in this paper, where products are sorted by their contribution margin per unit of time in the bottleneck resource and machines are assigned in order of flexibility index (*FI*) calculated as explained in the Methodology section, as is shown in Table 4. Shadowed cells are the minor group of looms for each loom. The final solution of the example is presented in Table 5.

Table 4
Flexibility Index Calculation

Loom	Groups					All	Groups /Loom Numerator	FI
	A	B	C	D	E			
2		1				1	1	0,2
4		1				1	1	0,2
5		1				1	1	0,2
6		1				1	1	0,2
7					1	1	1	0,2
9					1	1	1	0,2
10				1		1	1	0,5
8		1			1	1	2	0,7
3			1	1	1	1	3	1,5
1	1	1	1		1	1	4	4
Looms /Group	1	5	3	2	5	10	Denominator	

Source: Authors´ contribution

Table 5.
TOC Heuristic solution.

Product			V	W	Z	X	Y	
Variable			x1	x2	x5	x3	x4	
Profit $ / minute			0.025	0.011	0.009	0.006	0.005	Total
min / roll			1,957	5,830	4,842	1,496	3,509	
Sales (rolls)			8	89	59	18	25	
min/month	loom	F I	Rolls	Rolls	Rolls	Rolls	Rolls	
43200	7	0.2					12	42,107
43200	9	0.2					12	42,107
43200	2	0.2	8					15,659
43200	4	0.2	0					0
43200	5	0.2	0					0
43200	6	0.2	0					0
43200	10	0.5			8			38,732
43200	8	0.7				18	1	30,438
43200	3	1.5			8	0	0	38,732
43200	1	4	0	7		0	0	40,810
Total			8	7	16	18	25	
Total Profit			158.1	213.7	328.5	197.6	538	1,436

Source: Authors ´contribution

Table 6.
Benchmarking Heuristic TOC versus Branch and Bound.

Problem	2	3	4
Variables (Products)	43	44	15
Constraints	100	100	41
Time B&B (secs)	243	124287	488
Time TOCh (secs)	<1	<1	<1
Óptimal TOCh	953.6	276.1	4,218.4
Óptimal B&B	1,039.4	287.1	4,406.1
TOCh/B&B	91.74%	96.16%	95.74%

Source: Authors´contribution

4. Results

Besides the example presented, different tests were made with heuristics based on the Theory of Constraints for an optimal product mix. The heuristic is used actually by a real textile company to make its aggregated planning. To test the utility of the heuristic in real environments, it three examples with real data were taken. The results are compared against the same cases using integer linear scheduling and solved by the Branch and Bound algorithm. The examples, from a real textile factory, can be downloaded in text format from https://db.tt/4EMzWnmk. The TOC Heuristic was implemented in Visual Fox Pro[32]. For the benchmark with Branch and Bound the LP-ILP 2.0 module from WinQSB [32]was used. Both programs were executed on the same computer. A detailed description of the tested cases can be downloaded from https://db.tt/8xcpBTRd. Table 6 summarizes the results.

It can be seen that the TOC heuristics gets results slightly below than the ones obtained with the Branch and Bound method. However, when compared to the detailed results of the Branch and Bound method, it is observed that the same values are achieved in many variables, especially in the first of the sorted list of references in descending order of contribution margin per minute. However, it is disconcerting to see that high values are assigned to some references that are at the bottom of that list.

This behavior has been studied in the scientific literature which states that TOC heuristics reaches the absolute optimum only when there is a constraint that falls far apart from other productive resources in performance [24].

Heuristic generates an array of products depending on their profitability per unit of time, which may be useful as prioritization criteria in trade policy and in infrastructure investment.

This procedure is implemented in planning, scheduling and production control software in a textile company and it is used as complementary criteria to prioritize deliveries and sales effort.

5. Conclusions

TOC heuristics is a planning tool of low computational cost with a good performance level that can be used for detailed production scheduling in different contexts.

TOC heuristic requires adaptations for a Flexible Hybrid Flow Shop, and in particular for the textile industry, especially for the parallelism conditions of the machines in the bottleneck stage.

The flexibility index introduced in this paper is a measure of the machine capacity to process different products that must be used to reserve the most flexible resources for specialized products without sacrificing productivity.

It is suggested to calculate the throughput as the difference between the selling price and the cost of processing instead of using Goldratt's formula which takes into account only the cost of raw materials.

Although the heuristic of the Theory of Constraints does not get close enough to the global optimum of the optimal product mix problem, it provides an overview of the classification of the products in ascendant order of profits. This overview might be useful in strategic market direction and capacity expansion projects.

When considering the details of scheduling in the plant, TOC heuristics are more specific and operational than models of linear programming. In addition, TOC heuristics are easy to implement since they do not involve complex calculations.

6. Acknowledgments

References

[1] Montoya-Torres, J. R.; Soto-Ferrari, M.; Gonzalez-Solano, F. Production Scheduling with Sequence-Dependent Setups and Job Release Times. Dyna, 77 (163), pp. 260-269, 2010.

[2] Zandieh, M.; Karimi, N. An Adaptive Multi-Population Genetic Algorithm to Solve the Multi-Objective Group Scheduling Problem in Hybrid Flexible Flowshop with Sequence-Dependent Setup Times. J Intell Manuf. 22(6), Pp 979-989, 2010.

[3] Qiao, P.; Sun, C. Research On Hybrid Flow Shop Scheduling Problem Based On Improved Immune Particle Swarm Optimization. In: 2nd International Conference on Artificial Intelligence, Management Science and Electronic Commerce (Aimsec), Pp 4240-4243, 2011.

[4] Yue-Wen, F.; Feng-Xing, Z.; Xiao-Hong, X.; Qing-Zhu, C.; Jia-Hua, W. Hybrid Flow Shop Scheduling Method Based on Multiagent Particle Swarm Optimization. In: International Conference on Information and Automation, Pp 755-759, 2011.

[5] Yalaoui, N.; Mahdi, H.; Amodeo, L.; Yalaoui, F. A Particle Swarm Optimization under Fuzzy Logic Controller to Solve a Scheduling Problem. In: International Conference on Communications, Computing and Control Applications (Ccca), 2011, Pp 1-6, 2011.

[6] Hidri, L.; Haouari, M. Bounding Strategies for the Hybrid Flow Shop Scheduling Problem. Applied Mathematics and Computation, 217, Pp 8248-8263, 2011.

[7] Gómez Gasquet, P. (2010). Programación de la Producción en un Taller de Flujo Híbrido Sujeto a Incertidumbre: Arquitectura y Algoritmos. Aplicación a La Industria Cerámica. Tesis Doctoral.

Universidad Politécnica de Valencia. Departamento de Organización de Empresas. 988 p., 2010.

[8] Guinet, A. Textile Production Systems: A Succession of Non-Identical Parallel Processor Shops. The Journal of the Operational Research Society, 42 (8), Pp. 655-671, 1991.

[9] Zhang, X.; Van De Velde, S. Approximation Algorithms for the Parallel Flow Shop Problem. European Journal of Operational Research, 216, Pp 544-552, 2012.

[10] Driessel, R.; Mönch, L. Variable Neighborhood Search Approaches for Scheduling Jobs on Parallel Machines with Sequence-Dependent Setup Times, Precedence Constraints, and Ready Times. Computers and Industrial Engineering, 61, Pp 336-345, 2011.

[11] James, R. J. W.; Almada-Lobo, B. Single and Parallel Machine Capacitated Lotsizing and Scheduling: New Iterative Mip-Based Neighborhood Search Heuristics. Computers and Operations Research, 28, Pp 1816-1825, 2011.

[12] Lin, S-W; Lee, Z-J; Ying, K-C; Lu, C-C. Minimization of Maximum Lateness on Parallel Machines with Sequence-Dependent Setup Times and Job Release Dates. Computers and Operations Research, 38, Pp 809-815, 2011.

[13] Chang, P-C; Chen, S-H. Integrating Dominance Properties with Genetic Algorithms for Parallel Machine Scheduling Problems with Setup Times. Applied Soft Computing, 11, Pp 1263-1274, 2011.

[14] Arango, J. A; Giraldo, J. A.; Castrillón, O. D. Programación de Máquinas Paralelas no Relacionadas con Tiempos de Montaje Dependientes de la Secuencia y Entrada Dinámica usando Algoritmos Genéticos. Revista Información Tecnológica 24(3), pp. 73-84, 2013.

[15] Castrillón, O. D.; Sarache, W.; Giraldo, J. A. Job Shop Methodology Based on an Ant Colony. Dyna, 76(159), pp. 177-184, 2009.

[16] Goldratt, E. M. The Goal. North River Press, 1984.

[17] Fredendall, L. D.; LEA, B-R. Improving the product mix heuristic in the theory of constraints. International Journal of Production Research, 35(6), 1997.

[18] Lee, T. N.; Plenert, G. Optimizing theory of constraints when new product alternatives exist. Production and Inventory Management Journal, 1993.

[19] Lea, B-R; Fredendall, L. D. The impact of management accounting, product structure, product mix algorithm, and planning horizon on manufacturing performance. International Journal of Production Economics, 79, 2002

[20] Mabin, V. J.; Davies, J. Framework for understanding the complementary nature of TOC frames: insights from the product mix dilemma. International Journal of Production Research, 2003.

[21] Aryanezhad, M. B.; Komijan, A. R. An improved algorithm for optimizing product mix under the theory of constraints. International Journal of Production Research, 42(20), 2004.

[22] Souren, R.; Ahn, H.; Schmitz, C. Optimal product mix decisions based on the Theory of Constraints? Exposing rarely emphasized premises of Throughput Accounting. International Journal of Production Research, 43(2), 2005.

[23] Onwubolu, G. C. Tabu search-based algorithm for the TOC product mix decision. International Journal of Production Research, 39(10), 2001.

[24] Mishra, N.; Prakash; Tiwari, M. K.; Shankar, R.; Chan F. T. S. Hybrid tabu-simulated annealing based approach to solve multi-constraint product mix decision problem. Expert Systems with Applications 29, 2005.

[25] Onwubolu, G. C.; Mutingi, M. Optimizing the multiple constrained resources product mix problem using genetic algorithms. Production Planning and Control. 12(1), 2001.

[26] Linhares, A. Theory of constraints and the combinatorial complexity of the product-mix decision. International Journal of Production Economics, 2009.

[27] Coll, V.; Blasco, O. M. Evaluación de la eficiencia mediante el análisis envolvente de datos. Juan Carlos Martínez Coll, 2006.

[28] Arango M., J. A. Determinación de la Mezcla Óptima de Productos para una Tejeduría Textil. Revista Scientia Et Technica, 15(42), 2009.

[29] Hsu, T.-C.; Chung, S.-H. The TOC-based algorithm for solving product mix problems. En: Production Planning and Control, 9(1), 1998.

[30] Vasant, P. Optimization in Product Mix Problem Using Fuzzy Linear Programming, 2004. On line. Date of consult: May, 2013. Available on: http://www.generation5.org/content/2004/data/productMix.pdf

[31] Bhattacharya, A; Vasant, P. Soft-sensing of level of satisfaction in TOC product-mix decision heuristic using robust fuzzy-LP. European Journal of Operational Research, 177, 2007.

[32] Microsoft. Visual FoxPro 9.0. Microsoft Corporation, 2004

[33] Chang, Y-L. Winqsb: decision support software for MS/OM. John Wiley & Sons Inc, 1998.

J. A. Arango-Marín, is an Industrial Engineer from the Universidad Tecnológica de Pereira (1986) and Magister in Operational Research and Statistics also from Universidad Tecnológica de Pereira. Currently he is a PhD candidate in Engineering at the Universidad Nacional de Colombia. From 1987 to 2007, he worked in several companies in the industrial, services, educational and government fields. Since 2008 he is an Associated Professor in the Industrial Engineering Department at the Engineering and Architecture Faculty in the Universidad Nacional de Colombia in Manizales. His research interests include Scheduling, Metaheuristics, Inventory Models, Logistics and Production Management.

J. A Giraldo García, is an Industrial Engineer from the Universidad Nacional de Colombia and has a PhD in Engineering at the Universidad Nacional de Colombia. Since 1983, he works as a Professor at the Industrial Engineering Department of the Engineering and Architecture Faculty in the Universidad Nacional de Colombia at Manizales. His research interests include Scheduling, Metaheuristics, Simulation and Software Development

O. D. Castrillón-Gómez, Is a Systems Engineer with specializations in Management and Quality and a PhD in Bioengineering. Since 2005, he works as a professor at Industrial Engineering Department of the Engineering and Architecture Faculty in the Universidad Nacional de Colombia at Manizales. His research interests include Scheduling, Metaheuristics, Simulation and Mathematical Modeling.