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A new heuristic algorithm to solve product-service mix analysis in enviroments with mobile bottlenecks and shared resources based on GTBM method

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***Abstract*— In this paper a new heuristic algorithm based on the GTBM (Global Throughput Buffer Management) method is proposed questioning the Theory of Constraints which was originally published in the early 90´s and also the method of dominant throughput applied in environments with shared resources and bottlenecks with variable location. It has been based on the typical configuration of discrete flow processes with parallel activities unbalanced and a simulation for comparative information was made. The effectiveness of 70.88% that is associated with PMA/GTBM algorithm versus TOC classic method is not negligible and after 1000 iterations random is possible to obtain sufficient confidence that there is no doubt to be taken into account. However, it remains a heuristic algorithm and, as such, is not 100% conclusive. Yet 29% of TOC classic method iterations allows a better solution.**

***Keywords—Global Throughput Buffer Management, Theory of Constraints, Mobile Bottlenecks, Product-Service Mix Optimization*.**

I. INTRODUCTION

The production mix analysis about finished goods and services is a classic research problem of interest to industry, especially when Lean Thinking organizations pretend to improve the economic value of their processes.

GTBM (Global Throughput Buffer Management) is a theoretical model that considers these potential losses and to calculate more realistically the actual economic throughput of a value stream [1]. From a quasi-experimental simulation of discrete event, in this article a heuristic procedure is supported to determine the production mix that achieves maximum ROI in environments with shared resources and no fixed bottle necks.

In the first part of this paper, a literature review is prepared and then a critique of traditional models that solve this problem is presented.

Subsequently, the approach of a new algorithm is presented and then the results of a discrete event simulation are analyzed, in which changes are evident in the mixed solution that provides higher gross profit. Finally the findings are discussed to make conclusions and recommendations.

II. LITERATURE REVIEW

A. The TOC approach of the Production Mix Problem

The optimization of the production mix that responds to a product-service mix in any company has been studied for many decades, because the profit must always be related to the installed capacity and gross margin generated by the products-services sold [5].

In the 50's, after World War II, there was a growth of mathematical models based on linear algebra that took force in quantitative methods of capacity analysis [6]. Since then, linear programming, integer programming, dynamic programming and transport models are widely spread, however, their deterministic rigidity and assumptions about the space of possible solutions were taken to explore other heuristic and stochastic approaches (given the nature of geometric growth of the possibilities of solution especially when it comes to many product lines-services and many sources of variability in productive resources) [7].

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Most models have attempted to solve the problem using the paradigm of costs, that is, assuming that seeking costs minimization, return on investment (ROI) must necessarily be higher; thus, in mathematical models it is often the objective function cost minimization [8]. In addition, the restrictions involved are usually established from availability of productive time in each resource regardless of the route of the process or dependency relationships (which may be different for different products) [5].

The Theory of Constraints (TOC), proposed by Eliyahu Goldratt (1947-2011) at the beginning of the 90 states that economic throughput, ie the gross contribution margin per unit of time, should be the critical variable analysis as opposed to only costs [3]. It states that the product mix and production mix should seek to maximize profitability as a key indicator, which is determined as the Economic Throughput minus operating expenses, all divided by investment (inventories) [4]. In a deterministic world, comparing product mixtures depend on the Economic Throughput, leaving operating expenses and investment as constants. In a stochastic reality, all variables are subject to variability and, therefore, the mixture which provides greater profitability will be maintained in a specific population data which in turn should be compared with the populations associated with other possible mixtures.

The TOC approach has been studied extensively and provides results more attached to reality than the classical approach of linear programming and the like. However, it remains on the thesis that the dominant throughput, heuristically, provides higher profitability by more than 90% of cases [9].

B. Math complexity of real life context and the Key Throughput approach

When the system maintains one bottleneck (according to the Theory of Constraints) no matter what the product-service mix and production mix is used, the problem is solved by assigning as many as possible to the product that provides greater economic throughput, calculated from the output in the bottleneck. This bottleneck, as established by TOC, is that resource whose demand exceeds its rate of production service [5].

Actually, this is a simplification and it's useful to define more specifically where there is a bottleneck in the flow of value stream [11]:

1. The bottleneck may be in the resource with increased workload (relationship between production load hours versus hours available).
2. The bottleneck may be in the resource with as many levels of dependency. Which is the same as saying that a resource can be very fast and have many hours available for production and yet become a bottleneck when all production flows through the possible routes must pass through it with logistical implications impeding the value stream.
3. The bottleneck can be the resource that has the greatest variability in productivity. In other words, it can be a resource that has a lot of availability, a large production rate and has few relationships of dependence and, however, be bottleneck due to the high variability in throughput generated.
4. The bottleneck may be in the resource with the lowest rate of production.
5. The bottleneck can be the resource that has a combination of the above four attributes.

As you can see, there are shared resources between different production routes that, due to their levels of dependency and what these levels cause in their workload, can become bottlenecks temporarily. If, to this is added that the possibility of variability also become the bottleneck for some periods of time, it is clearly likely moving bottlenecks depending on the production mix [10].

In this scenario, it is widely used Stein's algorithm [2] which is based on heuristically find the dominant throughput in the production mix, and from this point, calculate the return on investment generated. The dominant throughput is established from the gross contribution margin per unit time in the output of the bottleneck.

This method, although it is widely used, does not take into account two key elements. The first is that there are significant differences between the Economic Throughput calculated from the production rate of the bottleneck and Economic Throughput calculated from the output rate of the value stream. Second, the Global Economic Throughput, calculated as a weighted average of all economic throughputs of the products may differ significantly from the dominant throughput. On these two foundations it is that a new heuristic algorithm (for solving the problem of product-service mix and production mix allowing greater profitability) is proposed.

III. GTBM PERSPECTIVE AND A NEW HEURISTIC ALGORITHM FORMULATION

Global Throughput Buffer Management (GTBM) is an analytical perspective of economic throughput that questions the traditional way of calculating this indicator by the classical theory of constraints, that is, from the output of the bottleneck of a supply system. GTBM, in contrast, argues that must be calculated from the exit of the value stream according to the output rate of the products calculated as the inverse of takt time [1].

For a supply system, which typically has shared resources and productivity rates are subject to variability, global economic throughput can be recalculated under the GTBM perspective and consider the analysis of the overall weighted average of throughput for a production mix as follows:

1. Calculating the root mean square of the variation between the production rate of the value stream with respect to bottleneck´s economic average throughput.
2. Calculate the weighted average throughput with respect to the proportional value of the amount allocated by each production mix being analyzed.
3. Select the production mix with the highest weighted average throughput.
4. Calculate the expected profit and return on investment for selected production mix.

The above steps establish the Production Mix Algorithm based on GTBM Method (PMA/GTBM) that has been designed from the assumptions of variability in production rates of all resources and the existence of shared resources along the path. To test its potential benefits, the results of a quasi-experimental simulation based on a typical assembly process of electronic devices are presented below.

IV. SOME EVIDENCES OF IMPROVEMENT

The findings in a quasi-experimental simulation data based on typical industrial electronics components assembly plant are presented below. The framework of Pallisade Suite 5.5 software was used. The basic assumptions of the study case used for the simulation model are:

a) Discrete Event Simulation was used.
b) Comparison of the typical dominant throughput algorithm of classical TOC versus PMA / GTBM proposal.
c) From a representative, random sample of 385 production orders processed in 2014 (sample size determined with an error of 5% and 95% statistical significance) frequency distributions were determined from exploring goodness setting multiple possible statistical models.
d) Application of the algorithm of the Dominant Economic Throughput[2] and Weighted Average Global Throughput algorithm calculated by the traditional method of the Theory of Constraints; 1000 iterations random.
e) Application of the PMA//GTBM Algorithm, 1000 iterations random.

A. Simulation context caracterization

The company has been selected as a case study is dedicated to the production of electronic devices with total assets reaching 125 million USD$ and the minimum desired ROI is 15% after payment of interest and taxes, which are estimated at 110 000 USD$ per month. In addition, 30% tax on income and total operating expenses amounted to 3 000 000 USD$ per month paid.

The company produces and sells three types of devices: P, Q and S; always maintaining a corporate mix proportion of 5: 1 between the more it is produced and sold and other products. In the production routes, there are involved 7 types of machines with different standard production times that have already been adjusted for scrap and rework (using Markov Chains) and, besides being shares resources, operated by different persons. In addition, there are standard production times calculated by part processed, except the final operations in order to produce P, Q and S, where the standard times are calculated by full assembly and operation machining: M4 and M5 respectively.

The devices require the production of its components-X, W, and Z. In addition, two machines called M1 and M2 generate a waste of 10% (each X wasted material can be sold as second at $ 20 / unit) and a 17% rework of M4 to M6 in the production of P is produced; because when it joins X to Z in the M4 machine, air bubbles which cause defects in the products P but that can be corrected again in the machine 6 in the path of the sub-component Z occur (each wasted Z must be treated for responsible disposal at a cost of $ 6.5 each).

Each device type P sold 850 USD $ each; the Q type sold 368 USD$ the unit and the type S, 390 USD $ each; machine minutes available vary and include scheduled stops. Production routes, resources involved and relevant data are presented below.

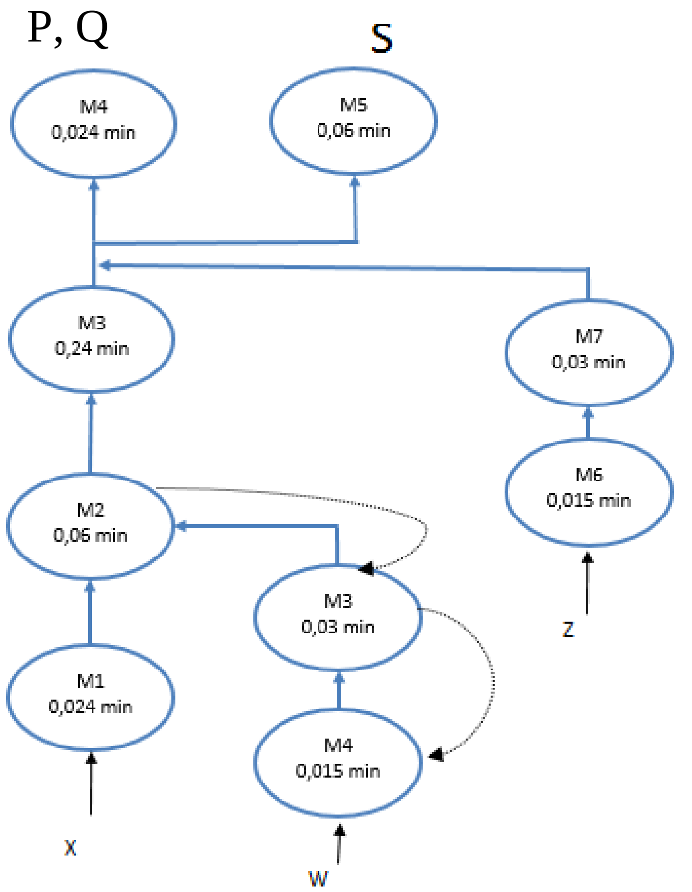

Fig. 1. Production routes and relevant resources involved in the case study.

TABLE I. BILL OF MATERIALS

Bill of Materials	Sub-components			
	Product or Sub-component	***X***	***W***	***Z***
	P	1	0	15
	Q	1	1	1
	S	1	1	1
	Material costs in **$ / part** without adjustment of rework and scrap	75	45	25

TABLE II. AVAILABILITY AND SCRAP PER MACHINE

Availability and Scrap per machine	Machines							
	Key Process Indicator (KPI)	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**
	Availability (Minutes)	12500	10000	8500	9500	10000	9500	8500
	% SCRAP	10%	10%	0%	0%	0%	5%	5%

B. Results

The simulation model shows evidence substantive differences between classical heuristics of the theory of constraints, which is based on the dominant throughput in the production mix (through product-service that contributes most to the gross contribution margin per minute) and the method of Weighted Average Global Throughput (WAGT) calculated from the output in the bottleneck.

In this case, it was found that the bottleneck is not fixed and alternates between M3 and M7. For the production mix 5P:1Q:1S, bottleneck is M7 while for mixtures 1P:5Q:1S and 1P: 1Q: 5S, M3 is the bottleneck. This does not change when a characteristic stochastic is left to the solution (due to the configuration of the loads in the process), however, the methods lead to different results for both the production mix that provides the highest ROI as to the amount of Economic Throughput anticipated and the resulting absolute ROI (return of investment).

For the classic method of TOC, the winning combination by calculating the Economic Throughput (from the output of the bottleneck) is 1P: 1Q: 5S and applying the method of selection of the highest Weighted Average Global Throughput (also calculated from output of the bottleneck), the production mix 5P:1Q:1S is selected.

In Table III, the non-stochastic results are presented. It can be seen that the total gross margin contribution is higher for classical TOC solution versus the weighted method and this is associated with a higher ROI expected; in this case, about 0.5% which suggests a virtual tie (although it can be higher up 21.3%).

TABLE III. SUMMARY RESULTS CLASSIC TOC VS WEIGHTED AVERAGE GLOBAL THROUGHPUT (NON-STOCHASTIC DATA)

CLASSIC TOC				**WEIGHTED AVERAGE GLOBAL THROUGHPUT**			
Mix	**1P:1Q:5S**	**QTY**	**Economic Throughput USD**	**Mix**	**5P:1Q:1S**	**QTY**	**Economic Throughput USD**
P		4569	$ 1,487,656.87	**P**		18398	$ 5,990,350.43
Q		4569	$ 944,392.74	**Q**		3679	$ 760,433.55
S		22849	$ 5,225,468.47	**S**		3679	$ 841,371.55
		TOTAL	$ 7,657,518.08			TOTAL	$ 7,592,155.52

Figure 2 shows the results for this difference about ROI (taking into account that these two methods assume the throughput of the value stream is equal to the one that comes from the bottleneck).

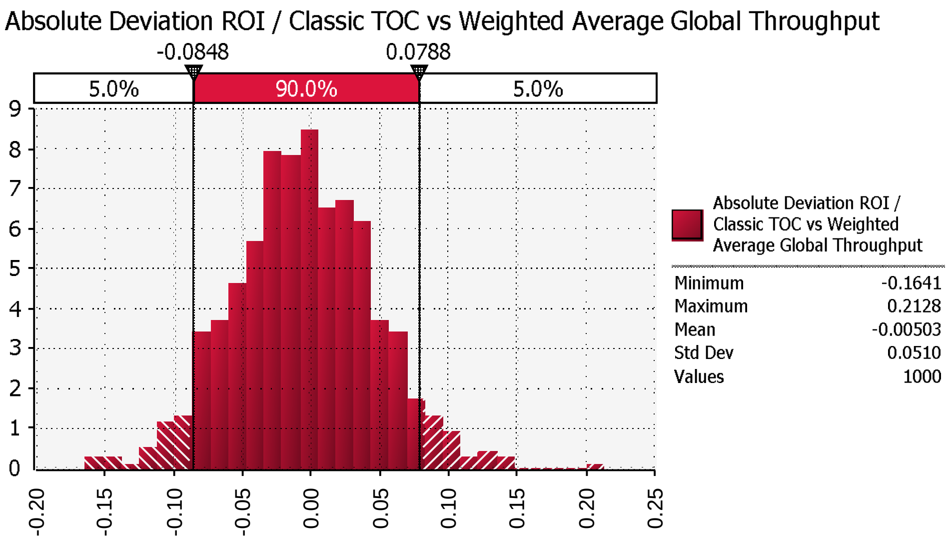

Fig. 2.Simulation Result of ROI Absolute Deviation between Classical TOC and Weighted average Global throughput .

Similarly, Figure 2 shows that after 1000 iterations (finding that production times fit well with Weibull and lognormal distributions and levels of Scrap fit well with normal distributions) remains a tie between ROI indicators achieved with the two methods. When making an Anderson-Darling test for the results of the 1000 iterations can be inferred that these differences are distributed according to a normal function with a reliability of 95% (p-value> 0.15) and the probability that the TOC classic method to obtain a higher ROI is 50%.

The assumption that the overall throughput of the value stream is equal to the output of the bottleneck is questioned plausibly by the GTBM method because it also depends on the variability of the resources that are no-bottlenecks and the path length of process [1]. Thus, in calculating the coefficient of variation between takt time of the value stream and bottleneck´s rate of production, differences between 12% and 20% were found. Applying these differences in calculating the respective Global Economic Throughput of M3 and M7 differences were identified in the solution provided by classical TOC which are shown in Table IV.

As seen, the production mix (selected by classical TOC) changes to 1P:5Q:1S while the solution provided by PMA/GTBM (5P:1Q:1S) remains. But at this stage, the difference in Economic Throughput is more than 350 000 $ USD and effectively is changed because the current throughput of production flow is not equal to the output of the bottleneck. Now the expected ROI with PMA/GTBM method not only corresponds with reality but is also higher than classic TOC (on average 3%, but can reach up to 22.3% as shown in Figure 3).

TABLE IV. SUMMARY RESULTS CLASSIC TOC VS PMA/GTBM (NON-STOCHASTIC DATA)

CLASSIC TOC				**PMA/GTBM**			
Mix	**1P:5Q:1S**	**QTY**	**Economic Throughput**	**Mix**	**5P:1Q:1S**	**QTY**	**Economic Throughput USD**
P		4569	$ 1,487,656.87	**P**		18398	$ 5,990,350.43
Q		22849	$ 4,722,790.47	**Q**		3679	$ 760,433.55
S		4569	$ 1,044,910.74	**S**		3679	$ 841,371.55
		TOTAL	$ 7,255,358.08			TOTAL	$ 7,592,155.52

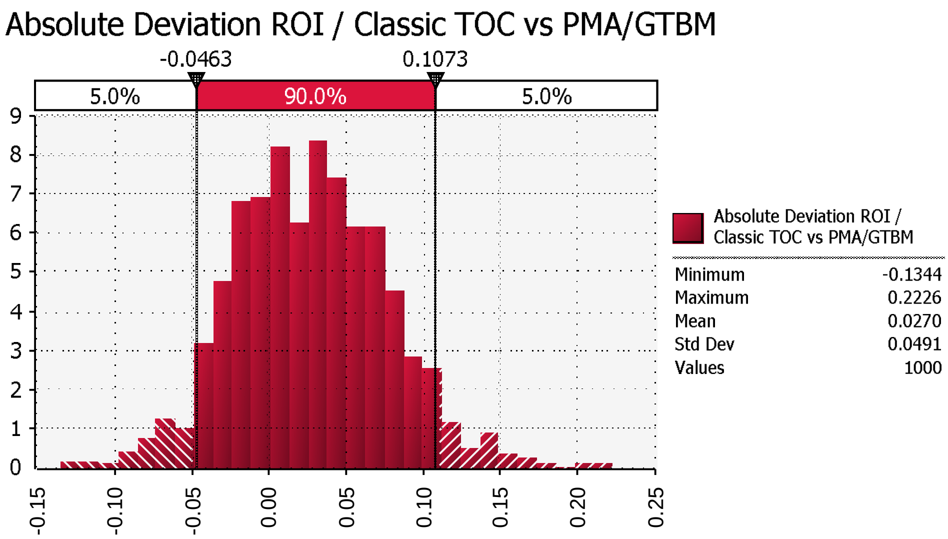

Fig. 3.Simulation Result of ROI Absolute Deviation between Classical TOC and PMA/GTBM.

Again, when making a Anderson-Darling test for the results of the 1000 iterations it follows that these differences are distributed according to a normal function with a reliability of 95% (p-value> 0.25) and the probability that the PMA/ GTBM method to obtain a higher return of investment (ROI) than the TOC Classic is 70.88%.

V. CONCLUSIONS AND FUTURE RESEARCH

The quasi-experimental simulation conducted for a production process of electronic devices with shared resources, rework, variability in production mix, resource availability and production time leads to the conclusion that the proposed algorithm based on GTBM method provides a more realistic view of the expected ROI on a value stream and determine the most effective production mix in terms of profitability.

The effectiveness of 70.88% that is associated with PMA/GTBM algorithm versus TOC classic method is not negligible and after 1000 iterations random is possible to obtain sufficient confidence that there is no doubt to be taken into account. However, it remains a heuristic algorithm and, as such, is not 100% conclusive. Yet 29% of TOC classic method iterations allows a better solution.

This leads us to raise other research questions. First, it seems necessary to perform simulations for cases with more than 100 or 200 items as happens in reality of many companies high mix-low volume and, thus, to determine whether there are variations in the results presented here.

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