Unbalancing Capacity: A Possible Way of Reducing Work-in-Process Inventory

Rogério F. da Silva, Renelson R. Sampaio, and Francisco U. Passos
Faculdade Senai-Cimatec/PPGMCTI, Salvador, Brazil
Email: {rflores72, renelson.sampa, uchoapassos}@gmail.com

***Abstract*—Balancing or unbalancing production lines is still a major subject on operations research, given the difficulty of assessing the benefits of specific lines configurations. Due to constant and dramatic changes in global industry scenario, new alternatives are pointed out every moment to improve decision-making on that subject. This article presents a simulation proposal to evaluate the impact of imbalance in assembly lines on their performance, especially work in process inventory. The hypothesis, script and questions to be answered with the help of simulation are elaborated, opening space to a new approach to design unbalanced assembly lines.**

***Index Terms*—unbalanced capacity, work-in-process, inventory, assembly line**

I. Introduction

There is no consensus about balancing or unbalancing serial production lines in order to achieve better configuration. Assembly line balancing is still a focal point on operations research as a provider of cost efficient production to serial lines [1]–[6]. On the other hand, many authors argue [7]–[23] that unbalanced serial lines might give better performance in throughput and service level than balanced ones. Regardless of trying to discuss the most appropriate way of manage the line to reach higher throughput, few attention has been given to the logistics impacts of balancing or unbalancing the line capacity, especially on Work-In-Process (WIP) cost.

WIP refers to partially finished goods waiting for completion. So, as the values of inventory increases and costumer demands a higher variety of products, industries tend to change the way that decision is made and WIP costs becomes an important concern.

The significance of WIP (because of the cost of inventory and because of its impact on production lead time) was already highlighted in a study that pointed allocation of workload and buffer spaces as a way of optimizing both decisions on increasing throughput (TR) and reducing WIP [24]. Nevertheless most of the studies have focused on finding better solutions to balance or unbalance production lines. For example, it's already demonstrated that the variability of the processes interfere in the amount of WIP, with affects lead time and queue time [25]. Using Little's Law [26] we can obtain:

$$\text{Queue time} = \left(\frac{CV_a^2 + CV_p^2}{2}\right)\left(\frac{u}{1-u}\right)\text{MT} \qquad (1)$$

where "u" represents the utilization level on waiting time, "MT" is the mean processing time and the variance is a combination of the coefficient of variation in arrivals and in processing time, respectively "CV_a" and "CV_p". So, if we want to reduce queue time and, consequently, WIP levels, we might:

- Reduce MT. With faster processes, we can reduce queue time;
- Reduce utilization level. On the other way, faster processes will consume parts faster and it will increase periods of time with a shortage of raw material. Note that reduce utilization is not a way to reduce WIP, but it can appear as a consequence of doing it;
- Reducing variation either in arrivals or in processing time. As the processes variations are not synchronized, the higher the variation, the more irregular the flow of material.

But in some occasions it's hard to diminish MT or variance in processes, due to specific aspects such as absence of technology, low quality raw material, outsourced work or bad trained personal. Then why not acquiring new or faster equipment in non-constraints as a possibility of reducing WIP levels? Changing characteristics of actual processes and unbalancing production lines can be justified by reduction on WIP and associated costs?

This article presents a simulation proposal to analyze impacts of unbalancing capacity of serial production lines on WIP cost[1]. This simulation is being developed as part of a study which aims to combine the unbalanced capacity design with better logistic performance. The model to be used during the simulation is been built in Witness Software.

Some important research about the topic of balancing or unbalancing assembly lines is described in the next section. The subsequent section presents the simulation draft and questions that intend to be answered during the research. Then we end this work considering the

Manuscript received October 11, 2015; revised May 25, 2016.

[1] As the idea of this work is to evaluate impacts on WIP, we are not using pure serial lines during simulation. Pure serial lines are used in automated transfer lines and cad work with reduced WIP. Therefore, the simulation is going to focus on buffered serial lines.

doi: 10.18178/jiii.4.3.198-203

relevance of the theme, concern points and possible directions for future research.

II. BALANCED VERSUS UNBALANCED LINES

A production line consists of a number of work stations in series, producing generally with buffers in between. There are several ways of classifying production lines, according to the way that the movement is coordinated, according to the lay-out of production, according to the capacity configuration, etc. Considering the production line designs, there is a significant number of studies involving balanced and unbalanced lines and considering synchronous and asynchronous lines.

Synchronous lines are the ones where the movement of jobs is coordinated; i.e. the jobs move to the next resource in a simultaneous way. These lines can be further separated in two other subcategories:

- Paced line. The time allowed for a resource to work on the job is limited;
- Unpaced line. There is no limit to the time allowed for a resource to work on the job.

Asynchronous lines, on the other way, are the ones where the movement of jobs is not coordinated; i.e. the jobs start as soon as the resources become available. The production immediately moves to the next work station when there is space for it. Generally the asynchronous lines are unpaced because of workstations operating at different Mean Times (MT), different breakdowns rates and different variabilities.

Fig. 1 shows the scheme of a serial production line with *m* workstations, where μ is the production mean time of each workstation and β is the buffer that can sometimes guarantee the continuity of work if a breakdown stops previous workstation.

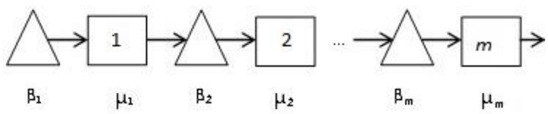

Figure 1. Production line with *m* stations and buffers.

If we consider the presence of buffers within the workstations, only the synchronous paced lines, due to the fixed cycle time, can work without buffers with no impact on throughput. Synchronous unpaced lines and asynchronous lines, due to the fluctuation among job number in the system, usually need buffers to prevent no available job (starvation) or no room to dispose a completed job (blocking) to one workstation.

A sizeable proportion of industries rely on unpaced production lines to produce their goods and services [11]. As there are a considerable number of processes in industry that can be represented as an asynchronous line or a synchronous unpaced line, WIP consists on a relevant issue in production management.

Another important observation is that outsourced manufactures usually have to deal with unpaced manual lines in developing countries, due the lack of high trained personal, high labor turnover and older technology [27]. Moreover, due to the global warming, world climate change and other issues related to sustainability, remanufacturing, reverse logistics and recycling are becoming more and more important and tend to interfere in industry with more variability in processes times.

The concepts of balanced (and furthermore unbalanced) lines took form to ensure a continuous functioning of line, predictable output and less WIP. Then production line balancing (and unbalancing) grew with a considerable body of literature last century and is still a big issue today.

III. LINE BALANCING PROBLEM

The main objective of production line designers and managers is to increase the efficiency of the line by maximizing the ratio between throughput and required costs [2]. So, the classical line-balancing problem consists on assign each task to a workstation maximizing its efficiency, i.e. minimizing idle time.

This problem was first addressed formulating balancing as a linear programing problem including all possible combination of station assignments [3]. But, as mentioned before, the multiplicity of conditions on real production systems opened space to several classifications of balancing problems as well as ways to solve them.

The main categorization splits Assembly Line Balancing Problems – ALPB in two categories [6]:

- Simple Assembly Line Balancing Problems – SALBP;
- General Assembly Line Balancing Problems – GALBP.

Most of the research in line balancing problems is concentrated on SALBP, which, as the name implies, includes very simple lines. The assumptions of SALBP are very restricting and it is not representative to many real production situations. Other characteristics of these configurations are mass-production of homogeneous product; deterministic operation times; no assignment restrictions; serial line lay-out; stations equally equipped and maximum efficiency purpose.

In order to better represent real world situations, the configurations were incremented with different sort of contributions. So actually there is an extensive literature production among ALBP.

A way of characterizing balancing problems [28] were presented dividing the assembly systems according to:

- Number of items that are made on the production line: single, mixed or multi;
- Line control: paced, unpaced asynchronous, unpaced synchronous;
- Type of installation: first time installation, reconfiguration;
- Level of automation: manual lines, automated lines.

Because of the variety of specific conditions, there are several other ways of classifying ALBP [1], [2], [6], [28].

For example, it's already said that most real production lines are unpaced. So, excluding common cycle time restriction, which characterizes paced lines, and using buffered assembly line, the balancing problem became more specific by the additional decision of dimensioning and positioning buffers [4], [5], [19], [29]–[31].

Other conditions are incremented, such as:

- Assembly different types of products at the same line, with different cycle times. So sequencing is a new issue;
- Multi-model and mixed model line, with different parts produced on the line. While multi-models lines refer to lines where different pieces are produced in batches, mixed model lines can produce individual different pieces randomly. Here the lot size is included as another issue;
- Higher variability on processes times, changing from deterministic to stochastic processes times;
- Lay-out of flow line production systems, changing from straight serial line to U-shaped, where simultaneous work is feasible;
- More complex lay-out, with parallel lines, or parallel tasks;
- Alternative processes, i.e. tasks performed by different equipment, with equipment or process selection problem;
- Two-sided line, station related assignment restriction, position related constraints, etc.

All these specific conditions intended to better understand the ALBP, presenting alternatives to real configurations. Even so, at the end, all these ALBP research were not yet conclusive. Besides the huge academic effort, among 312 different research papers, it was found only 15 papers related to real world assembly systems [28]. This disparity points out the huge gap between the models and real-world configuration problems.

III. Unbalanced Lines

The assembly of a truly ideal balanced line, where buffers are not necessary, is extremely rare. Even so, compared with balanced lines, much less research has addressed unbalanced lines [11], [32]. And this is not a new issue. Research about imbalance started out in the 1960s, i.e. some years later than the first articles about line balancing [33], [34]. About 30 years later [9], it was pointed out that this lack of research in literature may be caused by:

- The difficult of analyzing lines with large degrees of freedom, or longer line lengths; and
- The widespread use of exponential mean operation time (MT) distribution in literature, which does not allow for the decoupling of MT and the Coefficient of Variation (CV).

The imbalance of a specific production can be obtained by different ways. So, similarly to the balancing line problems, different approaches have been used to obtain distinct goals.

For example, we can unbalance an assembling line by [11]:

- Unbalanced mean service times (MT imbalance);
- Unequal coefficient of variation at service times (CV imbalance);
- Combined unbalance mean service times and unequal coefficient of variation (MT and CV imbalance);
- Unreliable lines;
- Buffer placement.

Despite the huge difference in academic effort, early papers reported better performances on unbalanced lines due to MT imbalance compared with balanced ones. Line performance was then evaluated comparing TR and WIP results. One of the main contributions were called the bowl phenomenon [13] because of the shape of the charge profile at the optimum configuration. In production lines with exponential work time distributions, optimal TR was reached with slower stations at the center and faster stations at extremities, resembling a bowl shape.

The better performances were later confirmed on several other conditions [7], [9], [14], [20], [35]. But other studies pointed out that the inverted bowl shape, with slower stations at the beginning and the end of the lines were more indicated in other configurations [7], [10], [36].

Another contribution was done latter with Theory of Constraints – TOC studies [15], [37], [38]. TOC approach considers that every assembly line has, or might have, at least a constraint or a bottleneck. Then a specific set of rules to manage the constraints is implemented to maximize the flow of material: the drum-buffer-rope – DBR, a mechanism to manage unbalanced plants. This approach leaded to new studies investigating performance in a comparison with TOC unbalanced lines, just in time – JIT and balanced lines [17], [18], [39], [40].

Another different approach was done considering lean processes and smaller and continuous improvement on non-bottleneck resources [25]. These improvements lead to better flow of material into the bottleneck and reduced the probability of starvation. Therefore, better results were found such as improved CT, reducing utilization and reducing process variability.

Since then, a lot of research has been done trying to solve questions like: What is the best way to configure stations with different capacities, variability and reliabilities to achieve better performance on TR or CT? Which factor has the biggest impact on gaining best results on utilization or less WIP? Where should be placed buffers and how big should they be?

There are still a considerable number of problems to be solved and a lot of controversy involved in unbalancing procedures. This work, specifically, are going to focus on unbalancing configurations and its impact on WIP and TR.

IV. Simulation Proposal

Our simulation is based on the dice game generally used on graduate classes to demonstrate DBR principles [41]–[43]. The game is usually played in two configurations: the first, simulating a balanced line, using the dice to represent variability on processes, and the second, an unbalanced MT line with a clear constraint, in order to apply DBR guidelines.

Although the dice game is very illustrative to comprehend impacts of variability and dependence on serial production lines, especially balanced ones, it is limited by the dice configuration itself. The configuration does not allow changing the variation range of dice values neither capacity difference between constraint and non-constraint resources. As typical dice has a standard configuration which varies as a random distribution with mean time 3.5 and minimum and maximum values respectively 1 and 6, we are not able to analyze impacts of changing the variation on the throughput. Similarly, as the two basic configurations only allow the capacity differentiation by adding a dice on the non-constraints resources, we are not able to evaluate the impacts of unbalance difference on the line.

Therefore, the idea of the simulation is to replicate dice game configurations, using a five step line production with a centralized bottleneck and DBR rules according to Fig. 2.

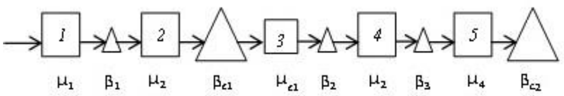

Figure 2. Simulation scheme with centralized constraint.

The five processes are represented by the squares with its associated buffers represented by the triangles. The model uses initially a single constraint centered at processes 3, represented by smaller square. This bottleneck resource has a higher MT, represented by μ_{c1}. The buffers are different in size as well, with higher buffers positioned to bottleneck, β_{c1}, and another higher buffer at the end of line, β_{c2}, protecting the delivery of finished parts. All other buffers and MT are the same during first part of the simulation.

The processes are unpaced, a single type of product is processed, excluding mix-model or multi-model lines, random distributions are used, lay-out is a straight serial line, no parallel tasks or alternative processes are allowed.

This configuration is suggested to allow DBR [44]–[48] rules:

- Using a buffer prior to all bottlenecks;
- Bottlenecks set the pace according to external demand;
- Bottlenecks tend to have higher utilization, with less idle time;
- Non-bottlenecks don't need to maintain higher utilization. Their goal is to guarantee bottleneck buffers on a specific range.

The hypothesis to be tested with this model is that higher levels of imbalance, characterized by different MT between bottleneck and other resources, would demand less protective inventory, therefore less WIP in the line.

Another point that will be evaluated is the behavior of line TR according to imbalance level.

ARENA software is pointed as one solution for assembly line systems design [2] offering simulation alternatives. Another similar program is Witness Software, which was chosen as the tool to simulate conditions related and test the hypothesis due to possibility of configuring DBR rules mentioned prior.

As the proposal is to evaluate the impacts of the imbalance on the line, different levels of imbalance are going to be simulated. To measure this imbalance, it will be used Smoothness Index (*SI*) and Balance Efficiency (*BE*).

$$\mathrm{BE} = \left[1 - \frac{\sum_{i=1}^{m} |t(S_i) - t_{av}|}{m * t_{av}}\right] * 100\% \quad (2)$$

$$\mathrm{SI} = \left[\sum_{i=1}^{m} \left(\mathrm{CT} - t(S_i)\right)^2\right]^{-0,5} \quad (3)$$

To calculate the index, m is the number of stations, S_i the total time required for executing the tasks assigned to stations and t_{av} represents the average workstation time across the entire line.

Line performance results are going to be limited on TR and WIP levels, in order to simplify analysis and test different conditions. So, the simulation will run with different model conditions and objectives, pointed on Table I.

Note that different objectives are set during the simulation. This is going to allow clear evaluations of each impact and progressive evolution on findings.

TABLE I. SIMULATION CONDITIONS AND OBJECTIVES

Conditions	Objectives
Different speed on non-constraints, variating the imbalance level of MT	Evaluate impact on WIP inventory Evaluate impact on line TR
Different probabilities distributions for processes	Evaluate impact on WIP inventory Evaluate impact on line TR Test adequacy of the model to different configurations
Longer processes, with more than five workstations, maintaining central bottleneck and different speed on non-constraints, using bowl shape	Evaluate impact of imbalance index and different lines configuration on performance results

The parameters that are going to be controlled and monitored during the simulation will be:

- *AIL* = average inventory level during the simulation;
- *BE* = balance efficiency;
- BL_j = Buffer upper limit for individual workstation j (j= 1, …, n);
- CT_b = bottleneck cycle time;
- CT_i = non bottleneck cycle time i (i = 1, …, m);
- *Distribution* = type of CT frequency distribution;
- *LE* = line efficiency;
- *BE* = balance efficiency;
- *LT* = Line throughput; number of pieces delivered after simulation;
- *IL* = inventory level at the end the simulation;
- *SI* = smoothness index;
- *Time* = time used to run simulation

The final purpose of the model is to identify a correlation between imbalance index and WIP level, paving the way to address future questions on processes design.

V. Conclusions

After discussing a lot of different approaches to the balancing and unbalancing problem on production management, we proposed a simulation model to evaluate the impact of balancing or unbalancing single serial assembly lines on WIP inventory.

Unbalancing production lines is still an open field on operations research and better understanding the behavior of these lines can help on identifying different approaches and new solutions on configuring new lines or improving existent ones.

It is important, because at the actual level of globalization, a representative number of companies have offices and sites thorough the world. Moving, shutting down or creating an entire plant, with the current technology is not a big issue anymore and can be decided in a heartbeat.

Associating capacity configurations with WIP inventory levels will help on stablishing a formula to determine optimal configuration based on logistics storage and total costs [49].

Furthermore, with the advance of technology, capacity changes can be continuously addressed by small improvements that require low investment. Then we will be able to verify if an amount of capital investment can be compensated by logistic costs, specifically WIP associated costs.

We could not forget the situation of developing countries, where conditions for creating unbalanced lines are more susceptible. Labor intensive, old technologies, non-specialized personnel are, for example, common conditions in this area that easily configure unpaced asynchronous lines.

The central idea of the simulation is to issue possibilities of changing capacity configuration to obtain better financial results. It can be achieved by either smaller improvements on non-constraints, or optimal configurations to new lines that will be designed.

So, the proposal of a simulation experiment to evaluate the impact of unbalancing assembly lines in order to achieve better performance, either in productivity or in financial results, can address a good number of future research.

References

[1] A. Scholl and C. Becker, "State-of-the-art exact and heuristic solution procedures for simple assembly line balancing," *Eur. J. Oper. Res.*, vol. 168, no. 3, pp. 666–693, 2006.

[2] B. Rekiek, A. Dolgui, A. Delchambre, and A. Bratcu, "State of art of optimization methods for assembly line design," *Annu. Rev. Control*, vol. 26, no. 2, pp. 163–174, 2002.

[3] M. E. Salveson, "The assembly line balancing problem," *J. Ind. Eng.*, vol. 6, no. 3, pp. 18–25, 1955.

[4] A. Suhail, "Reliability and optimization considerations in a conveyor-paced assembly line system," *Int. J. Prod. Res.*, vol. 21, no. 5, pp. 627–640, 1983.

[5] J. A. Buzacott, "Prediction of the efficiency of transfer lines without internal storage," *Int. J. Prod. Res.*, vol. 6, no. 3, 1968.

[6] I. Baybars, "A survey of exact algorithms for the simple assembly line balancing problem," *Manage. Sci.*, vol. 32, no. 8, pp. 909–932, 1986.

[7] G. Yamazaki, H. Sakasegawa, and J. G. Shanthikumar, "On optimal arrangement of stations in a tandem queueing system with blocking," *Manage. Sci.*, vol. 38, no. 1, pp. 137–153, 1992.

[8] F. B. De Souza and S. R. I. Pires, "Análise e proposições sobre o balanceamento e uso de excesso de capacidade em recursos produtivos," *Gestão & Produção*, vol. 6, no. 2, 1999.

[9] S. G. Powell, "Buffer allocation in unbalanced three-station serial lines," *Int. J. Prod. Res.*, vol. 32, no. 9, pp. 2201–2217, 1994.

[10] S. Shaaban and T. McNamara, "The effects of joint operations time means and variability unbalance on production line performance," *Int. J. Manuf. Technol. Manag.*, vol. 18, no. 1, pp. 59–78, 2009.

[11] S. Hudson, T. McNamara, and S. Shaaban, "Unbalanced lines: where are we now?" *Int. J. Prod. Res.*, vol. 53, no. 6, pp. 1895–1911, 2015.

[12] C. M. Liu and C. L. Lin, "Performance evaluation of unbalanced serial production lines," *Int. J. Prod. Res.*, vol. 32, no. 12, pp. 2897–2914, 1994.

[13] F. S. Hillier and K. C. So, "On the robustness of the bowl phenomenon," *Eur. J. Oper. Res.*, vol. 89, no. 3, pp. 496–515, 1996.

[14] F. S. Hillier and R. W. Boling, "On the optimal allocation of work in symmetrically unbalanced production line systems with variable operation times," *Manage. Sci.*, vol. 25, no. 8, pp. 721–728, 1979.

[15] E. M. Goldratt, "The unbalanced plant," in *Proc. APICS 24th Annual International Conference Proceedings*, 1981.

[16] C. W. Craighead, J. W. Patterson, and L. D. Fredendall, "Protective capacity positioning : Impact on manufacturing cell performance," *Eur. J. Oper. Res.*, vol. 134, pp. 425–438, 2001.

[17] S. S. Chakravorty and J. B. Atwater, "A comparative study of line design approaches for serial production systems," *Int. J. Oper. Prod. Manag.*, vol. 16, no. 6, pp. 91–108, 1996.

[18] J. B. Atwater and S. S. Chakravorty, "Does protective capacity assist managers in competing along time-based dimensions?" 1994.

[19] K. R. Baker, S. G. Powell, and D. F. Pyke, "Buffered and unbuffered assembly systems with variable processing times," *J. Manuf. Oper. Manag.*, vol. 3, no. 3, pp. 200–223, 1990.

[20] T. E. El-Rayah, "The effect of inequality of interstage buffer capacities and operation time variability on the efficiency of production line systems," *Int. J. Prod. Res.*, vol. 17, no. 1, pp. 77–89, 1979.

[21] M. A. Millstein and J. S. Martinich, "Takt Time Grouping: implementing kanban-flow manufacturing in an unbalanced, high variation cycle-time process with moving constraints," *Int. J. Prod. Res.*, no. ahead-of-print, pp. 1–15, 2014.

[22] C. E. Lopez, "Unbalanced workload allocation in large assembly lines," *Dissertations & Theses – Gradworks*, 2014.

[23] X. Pan, J. Wu, Q. Zhang, D. Lai, X. Fu, and C. Zhang, "The study of buffer allocation problem in complex production line," *Telkomnika Indones. J. Electr. Eng.*, vol. 12, no. 3, pp. 2342–2349, 2014.

[24] M. S. Hillier, "Designing unpaced production lines to optimize throughput and work-in-process inventory," *IIE Trans.*, vol. 45, no. 5, pp. 516–527, 2013.

[25] M. G. Filho and R. Uzsoy, "Assessing the impact of alternative continuous improvement programmes in a flow shop using system dynamics," *Int. J. Prod. Res.*, vol. 52, no. 10, pp. 3014–3031, 2014.

[26] W. J. Hopp and M. L. Spearman, *Factory Physics*, Waveland Press, 2011.

[27] A. Montano, J. R. Villalobos, M. A. Gutierrez, and L. Mar, "Performance of serial assembly line designs under unequal operator speeds and learning," *Int. J. Prod. Res.*, vol. 45, no. 22, pp. 5355–5381, 2007.

[28] N. Boysen, M. Fliedner, and A. Scholl, "Assembly line balancing: Which model to use when?" *Int. J. Prod. Econ.*, vol. 111, no. 2, pp. 509–528, 2008.

[29] F. S. Hillier and K. C. So, "The effect of machine breakdowns and interstage storage on the performance of production line systems," *Int. J. Prod. Res.*, vol. 29, no. 10, pp. 2043–2055, 1991.

[30] F. S. Hillier and K. C. So, "Some data for applying the bowl phenomenon to large production line systems," *Int. J. Prod. Res.*, vol. 31, no. 4, pp. 811–822, 1993.

[31] A. Dolgui, A. Eremeev, A. Kolokolov, and V. Sigaev, “A genetic algorithm for the allocation of buffer storage capacities in a production line with unreliable machines,” *J. Math. Model. Algorithms*, vol. 1, no. 2, pp. 89–104, 2002.

[32] S. G. Powell and D. F. Pyke, “Buffering unbalanced assembly systems,” *IIE Trans.*, vol. 30, no. 1, pp. 55–65, 1997.

[33] K. F. H. Murrell, “Operator variability and its industrial consequences,” *Int. J. Prod. Res.*, vol. 1, no. 3, pp. 39–55, 1961.

[34] L. E. Davis, “Pacing effects on manned assembly lines,” *Int. J. Prod. Res.*, vol. 4, no. 3, pp. 171–184, 1965.

[35] F. S. Hillier and R. W. Boling, “Toward characterizing the optimal allocation of work in production line systems with variable operation times,” *Adv. Oper. Res.*, pp. 109–119, 1977.

[36] R. Pike and G. E. Martinj, “The bowl phenomenon in unpaced lines,” *Int. J. Prod. Res.*, vol. 32, no. 3, pp. 483–499, 1994.

[37] E. M. Goldratt and J. Cox, *The goal: Excellence in Manufacturing*, North River Press Croton-on-Hudson, 1984, vol. 262.

[38] M. Gupta and D. Snyder, “Comparing TOC with MRP and JIT: A literature review,” *Int. J. Prod. Res.*, vol. 47, no. 13, pp. 3705–3739, 2009.

[39] W. A. Sloan, *A Study on the Effect of Protective Capacity on Cycle Time in Serial Production Lines*, Mississippi State University, 2001.

[40] S. Kim, J. F. Cox, and V. J. Mabin, “An exploratory study of protective inventory in a re-entrant line with protective capacity,” *Int. J. Prod. Res.*, vol. 48, no. 14, pp. 4153–4178, 2010.

[41] O. P. Hilmola, “Using Goldratt’s dice-game to introduce system dynamics models and simulation analysis,” *Int. J. Inf. Oper. Manag. Educ.*, vol. 1, no. 4, pp. 363–376, 2006.

[42] I. Lange and A. Ziegenbein, “The constraints game - learning the Theory of Constraints with a dice game,” in *Proc. 9th Workshop of the IFPI WG 5.7 Special Interest Group on Experimental Interactive Learning in Industrial Management*, 2005, p. 95.

[43] M. Gupta and L. Boyd, “An Excel-based dice game: an integrative learning activity in operations management,” *Int. J. Oper. Prod. Manag.*, vol. 31, no. 6, pp. 608–630, 2011.

[44] S. C. Gardiner, J. H. Blackstone Jr, and L. R. Gardiner, “Drum-buffer-rope and buffer management: Impact on production management study and practices,” *Int. J. Oper. Prod. Manag.*, vol. 13, no. 6, pp. 68–78, 1993.

[45] S. Y. Wu, J. S. Morris, and T. M. Gordon, “A simulation analysis of the effectiveness of drum-buffer-rope scheduling in furniture manufacturing,” *Comput. Ind. Eng.*, vol. 26, no. 4, pp. 757–764, 1994.

[46] J. B. Atwater and S. S. Chakravorty, “A study of the utilization of capacity constrained resources in drum-buffer-rope systems,” *Prod. Oper. Manag.*, vol. 11, no. 2, pp. 259–273, 2002.

[47] E. Schragenheim and B. Ronen, “Drum-buffer-rope shop floor control,” *Prod. Invent. Manag. J.*, vol. 31, no. 3, pp. 18–22, 1990.

[48] V. D. R. Guide Jr, “Scheduling using drum-buffer-rope in a remanufacturing environment,” *Int. J. Prod. Res.*, vol. 34, no. 4, pp. 1081–1091, 1996.

[49] R. F. da Silva and R. R. Sampaio, “Capacity unbalancing and total logistic cost,” *Bus. Manag. Rev.*, vol. 4, 2014.

Rogério F. Silva was born in Salvador, Bahia, Brazil, on May, 1972. mechanical engineer by Universidade Federal da Bahia- UFBA, Salvador-BA, in 1994, specialized in business by Universidade Salvador – UNIFACS, Salvador-BA, in 1997, master science in business by Universidade Federal da Bahia in 2004, Salvador-BA, and ongoing doctoral degree in computational modelling and industry technology by SENAI-CIMATEC, started in 2013, focusing on production management.

He worked as process engineer, quality engineer, production manager, maintenance manager, logistics manager and general director in companies like Sisalana S/A, Gerdau S/A, GrafTech Inc., Natuzzi Inc. and DeVry Inc. He worked as professor as well in graduate and undergraduate programs, focusing in production and logistics management. He worked also as program dean, dean of academic affairs and general director in Faculdade Ruy Barbosa-DeVry. Actually is administrative and logistics director on a paper industry located in Camaçari, Bahia, Brazil. His major works are: Construção do conhecimento nas organizações na perspectiva das redes sociais, Salvador, Bahia, EDUNEB, 2013; Capacity unbalance and total logistic cost, Business Management Review, 2014; and Gestão de Estoques, São Paulo, São Paulo, Pearson Educational do Brasil, 2015. Production and logistics managemens are his research interests.

Prof. Silva was part of CienteFico (ISSN 1677-1591) referee panel from 2010 to 2013 and was a professor honored of several undergraduate classes.

Renelson R. Sampaio was born in Maceio, Alagoas, Brazil. Bachelor of sciences in physics by Universidade Federal de Minas Gerais – UFMG, in 1973, specialized in mathematics by MAT in 1974 and specialized in physics by Universidade de Brasilia – UNB in 1975, master in history and social studies of science by University of Sussex, England in 1979; doctoral in science policy research unit by University of Sussex, England; pos doc in economy of technological innovation by Wisconsin University in 2011. Field of study is social applied sciences.

He worked as full professor in several universities as Faculdade SENAI-CIMATEC, Faculdade Visconde de Cairu, Faculdade Ruy Barbosa, etc. Actually is professor in graduate and undergraduate programs at SENAI-CIMATEC. His more recent works are: Reflexões sobre as competências dos núcleos de inovação tecnológica, Cadernos de Prospecção, 2015; Compartilhamento do conhecimento em um projeto automotive, RAE, 2014, and; Using Luhn-s Automatic Abstract Method to Create Graphs of Words for Document Visualization. Social Networking, 2014. Technological innovation and dissemination of knowledge are his research interests.

Prof. Sampaio is part of GEPROS (ISSN 1984-2430) referee panel since 2007 and was a professor honored with the title of Destaque Acadêmico in 2011 and 2013 by Faculdade SENAI-CIMATEC.

Francisco U. Passos was born in Fortaleza, Ceara, Brasil in July, 1948. Chemical engineer by Universidade Federal do Ceara – UFC, in 1971, master in business Universidade de São Paulo - USP in 1995; doctoral in business by Universidade de São Paulo - USP in 2000. Field of study is social applied sciences.

He worked engineer and manager in several industries, as Standard Eletrica S/A, Nuclebras - Industrias Nucleares Brasileiras, Avibras and Centro Tecnológico da Marinha. Actually is professor in graduate and undergraduate programs at SENAI-CIMATEC. His more recent works are: Compartilhamento do conhecimento em um projeto automotive, RAE, 2014; How Does Knowledge Diffusion Impact Maintenance Performance? Lessons from a Survey in a Brazilian Petrochemical Company. International Business Research, 2014, and; Fluxos de informação e conhecimento no desenvolvimento de produto na indústria automotiva - uma comparação entre as redes formal e informal, Revista Produção Online, 2013. Social applied sciences and business are his research interests.

Prof. Passos is part of RAUSP (ISSN 1984-6142) referee panel since 2006 and was a professor of the year by UNIFACS in 2005 and a professor honored of several undergraduate classes.