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CAPACITY UNBALANCING AND TOTAL LOGISTIC COST

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ABSTRACT

This article presents a discussion about productive capacity balancing and its effects in the total logistical costs, suggesting a mathematical model for the optimization of the capacity structure. To propose the model a literature study based on journal articles and books were conducted, using Theory Of Constraints – TOC as the theoretical framework. At the end, the model suggests that the inventory costs, the coefficient of variation in processing time and the coefficient of variation in arrivals are the relevant variables to verify if the investment in extra capacity is feasible.

Keywords: *Unbalancing; capacity; constraint; inventory; cost*

1. INTRODUCTION

In manufacturing systems design, as well as in several engineering fields, there are practices that are rarely or hardly changed, either due the objectivity of its concepts, the practicality of its implementation, or simply by the success of a previous paradigmatic solution. This is the case of line balancing and capacity balancing. Being the dominant methodology since the dawn of the industrial revolution, capacity balancing is characterized by the pursuit of establishing a productive system in which all production centers have the same productive capacity among themselves. This practice, according to Souza & Pires (1999), is justified by the attempt to continuously maintain all features enabled, amortizing investments and seeking to establish a uniform material flow through the factory.

Such a technique had been first questioned in the 80's by Goldratt, who pointed out that not only the problems caused by unbalanced line, but by attempting to reach the global optimization of the system by optimizing the parts of the system, subsequently creating the Theory of Constraints, or Theory of Constraints – TOC (Goldratt, 1981). Since then, several authors (Atwater & Chakravorty, 1994; Chakravorty & Atwater, 1996; Craighead, Patterson, & Fredendall, 2001; Goldratt & Cox, 1984; Hopp & Spearman, 2011; Liu & Lin, 1994; Lopez, 2014; Millstein & Martinich, 2014; Pan et al., 2014; Shaaban, McNamara, & Hudson, 2014; Tenhiälä, 2011) studied ways to better manage their production systems by exploiting its constraints and many production lines ended up being naturally unbalanced or managed to ensure the existence of a single or few resources with capacity constraint, fully controlled and exploited for ensure maximum overall performance.

The unbalance of the line is obtained through protective capacity, characterized as a given amount of extra capacity added at non-constraints above the system constraint's capacity, used to protect against statistical fluctuations (Craighead et al., 2001).

Among the various studies done on the unbalancing there are a comparison between the performance of traditional balanced production lines versus the balanced lines run according to the methodology Just In Time - JIT and unbalanced lines run according to the TOC (Chakravorty & Atwater, 1996). Another study analyzed (Craighead et al., 2001) the impacts of positioning and layout of protective capacity on the performance of the production system and there was presented a quantitative approach that strengthens defense unbalance capacity over the traditional approach of balancing (Souza & Pires, 1999).

Still, even after a few decades of the publication of these first works, not so many projects for new plants took into account the imbalance, and even rarer interventions in existing production lines to add protective capacity with the goal of improving productive performance or minimize the logistics costs. After all, who in a good sense would make an investment for increasing the capacity of equipment in a plant to gain idle time? Is it worth investing in non-constraint equipment rather than adding capacity to the bottleneck? Does excess capacity in non-constraints influence the inventory level of the line?

This work has the objective of analyzing the implications of the capacity imbalance in the total performance of the production system, establishing criteria to facilitate decision-making regarding the allocation of capacity in serial production lines.

The first part of the work presents the basic principles of the Theory of Constraints and Capacity Imbalance. Then there will be assessed the impacts of additional capacity both in logistical and financial performance of the system to, finally, propose the framework decision on projects of capacity production systems.

2. A THEORY OF CONSTRAINTS AND CAPACITY UNBALANCING

The Theory of Constraints - TOC emerged from software created by the Israeli physicist Elyahu Goldratt for the product management of a friend's industry. This software (OPT - Optimized Production Technology) turned out to be very efficient, but its implementation was constantly diverging from practices and indicators commonly established. The commercialization of this software gave Goldratt the opportunity to confront their ideas with practices across industries. These experiences led him to extrapolate the application of TOC beyond the management of production, through accounting, marketing, managing people, projects, strategy, among other areas (Goldratt, 1996).

The basic principle of the Theory of Constraints is that companies are like systems and that, similarly to a chain, has the performance limited by the performance of its weakest element. Thus, in a production unit, there will always be a resource-constrained capacity, a bottleneck, which limits the performance of the process. The simplest way to manage a system, therefore, would be through the management of its constraint.

> In our reality any system has very few constraints (this is what is proven in The Goal, by the Boy-Scout analogy) and at the same time any system in reality must have at least one constraint.(Goldratt, 1990b)

One of the direct consequences of this statement is expected in relation to production systems of balanced capacity, since one would imagine that these systems do not have bottlenecks or restrictions and that might, therefore, have its optimum performance. However the natural statistical fluctuations of each step of the process act in a negative way with the overall result. Observing a hypothetical example of a system with two machines with the same productive capacity, A and B, with the normal variation between 9 and 11 units per hour, an average of 10 units per hour, would have the following configuration options in Table 1.

To make is easy to understand, four different moments has been suggested: Time 1 to Time 4. Considering that the production can be 9 or 11 items per period, with an average 10 items per period for each machine. In the case of a random variation, each option is equally likely and should result as most expected value of each sector the average reported in the last row. We found that, though it had the average of 10 individual units in each machine, the resulting production of the line was only 9.5. If we increase the variation of each stage to 8 and 12, the negative effect on the overall result is even bigger, reducing the resulting production of 9.5 to 9.0, as shown in Table 2. Note that the production configuration is maintained by changing only the production variability in A and B. Likewise, the inclusion of an additional step in the scenario would also cause a negative effect on the overall average. Comparing with the example of Table 1, the line average is reduced from 9.5 to 9.25 by adding more one production center. This is the example of the Table 3.

So, to guarantee that a system with balanced capacity would produce the average of the individual machines, it would be necessary either a perfect synchronization of variation in all machines or a good amount of inventory between processes. I.e., when there was a parade of equipment for breaking into a unit, all others would have to stop; when a unit could perform above average, all others would have to achieve. Such synchronization is impossible to obtain a random processes. So, what we see in most cases is a big amount of work in process inventory to guarantee maximum utilization. And the higher the number of SKU's (stock keeping units) produced, the higher the inventory.

This argument was presented creatively (Goldratt & Cox, 1990) through analogies with marches and Scout games, representing the fundamental logic of maximization of flow proposed by TOC.

As productive systems typically have more than one production unit connected in series, it is possible to realize the harmful effects of the variation in the process has on the overall result. It was in this way to eliminate or reduce inventories that programs of total quality control (Total Quality Control - TQC) spared no effort to reduce process variability, reducing the need for in-process inventory. Still, (Krajewski, King, Ritzman, & Wong, 1987) argue that Japanese managers allow 12% to 18% additional capacity in its production systems.

The only way left to ensure continuity of flow and block the effect of these changes is through the addition of material in process inventory between areas. Thus, to keep parts between processes, it is possible to compensate for a negative change and keep delivering on average. This is what happens in balanced lines, even at the Just In Time - JIT, which seeks to maintain the minimum work in process.

The solution of the Theory of Constraints, known as Lung-Drum-Buffer-Rope or Drum-Rope - DBR, for series production rightly seeks to establish safety stocks only in "few" bottlenecks in each process, unbalancing the system, allowing minimal change in flow and a maximum capacity utilization of the neck, with a minimum of stock.

3. IS UNBALANCE FEASIBLE?

Despite being clearly perceived the problems that a balanced line to ensure full utilization of its capacity with the extensive research done by comparison with the performance of unbalanced lines (Atwater & Chakravorty, 1994; Chakravorty & Atwater, 1996; Corbett Neto, 1997; Craighead et al., 2001; Csillag & Neto, 1998; Goldratt & Cox, 1990; Goldratt, 1981; Lepore & Cohen, 1999; Liu & Lin, 1994; Noreen, Smith, & Mackey, 1995; Pan et al., 2014; Shaaban et al., 2014; Smith, 1999; Souza & Pires, 1999), investment in equipment to have spare capacity is still an expensive and important decision.

In projects of new production facilities is usually not yet known behavior patterns of production and its variability, suppliers interruption, equipment breakdowns, production mix variation, etc., which makes difficult the estimate of the amount of protective capacity. On the other hand, production systems already installed and sufficient data to determine with considerable accuracy the amount of stock for their protective restrictions and the expected speed of replacement, the inherent difficulties in changing the lay-out, new equipment installation and production interference tend to postpone any intention of investing in extra capacity, if it is not clearly justified.

How then can we easily assess the feasibility of unbalance capacity, either in a new production project is on an existing unit? Because this it is a strategic decision, which usually involves the participation of senior management, our suggestion is for an assessment of the financial impact of the decision to be able to meet a large part of organizations.

Considering that the largest portion of the capitalist organizations goals seek to maximize their financial results, some authors (Corbett Neto, 1997; Goldratt, 1990a; Guerreiro, 1996; Noreen et al., 1995) suggest the indication of Return Over Investment - ROI as the central measure of financial performance, the overall goal. The translation of local decisions measurements in this one, overall, would facilitate the process of decision making, avoiding any conflicts between more than one measure. The ROI would be characterized as:

$$ROI = \frac{Gain - Operational\ Expense}{Investiment} \quad (Eq. 1)$$

Gains is obtained as the difference between revenue and variable costs of all business; operational expenses are all company's fixed costs and investment can be understood as all the assets, including stocks gain, according to Goldratt (1990a). Thus, the general idea is to evaluate the impact of the change in the structure of productive capacity in a company and what impact your ROI. So what variables should be considered in evaluating this impact?

As we demonstrate in section 2, the variability of the process, as well as the number of steps, interfere in the amount of work in process (WIP), or the queue time. Using Little’s law (Hopp & Spearman, 2011), we can get:

$$Queue\ time = \left(\frac{CV_a^2 + CV_p^2}{2}\right)\left(\frac{u}{1-u}\right) t_p \quad (Eq. 2)$$

Where “t_p” is the average processing time, the variance is measured as a combination of both the coefficient of variation in arrivals “CV_a” and the coefficient of variation in processing time “CV_p” and “u” represents the utilization level on waiting time.

What is needed to be done now is to translate queue time in a financial indicator. This can be done considering the value that the company could be gaining with this resource as indicated by (Goldratt, 1990a). The principle is to know how much cash can be trapped in inventory to achieve an optimal throughput. (Lepore, 2011)

$$I\$D = inventory * \$ * \text{number of days} \quad (Eq.3)$$

So, if we multiply the amount of inventory times the cost per time of our investment times the number of days (queue time), we have an idea of the inventory cost. The result of this three equations is:

$$ROI = \frac{Gain - Operational\ Expense}{(queue\ time)(inventory\ cost)} \quad (Eq.4)$$

Note that the equation means that there will be always some wait in the queue, because the equation 1 and inventory cost only becomes zero when one of the terms in the equation becomes zero. In proposing the unbalance of a production facility, in practice we suggest buying extra capacity through equipment or resources beyond the rated capacity of the bottleneck, not the bottleneck sectors. This means that we are suggesting changing the financial investment portion of equation 1, increasing the denominator. As we expect an increase of ROI, investment in capacity would need to generate an offsetting increase in the gain or reduction in Operating Expenses, or reducing inventory investment, or a combination of these options. Table 4 summarizes the possible effects of unbalance line in each of the operators and suggests how to calculate the financial impact: One of the difficulties of calculating the financial impact lies in the nature of expenses and returns obtained and their distribution in time. Expenditures such as overhead costs to operate the extra capacity tend to occur monthly and steadily, but spending as the value of investment to be made for capacity is punctual. Gains arising from the capacity and sales increase are also constants and gains on inventory reduction are progressive.

Managerial accounting points out several ways to reach a decision, but, there were already pointed out (Smith, 1999) many shortcomings and pitfalls of Generally Accepted Accounting Principles (GAAP - Generally Accepted Accounting Principles) for decision making and especially in which refers to the process of inventory reduction, much to evolve.

The use of techniques of discounted cash flow, for example, help design the values in time to the present value and reach a relatively stable basis for comparison, but one of the most important factors would be related to the determination of the actual value of the stocks in this calculation. Advances in electronics and information technology and recent changes in the industry has enabled a steady reduction in capital costs and equipment, while the ever-increasing customization of consumer goods, reducing their life cycle and environmental concerns tend to increase the cost of holding inventory. I.e., stocks tend to get more and more expensive and increased investment in technology makes increasingly smaller capacity.

4. CONCLUSION

Despite many published studies (Chakravorty & Atwater, 2005; Lopez, 2014; Millstein & Martinich, 2014; Pan et al., 2014; Souza & Pires, 1999; Tenhiälä, 2011) about the benefits of unbalance capacity in production lines, there are not yet available, especially for decision makers, instruments that allow the analysis of all impacts resulting from this imbalance in the overall company goal. This study examined the implications of the imbalance of capacity in the overall performance of the production system and its main contribution to establish some criteria to facilitate decision making, especially for-profit organizations.

The first clear perception is that the imbalance capacity is not a panacea applicable to any production unit. To identify which variables should be used in decisions of such organizations, points to the formulation of a more comprehensive model that takes into account from the evaluation of the impact of the imbalance in inventories, calculating the resulting capacity increase in time response of non-bottlenecks and statistical pattern of failures to determine the estimated inventory reduction. Additionally, the evaluations proposed by Accounting Gain (Goldratt, 1990a) can be included, as the financial analysis of long-term tools, because, as warned (Cogan, 2007), companies that adopt the TOC should be attentive to their short-term focus.

Another important factor to be highlighted is the importance of the strategic assessment of the decision to increase capacity. Besides not every organization has as main objective the investment return, the initial focus of this work, the evaluation of specific aspects of each organization should be fundamental to decision making.

> Other types of organizations will have different goals. The goal of a hospital, a city or an army will certainly (hopefully) not be to make money. The biggest obstacle in determining the goals of

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these organizations is the realization that a goal and a measurable unit of that goal must be determined concurrently. (Goldratt, 1987)
The ability to implement an organization´s strategy is dependent on aligning internal resources so that they act in concert to improve and execute the strategy. (Smith, 1999)

Thus, this work opens the way for future research that allows the integrated modeling of the impacts of capacity imbalance in the production line, through the statistical and mathematical aspects on the production line, in order to estimate the direct impact on stocks, their consequences on the financial indicators – or productivity for non-profits – organizations.

Another important contribution is the presentation of a mathematical model that can serve as the basis to a computational model for decision making, paving the way for future work in the area.

TABLES

	Production A	Production B	Line production
Time 1	11	11	11
Time 2	11	9	9
Time 3	9	11	9
Time 4	9	9	9
Average	**10**	**10**	**9,5**

TABLE 1: Results of a balanced line with two machines

	Production A	Production B	Line production
Time 1	12	12	12
Time 2	12	8	8
Time 3	8	12	8
Time 4	8	8	8
Average	**10**	**10**	**9,0**

TABLE 2: Results of a balanced line with two machines and a higher variation

	Production A	Production B	Production C	Line production
Time 1	11	11	11	11
Time 2	11	11	9	9
Time 3	11	9	11	9
Time 4	11	9	9	9
Time 5	9	11	11	9
Time 6	9	11	9	9
Time 7	9	9	11	9
Time 8	9	9	9	9
Average	**10**	**10**	**10**	**9,25**

TABLE 3: Results of a balanced line with three machines

ROI portion	Effect of a non-constraint investment	How to calculate
Throughput (T)	Unchanged when the bottleneck is already operating at maximum efficiency Increases when protective capacity reduces occurrences of stock breaks the bottlenecks Increases when the protective capacity reduces batch sizes in non-bottlenecks, reducing the cycle time	Value of the additional revenue by increasing efficiency in the neck, or a reduction in cycle time, if any.
Operational Expense (OE)	Unchanged when the investment does not result in increased fixed costs Increases when investment in protective capacity implies higher fixed costs, as operators, energy, etc.	Value of the additional operating expense of extra capacity, if any.
Investment (I)	Increases with the amount invested in extra capacity. Reduces with reduced levels of work in process and finished products derived from spare capacity.	Value of the investment in extra capacity Value expected reduction in inventory levels.

TABLE 4: Impact of an investment at a non-constraint (extra capacity)

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