

Capacity Distribution in Production Line Design: What Questions Have not been Asked?

Rogério Flores da Silva^{a*}, Renelson Ribeiro Sampaio^b

^aUniversidade Católica do Salvador, Av. Prof. Pinto de Aguiar, 2589, Salvador, CEP:41.740-090, Brazil

^bSenai-Cimatec, Av. Orlando Gomes, 1845, Salvador, CEP: 41.650-010, Brazil

^aEmail: rflores72@gmail.com

^bEmail: renelson.sampa@gmail.com

Abstract

There has been significant work published about positive results of production systems with unbalanced capacity against the typical balanced lines. While complementary research suggests sophisticated ways to increase the flow of materials on the production lines by balanced or unbalanced capacity, many practitioners use trial-and-error approaches to solving optimization problems. Although a lot of progress has been made during the last decades, there's still a gap in organizing scientific production about capacity planning among different areas of knowledge, such as finance, supply chain and production. The purpose of this work is to analyze the different approaches that have been used on capacity planning of production lines and tie a set of important questions to be solved in future research to better apply technological tools maximizing the efficiency of production lines projects. Using a review of literature and listing the problems still unaddressed, this work grouped a major framework of questions to orient future research.

Keywords: capacity management; protective inventory; resource allocation.

1. Introduction

The design of production systems and capacity allocation is a highly relevant topic in industrial engineering [1]. Its construction is linked to aspects such as specifying the sequence of activities necessary to produce goods or services, the ideal physical arrangement, the quantity of resources used, determining the amount of work in each work center, among other important aspects for the performance of company operations. The design of the production line, therefore, ends up being vital for the subsequent performance of operations and must involve items such as implementation costs, line flexibility, the final quality of the product or service, delivery time to market, the volume and diversity of items, the efficiency with which the products or services are expected to be delivered, among others.

Received: 9/19/2025

Accepted: 11/19/2025

Published: 11/29/2025

* Corresponding author.

According to [2], companies spend billions of dollars every year on the design, installation, operation, and maintenance of production lines. Therefore, even small improvements in efficiency or reductions in inventory costs can result in substantial savings over the life expectancy of a production line. [3] argue that the goal of line designers, as indicated by most manufacturing literature, is to investigate how to improve or optimize the efficiency of production lines according to a wide variety of objectives, sometimes in conflict with each other. Approaches to addressing this problem would involve a vast number of techniques and methods, reflecting the complexity of production systems. Additionally, the complexity of production systems is often exacerbated by the stochastic nature of variables that are part of some production lines, due to various interferences that further complicate the work of designers. Tempelmeier [4] highlights that industrial planners, who are responsible for providing economically sufficient capacity, are faced with several design factors that affect the productivity of a production system. These factors are constantly under stochastic influences, such as equipment breakdowns, variable process times, etc. According to [5], the main objective of assembly line designers is to increase line efficiency by maximizing the ratio between production and necessary costs. Therefore, when designing a production system, it is essential to comprehensively evaluate line performance, including the impact on inventories and their costs. Indeed, for the design of a production system, evaluating system performance is extremely relevant, both in terms of production performed by the line [6] and in terms of controlling the inventory necessary to achieve this production [7, 8, 9].

The design of a production line involves solutions that seek a combination of the following objectives:

- Maximize the system's production volume or throughput
- Minimize the assets required for system operation, such as material inventories, the number of machines, labor, or other resources
- Minimize process cycle times and lead time

Some authors may include minimizing resource idle time in their objectives, but this is a point of disagreement among some researchers, since there may be a conflict between this objective and the reduction of in-process inventories when reducing the idle time of some types of resources. This article presents a review of the main research already done in the field regarding resource allocation and capacity management and presents some problems that are so far unaddressed, pointing out an alternative for future research.

2. Review of Literature

According to [10], a production line is nothing more than a set of workstations in sequence, which can be presented in various configurations with the objective of processing a product or performing a service, with the possibility of work-in-process inventory (or queues) between the workstations. The production line, according to Reference [11], is also known as a flow line. They define the line design problem as the one that is dedicated to choosing the size of buffers or resource parameters to maximize performance or minimize costs subject to imposed constraints.

Dallery and Gershwin [11] define the line design problem as one that is dedicated to choosing the size of buffers

or resource parameters to maximize performance or minimize costs subject to imposed constraints. To solve this problem, it becomes necessary to evaluate which performance measures of the lines. Therefore, line performance measures invariably involve measures related to objectives such as:

- Maximizing the line production rate by increasing the number of items or customers processed per unit of time
- Minimizing the costs of assets used in the system, whether they are fixed assets, such as equipment, machinery, vehicles and facilities, or current assets, such as inventory of raw materials, work-in-process or finished goods
- Minimizing other resources used in the production system, such as labor, energy, etc.
- Minimizing cycle times
- Minimizing total lead times

2.1. Line Capacity Distribution

Much of the literature on manufacturing proposes to investigate how to improve or optimize the efficiency of production lines according to a wide variety of objectives, often conflicting [3]. Thus, for example, a given organization may seek to maximize the utilization of its equipment by reducing machine downtime, while another aims to reduce its inventory and ensure faster delivery, and a third intends to achieve the highest production rate. Due to this variety of objectives and adding to the diversity of characteristics within the production lines, it is possible to make some distinctions between the design alternatives for production systems regarding the distribution of capacities. A first approach to distributing workstation capacities seeks the optimal partitioning of the total workload across stations, minimizing total idle time and is known as line balancing. Another approach does not concern itself with the idle time of non-bottleneck stations and deliberately employs the use of excess capacity in pre-determined positions, being called line unbalancing [12]. They will be discussed separately in the following subsections.

2.2. Balanced Lines

An assembly line consists of a set $k = 1, \dots, m$ of workstations arranged to repeatedly perform operations on each part. The total work required to process each part is divided into an elementary set $V = 1, \dots, n$ of operations, named tasks. Tasks are indivisible units of work, and each task is associated with a processing time t_j , named task time. Due to organizational and technological limitations, tasks cannot be performed in an arbitrary sequence but are subject to precedence constraints. The line balancing problem can be represented by determining the tasks and their sequence to equally distribute (or balance) the work among the stations to achieve a goal. The precedence chart is one way to present these types of constraints, with one node formed for each task, and node weights representing times and arcs, reflecting the precedence limitations. Figure 1 below shows an example of precedence.

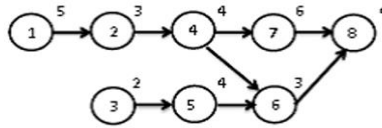


Figure 1: precedence chart

The feasibility of line balancing, or the equitable arrangement of tasks between stations, must ensure that no precedence relationship is violated. Thus, given a set S_k of tasks arranged for a station k , constituting the station's workload, the station time is given by the sum of the task times $t(S_k)$:

$$t(S_k) = \sum_{j \in (S)} t_j \quad (1)$$

In such a way that the cycle time c is always greater than the station times and their difference is the idle or unproductive time, idle time (IT):

$$IT = c - t(S_k) \quad (2)$$

Line balancing arises from the need to increase line efficiency by maximizing the ratio between the productive rate (Throughput - TR) and the required costs, the main objective of line designers [13]. Thus, the classic line balancing problem (Assembly Line Balancing Problem - ALBP) is to determine the tasks for the workstations to maximize their efficiency, or, in other words, to reduce idle time. This problem was initially addressed by formulating balancing as a linear programming problem including the possible combinations of workstation assignments [14]. But the multiplicity of conditions in a real production system ended up opening space for a series of classifications, as well as diverse ways of solving these problems.

The main categorization of ALBP divides it into two categories:

- Simple Assembly Line Balancing Problem (SALBP);
- General Assembly Line Balancing Problem (GALBP).

Most research in line balancing is concentrated on SALBP, which, as the name itself suggests, includes very simple problems. The assumptions of SALBP are very restrictive and do not represent many of the real production problems. The SALBP is then subdivided for when the line cycle time is given and fixed (SALBP-1) or when the number of workstations is given and fixed (SALBP-2). Thus, considering:

- N - Number of tasks
- k - Number of workstations
- t_i - Time of the task i (deterministically known)
- CT - Cycle time of the line
- P_i - Set immediately preceding task i

Using some weights w for the allocation of stations:

$$w_{ik} = w_k \quad \forall k \quad (3)$$

$$N * w_k \leq w_{k+1} \quad (4)$$

SLABP-1 can be represented as the following integer programming problem:

$$\sum_{i=1}^N \sum_{k=1}^N w_{ik} * x_{ik} \rightarrow \min x_{ik} \quad (5)$$

Subject to, for each task, i.e. $\forall i=1, \dots, N$;

$$\sum_{k=1}^N x_{ik} = 1 \quad (6)$$

And for each workstation i.e. $\forall k=1, \dots, N$;

$$\sum_{i=1}^N t_i x_{ik} \leq C \quad (7)$$

$$x_{i2k1} \leq \sum_{k=1}^{k_1} x_{i1k} \quad \forall i_2, k = 1, \dots, N \quad \text{and} \quad i_1 \in P_{i2} \quad (8)$$

$$x_{ik} \in 0,1 \quad (9)$$

Considering that x_{ik} is equal to 1 if task i is associated with workstation k , otherwise x_{ik} is equal to zero,

Despite the immense academic effort, a very low proportion of publications about line balancing still involve real-world business problems. [15] present a survey involving more than 312 different published works, of which only 15 were related to real-world production systems. This disparity reveals a huge gap between the models and the configurations of real-world production systems.

2.3. Unbalanced Lines

The operation of a perfectly balanced line, where buffers are unnecessary, is extremely rare. Still, when compared to research according to line type, a much smaller amount is directed towards unbalanced lines [3, 16]. And this is not a new topic in academia. Research on unbalanced lines began in the 1960s, some years after the publication of the first articles about line balancing [17, 18]. And about 30 years later [19] it was still commented that this lack of research in literature was due to:

- the difficulty of analyzing lines with many degrees of freedom or longer production lines

- widespread use of models in the literature with exponential frequency distribution for the average process time, which prevents the decoupled analysis of the average process time and its coefficient of variation

The ideal condition involves meeting the needs of a perfectly balanced production line. But in many cases, this ideal condition is impossible to meet. An unbalanced line is, obviously, the one that is not perfectly balanced. Thus, similarly to line balancing problems, different approaches can be used to achieve different objectives [3]. Imbalance can be due to:

- Different average process times (TM)
- Different coefficients of variation of process times (CV)
- Combination of different average process times and coefficients of variation of process times
- Production lines and unreliable workstations
- Positioning and dimensions of buffers

Powell and Pyke [16] previously pointed out that unbalanced systems can achieve higher productivity than some unbalanced systems, so that line designers may deliberately create unbalanced lines. Atwater and Chakravorty Reference [20] studied the possibility of protective capacity serving as a resource to reduce transit times, especially those related to stockpiles. One of the main contributions in this area was named the “bowl effect” or “bowl shape” because of the shape of the process time graphs. The optimal TR would be achieved with slower workstations at the beginning and end of the line and faster in the center, resembling the shape of a bowl.

Hillier and Boling [21] analyzed lines of up to 4 stations with exponential time distribution between tasks, resulting in a gain in the productive rate - TR when compared to the balanced line. The result was ratified with investigations of up to six workstations with Erlang time distribution and TR improvements [22, 23] and with simulations of up to twelve workstations and exponential, normal and lognormal process time distributions [24].

Hudson, McNamara, and Shaaban [3] pointed out that [25] proposed a rule that located the worst-performing stations (lowest productive rate - TR or longest cycle time - CT) at the end of each line with other stations placed in any arrangement, in addition to a second rule that distributed the middle stations in a bowl shape. Good results were also found for the bowl shape. [26] used asymmetrical frequency distributions of cycle time with a bottleneck in lines with up to thirty workstations and work and found support for the better performance of the bowl shape. The results were also confirmed with lines of nine workstations, exponential CT distribution, and finite or non-existent bottlenecks. The robustness of the bowl shape configuration was confirmed for lines maintaining the improvement in productive rate - TR even in high degrees of imbalance of up to 10% difference between average time of the stations [26, 27]. Performance improvement using capacity imbalance across average cycle times was also investigated by [28], who found better machine efficiency, with less idle time using the bowl configuration. However, when observing work-in-process inventory (WIP), they found better performance by distributing workstations from slowest to fastest following the direction of product flow. Fry and Russell [29] tested, through simulations, six different types of capacity distribution configuration: balanced, bowl, V-shaped, linear, stepped, and segmented, as illustrated in Figure 2:

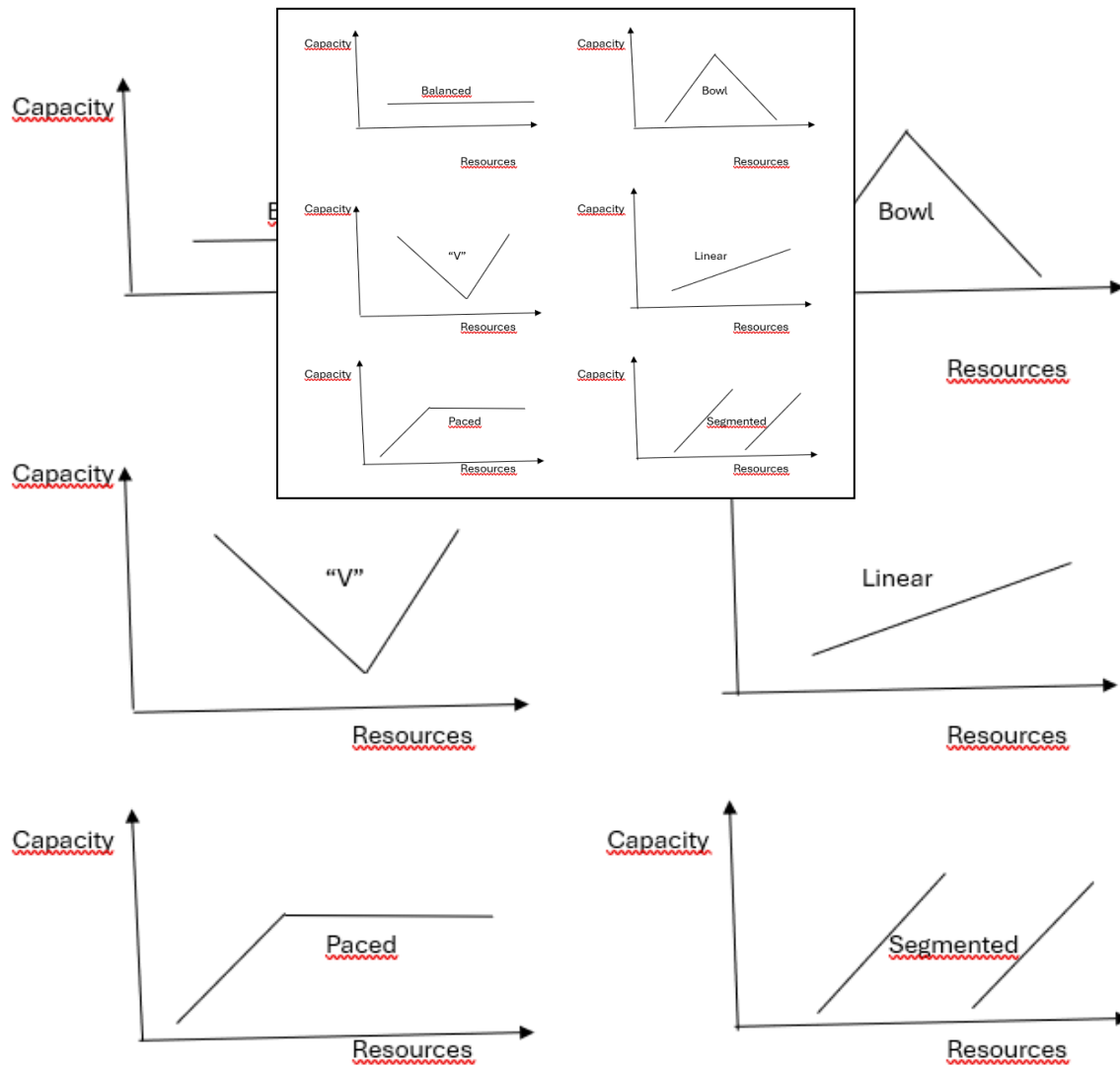


Figure 2: precedence chart

The results obtained indicate that the degree of variability of the processes and the size of the excess capacity of the non-bottlenecks is determinant in indicating which distribution has the best performance. Thus, production lines with a small amount of excess capacity (less than 10%), unbalanced configurations would have results equal to or better than the balanced configuration, in terms of TR and WIP. However, when the line capacity is well above market demand (greater than 20%), the balanced configuration proved to be more effective. Hudson, McNamara, and Shaaban [3] summarize that, although improvements were found for some of the bowl-shaped configurations, other imbalance patterns also showed equal or better performance than balanced lines, especially when the degree of imbalance was increased. The superiority of the bowl shape disappeared when the degree of imbalance was increased and for large buffer sizes, with the worst results in terms of machine downtime being found when the fastest workstations were positioned at the end of the production line.

Another contribution was made with the Theory of Constraints - TOC [30, 31, 32]. The approach considers that every production line has, or should have, at least one bottleneck or constraint. In this way, a specific set of rules

is proposed to manage the bottlenecks and optimize the flow of material: the drum-buffer-rope. This approach helped to spread the proposal of unbalanced lines under certain conditions, and new studies emerged comparing the performance of lines under different configurations, such as balanced versus unbalanced asynchronous lines and Just In Time - JIT [33, 34, 35].

It is important to mention that the principles of Just In Time and Kanban also consider that idle time of machines or stations is not the main problem of an assembly line. Ensuring that the material flow is constant, perfect line balancing would not be essential. Japanese managers, for example, would allow 12 percent to 18 percent of additional capacity in their production systems to guarantee Kanban [36].

These improvements lead to better material flow at the bottleneck and reduce the possibility of stoppage due to lack of material (starvation). In this way, better results are found in cycle time (CT) and a reduction in process variability. Most studies have been conducted based on production lines with few workstations, but there are also studies evaluating bigger lines. Some studies focus on the allocation and size of buffers as a form of imbalance, while others evaluate imbalance for different average process times, and others combine both effects. There are also studies focused on unbalanced lines and protective capacity. Table 1 summarizes some important studies and the characteristics used at the production lines, such as the number of workstations of the production line (N), the type of probability distribution used in the model, and the approach to resolution.

Table 1: Production lines characteristics

Paper	N	Distribution	Model
[40]	3	Normal	Analytical
[21]	3	Erlang	Analytical
[22]	3	Erlang	Simulation
[24]	Up to 12	Exp, Nor, Lognor	Simulation
[26]	30	Asymmetric	Simulation
[27]	9	Exponential	Simulation
[41]	5 and 8	Exponential	Simulation
[42]	4 – 10	-	Simulation
[43]	3, 4 and 12	-	Simulation
[44]	Up to 8	Lognormal	Simulation
[41]	5, 8 and 10	-	Simulation
[45]	2 – 3	Erlang	Anal. and Sim.
[46]	3	Exponential	Analytical
[47]	5	Normal	Anal. and Sim.
[48]	5 and 8	Weibull	Simulation
[49]	6	-	Simulation
[50]	4	Lognormal	Simulation
[51]	4	Lognormal	Anal. and Sim.
[52]	3	Exponential	Analytical

[53]	3 and 4	Exponential	Anal. and Sim.
[54]	3 – 7	Normal	Simulation
[33]	6	Normal	Simulation
[55]	3 – 27	Normal	Simulation
[37]	5	Lognormal	Simulation
[56]	4	-	Anal. and Sim.
[16]	2 – 4	Normal	Simulation
[57]	5 – 10	R. Shift Weibul	Simulation
[58]	3 and 8	Normal	Anal. and Sim.

Regarding methodology, research with smaller production lines typically uses analytical mathematical optimization models. For models with lines with more than 4 workstations, simulation and algorithm development prevail, given the difficulty of working with mathematical models for more complex situations.

It was in the second half of the 1990s that the main research involving both the comparison of the performance of unbalanced production lines and situations that favor the use of lines with balanced capacity were found [33, 37, 38, 39]. Since then, according to [3], much research has been done, but much uncertainty still exists involving the design procedures for unbalanced lines.

Table 2 below presents a summary of the main published works dealing with the topic of unbalanced lines. The table summarizes the approach used to address the subject in chronological order.

Table 2: Summary of the main contribution

Paper	Approach
[18]	Through simulation, it compares the performance of non-cadenced lines of various formats with cadenced lines.
[22]	Analytically evaluates the Performance of unbalanced production lines by comparing them with balanced production lines with up to 3 workstations.
[24]	Use simulations to test the effect of various types of imbalance on production rate and inventory levels under various configurations.
[23]	Tests results for ideal duration of unbalanced lines by changing the number of stations on the line, the space available for storage and the variability of operating times
[59]	It presents an analytical model of a line with 3 unreliable workstations with finite buffers.
[60]	Tests the robustness performance of lines with the Bowl Phenomenon through simulations.
[20]	Analyzes the effect of protective capacity in JIT lines and in lines with a bottleneck and the effect of the size and frequency of interruptions.
[61]	Evaluates the additional capacity added in the non-bottleneck and the

effect on Bottleneck Shiftiness.

- [33] Tests the performance of 3 different configurations, with Theory of Constraints, JIT and balanced line.
 - [27] Evaluate the robustness of the Bowl Phenomenon by testing the error in the imbalance estimate and the line's performance.
 - [16] It Creates a heuristic of rules that can be used to improve simple lines with random processing times and tests on longer lines - 4 stations.
 - [39] It presents a quantitative analysis of the balance and use of excess capacity in productive resources.
 - [37] Assess the best position to allocate protective cover on an unbalanced line.
 - [62] Alternating different levels of production capacity in non-bottleneck areas and verifying the impacts on average processing time and bottleneck shiftiness.
 - [63] Proposes an algorithm to solve the problem of optimal allocation of resources in longer production lines.
 - [53] Evaluates buffer and workload allocation on non-paced lines to propose heuristics to optimize TR and reduce inventory costs. Presents a model for lines with 3 and 4 stations and uses simulation for longer lines - 7 stations.
 - [57] Investigates the benefits of deliberately unbalancing cycle times for unreliable automated lines using simulation on lines with various sizes, buffer capacities, degrees, and patterns of unbalancing.
 - [54] Analyzes the presence of the Bowl Phenomenon in lines with integer working times through simulation.
 - [3] Conduct a literature review on the work produced about line imbalance.
-

Thus, very little has also been produced that involves the modeling of real production lines, in works on the distribution of productive capacities, regardless of whether they are balanced or unbalanced configurations [26]. It's also noticed that when using buffer control mechanisms, such as drum-buffer-rope, from Theory of Constraints, there is no studies relating to the total imbalance and the efficiency of the production line at all [64], which leaves room for some important questions raised by production managers.

3. Literature Review Analysis

A direct observation of the studies presented confirms [36] in which the prevalence is in research using simulation and shorter production lines. In our literature review, 64.3% of the papers listed in Table 1 used simulation, compared to 21.4% simulation and analytical and only 14.3% analytical. It is also possible to see that the most recent scientific production tends to point to the benefits of unbalanced production lines, although some work has still been done on production line balancing methods. But why, even though it is a clearly verifiable trend, is there still no consensus on the prevalence of capacity imbalance [64], and why is there no clear research focus on how to achieve the "best" capacity imbalance? Furthermore, why is there so little research done on real-world cases, with simulation studies being preferred instead? One way to verify the

relevance of a topic to the business environment is by assessing its financial impact and consequences, both in terms of reducing operational costs and maximizing gross revenue. Although we know that the impact of capital expenditure is relevant in the design of productive industrial units, no survey or direct mention of financial results obtained through optimization in capacity management projects was found in the literature. It is noticeable that research on unbalanced lines focuses on identifying the dynamics of imbalance under different operating conditions, mostly using simulation techniques. Surely these studies broaden our knowledge on the subject and help to highlight the gap that still exists in proposing a more effective model for designing production lines. But this isn't enough. Another important variable not considered in these studies, especially when we observe current business practice, is the impact of the variability of the production mix used in the assembly line. The dynamics of today's business environment mean that constant changes to manufactured products, design modifications, and updates are frequent and ongoing. It's rare to find companies that continue producing the same stock keeping unit (SKU) for an extended period without any alterations. Production lines need to be designed to ensure flexibility in offering new products, with different production cycle times per workstation, without requiring significant capacity changes. This is because modern consumer society is characterized by high volatility in demand and increasingly shorter product life cycles [6].

The literature review showed that researchers are very interested in understanding the dynamics of production systems without finding in these articles a deeper investigation into the effect of varied production mix and its impact on operational capabilities. Besides this impact of a variety of production mix, we couldn't find papers pointing out the financial results of the imbalance, even in throughput or inventory levels. The question about how to design a production line has been studied for more than 60 years, but most of the concern is still focused on how it works than how much the benefit is. Based on the survey and the problems still unsolved, we can suggest the following questions be the basis of future research:

- What are the aspects that should guide the decision of a capacity planning?
- Is it possible to reach the optimal status of financial feasibility for a production line design? How should it be calculated?
- How important is the product mix variability of a production line over the imbalance strategy?
- Does production line imbalance strategy reduce inventory level?

When focusing on the financial results and the feasibility of the strategy, probably more importance would be given by the decision makers and entrepreneurs, fostering more applied scientific production.

4. Limits of the Review

The purpose of this article is to enumerate some important questions still unaddressed about capacity planning in production lines, more specifically involving balancing and unbalancing them. The central objective of this work is to produce a literature review on the topic of capacity management, identifying open questions. However, this research is not expected to be complete and exhaust all possibilities of projects in production lines. Since there is a huge range of possibilities, from continuous production lines to batch processes, involving various alternative configurations, it would be unfeasible to seek a complete review. Furthermore, every model

is a small imitation of something real, and it would be very presumptuous to seek list all surveys that could represent a huge range of environments, even more so in a first attempt.

To better evaluate this issue, we sorted out the most pertinent studies and papers since the 1960's. The major keywords used for the research were capacity planning, balancing, unbalancing assembly lines, resource allocation and buffer management. Based in these first results, the research was open to more relevant works that based the topic.

Little research was found focused on analytical and mathematical models, which also suggests a promising avenue for future research.

However, there are still some limitations that can affect the study, such as the coverage of the topic focusing in unbalancing capacity and the accuracy and reliability of the research system. We applied exclusion and inclusion criteria and created a research string in the data selection process to minimize the possibility of leaving relevant research out of the literature review, but it can't be ruled out.

5. Conclusion

Based on the review of literature conducted, it was found that most of the scientific production focuses on simulation models of smaller production lines, with up to 5 workstations. Even with significant progress, the low prevalence of case studies and real-world applications, where it is possible to evaluate the return on investment in extra protective capacity, is still evident. Capacity imbalance is shown as a trend, but very few application proposals are presented. The first topic proposed for future research, therefore, is combining theoretical studies with case studies, to better validate the models applied.

The second topic involves the central questions: If it's possible to achieve better productivity results by investing in extra capacity for certain resources, how much additional capacity would be feasible to incorporate into the project? And how would we measure the results? Such questions are more detailed at the preview literature review analysis.

Thus, a lack of research was found that provides a basis for the financial decision to unbalance production lines, as well as justification for the level of unbalance that can be justified: how much productive capacity can be added at specific points in the line to make the investment worthwhile, and approaches for future work were suggested.

The third and final topic suggested by this review is related to the lack of analytical models to represent mainly the unbalanced production lines and the feasibility of working with a flexible and mutant product mix, that allows changes in product cycle times, additions or removals of tasks without significant changes at the production line structure, while guaranteeing optimized results. The suggestions presented are not exhaustive and should only contribute to a new direction in future work, in a way that many other questions may arise from future branches.

6.Conflict of Interest

The author declares that he has no conflict of interest.

References

- [1] A. Dolgui; N. Guschinsky and G. Levin. "A mixed integer program for balancing of transfer line with grouped operations." in: *Proceedings of the 28th International Conference on Computer and Industrial Engineering*, 2001, pp. 5-7.
- [2] S. Shaaban; T. McNamara and S. Hudson. "Mean time imbalance effects on unreliable unpaced serial flow lines". *Journal of Manufacturing Systems*, 2014.
- [3] S. Hudson; T. McNamara and S. Shaaban. "Unbalanced lines: where are we now?". *International Journal of Production Research*, v.53, pp; 1895-1911, 2015.
- [4] H. Tempelmeier. "Practical considerations in the optimization of ow production systems". *International Journal of Production Research*, v.41, pp. 149-170, 2003.
- [5] B. Rekiek; A. Delchambre; A. Dolgui and A. Bratcu. "Assembly line design: a survey," in *Proceedings IFAC Volumes*, 2002b.. pp. 4474-6670.
- [6] J. LI; D. E. Blumenfeld and S. P. Marin. "Production system design for quality robustness". *IIE Transactions*, v. 24, pp. 162-176, 2008.
- [7] S. Axsater. *Inventory Control*. Lund: LLC, 2006.
- [8] A. W. Sloan. *A Study on the Effect of Protective Capacity on Cycle Time in Serial Production Lines*. S1: Mississippi State University, 2001.
- [9] D. R. Anderson; C. L. Moodie. "Optimal buffer storage capacity in production.". *The International Journal of Production Research*, v.7, pp. 233-240, 1968.
- [10] W. J. Hopp; M. L. Spearman. *Factory physics*. Long Grove: Waveland Press, 2011.
- [11] Y. Dallery; S. B. Gershwin. "Manufacturing ow line systems: a review of models and analytical results". *Queueing systems*, v. 12, n. 1-2, pp. 394, 1992.
- [12] K. N. Genikomsakis; V. D. Tourassis. "A simulation-based assessment of alternative assembly line configurations". In: *Systems, Man and Cybernetics*, 2008. SMC 2008. IEEE International Conference on. [S.l.]: IEEE, 2008. pp. 1626-1631.
- [13] B. Rekiek; A. Dolgui; A. Delchambre; A. Bratcu. "State of art of optimization methods for assembly

line design". *Annual Reviews in Control*, v. 26, n. 2, pp. 163-174, 2002.

- [14] M. E. Salveson. "The assembly line balancing problem". *Journal of Industrial Engineering*, v. 6, n. 3, pp. 1825, 1955.
- [15] N. Boysen; M. Fliedner; A. Scholl. "Assembly line balancing: Which model to use when?" *International Journal of Production Economics*, v. 111, n. 2, pp. 509-528, 2008.
- [16] S. G. Powell; D. F. Pyke. "Buffering unbalanced assembly systems". *IIE transactions*, v. 30, n. 1, pp. 55-65, 1997.
- [17] K. F. H. Murrell. "Operator variability and its industrial consequences". *The International Journal of Production Research*, v. 1, n. 3, pp. 39-55, 1961.
- [18] L. E. Davis. "Pacing effects on manned assembly lines". *International Journal of Production Research*, v. 4, n. 3, pp. 171-184, 1965.
- [19] S. G. Powell. "Buffer allocation in unbalanced three-station serial lines". *International Journal of Production Research*, v. 32, n. 9, pp. 2201-2217, 1994.
- [20] J. B. Atwater; S. S. Chakravorty. "Does protective capacity assist managers in competing along time-based dimensions?" *Production and Inventory Management Journal*, 1994.
- [21] F. S. Hillier; R. W. Boling. "Effect of some design factors on efficiency of production lines with variable operation times". *Journal of Industrial Engineering*, v. 17, n. 12, pp. 651, 1966.
- [22] F. S. Hillier; R. W. Boling. "Toward characterizing the optimal allocation of work in production line systems with variable operation times". *Advances in Operations Research*, pp. 109-119, 1977.
- [23] F. S. Hillier; R. W. Boling. "On the optimal allocation of work in symmetrically unbalanced production line systems with variable operation times". *Management Science*, v. 25, n. 8, pp. 721-728, 1979.
- [24] T. E. El-Rayah. "The effect of inequality of interstage buffer capacities and operation time variability on the efficiency of production line systems". *International Journal of Production Research*, v. 17, n. 1, pp. 77-89, 1979.
- [25] G. Yamazaki; H. Sakasegawa; J. G. Shanthikumar. "On optimal arrangement of stations in a tandem queueing system with blocking". *Management Science*, v. 38, n. 1, pp. 137-153, 1992.
- [26] R. Pike; G. E. Martinj. "The bowl phenomenon in unpaced lines". *The International Journal of Production Research*, v. 32, n. 3, pp. 483-499, 1994.

- [27] F.. S. Hillier; K. C. So. "On the robustness of the bowl phenomenon". *European journal of operational research*, v. 89, n. 3, pp. 496-515, 1996.
- [28] S. Shaaban; T. McNamara. "The effects of joint operations time means and variability unbalance on production line performance". *International Journal of Manufacturing Technology and Management*, v. 18, n. 1, pp. 59-78, 2009.
- [29] T. Fry; G; Russell. "Capacity allocation strategies in a hypothetical job-shop". *The International Journal of Production Research*, v. 31, n. 5, pp. 1097-1115, 1993.
- [30] E. M. Goldratt. "The unbalanced plant". In: *APICS 24th Annual International Conference Proceedings*. [S.l.: s.n.], 1981.
- [31] E. M. Goldratt; J. Cox. *The Goal*. Great Barrington: North River Press, 1984. pp. 385.
- [32] M; Gupta; D. Snyder. "Comparing TOC with MRP and JIT: a literature review". *International Journal of Production Research*, v. 47, n. 13, pp. 3705-3739, 2009.
- [33] S. S. Chakravorty; J. B. Atwater. "A comparative study of line design approaches for serial production systems". *International Journal of Operations & Production Management*, v. 16, n. 6, pp. 91-108, 1996.
- [34] W. A. Sloan. "A Study on the Effect of Protective Capacity on Cycle Time in Serial Production Lines". [S.l.]: *Mississippi State University*, 2001.
- [35] S. Kim; J. F. Cox; V. J. Mabin. "An exploratory study of protective inventory in a re-entrant line with protective capacity. *International Journal of Production Research*", v. 48, n. 14, pp. 4153-4178, 2010.
- [36] L. J. Krajewski; B. E. King; L. P. Ritzman; D. S. Wong. "Kanban, MRP and shaping the manufacturing environment". *Management Science*, v. 33, n. 1, pp. 39-57, 1987.
- [37] C. W; Craighead; J. W. Patterson; L. D. Fredendall. "Protective capacity positioning: Impact on manufacturing cell performance". *European Journal of Operational Research*, v. 134, pp. 425-438, 2001.
- [38] C-M. Liu; C-L. Lin. "Performance evaluation of unbalanced serial production lines". *International Journal of Production Research*, v. 32, n. 12, pp. 2897-2914, 1994.
- [39] F. B. Souza; S. R. Pires. "Analise e proposicoes sobre o balanceamento e uso de excesso de capacidade em recursos produtivos". *Gestao & Producao*, v. 6, n. 2, 1999.
- [40] W.-M; Chow. "Buffer capacity analysis for sequential production lines with variable process times". *International Journal of Production Research*, v. 25, n. 8, pp. 1183-1196, 1987.

- [41] S. Shaaban; S. Hudson. "The performance of unpaced serial production lines with unequal coefficients of variation of processing times". *International Journal of Computer Applications in Technology*, v. 34, n. 2, pp. 122-128, 2009.
- [42] C. A. Carnall; R. Wild. "The location of variable work stations and the performance of production flow lines". *The International Journal Of Production Research*, v. 14, n. 6, pp. 703-710, 1976.
- [43] P. D. L. Wyche; R. Wild. "The design of imbalanced series queue ow lines". *Journal of the Operational Research Society*, v. 28, n. 3, pp. 695-702, 1977.
- [44] H.-S. Lau. "On balancing variances of station processing times in unpaced lines". *European Journal of Operational Research*, v. 61, n. 3, pp. 345-356, 1992.
- [45] N. P. Rao. "On the mean production rate of a two-stage production system of the tandem type." *The International Journal of Production Research*, v. 13, n. 2, pp. 207-217, 1975.
- [46] E. J. Muth; A. Alkaff. "The bowl phenomenon revisited". *International Journal of Production Research*, v. 25, n. 2, pp. 161-173, 1987.
- [47] S. Hutchinson; J. Villalobos; M. Beruvides. "Effects of high labor turnover in a serial assembly environment". *International Journal of Production Research*, v. 35, n. 11, pp. 3201-3224, 1997.
- [48] S. Shaaban; T. McNamara. "Improving the efficiency of unpaced production lines by unbalancing service time means. International". *Journal of Operational Research*, v. 4, n. 3, pp. 346-361, 2009.
- [49] A. L. Patti; K. J. Watson. "Downtime variability: the impact of duration frequency on the performance of serial production systems". *International Journal of Production Research*, v. 48, n. 19, pp. 5831-5841, 2010.
- [50] S. N. Kadipasasaoglu; W. Xiang; S. F. Hurley; B. M. Khumawala. "A study on the effect of the extent and location of protective capacity in ow systems." *International Journal of Production Economics*, v. 63, n. 3, pp. 217-228, 2000.
- [51] J. H. B. Jr.; J. F. C III. "Designing unbalanced lines-understanding protective capacity and protective inventory". *Production Planning & Control*, v. 13, n. 4, pp. 416-423, 2002.
- [52] M. C. Freeman. "The effects of breakdowns and interstage storage on production line capacity". *Journal of Industrial Engineering*, v. 15, n. 4, pp. 194-200, 1964.
- [53] M. S. Hillier. "Designing unpaced production lines to optimize throughput and work-in-process inventory". *IIE Transactions*, v. 45, n. 5, pp. 516-527, 2013.
- [54] P. B. Castellucci; A. M. Costa. "A new look at the bowl phenomenon". *Pesquisa Operacional*, v. 35, n.

1, p. 57-72, 2015.

- [55] W.-C. Chiang; T. L. Urban; X. Xu. "A bi-objective metaheuristic approach to unpaced synchronous production line-balancing problems". *International Journal of Production Research*, v. 50, n. 1, pp. 293-306, 2012.
- [56] A. Dolgui; A. Eremeev; A. Kolokolov; V. Sigaev. "A genetic algorithm for the allocation of buffer storage capacities in a production line with unreliable machines." *Journal of Mathematical Modelling and Algorithms*, v. 1, n. 2, pp. 89-104, 2002.
- [57] S. Shaaban; T. McNamara; S. Hudson. "Mean time imbalance effects on unreliable unpaced serial flow lines." *Journal of Manufacturing Systems*, 2014.
- [58] T. L. Smunt; W. C. Perkins. "Stochastic unpaced line design: A reply." *Journal of Operations Management*, v. 8, n. 1, pp. 55-62, 1989.
- [59] S. B. Gershwin; I. C. Schick. "Modeling and analysis of three-stage transfer lines with unreliable machines and finite buffers". *Operations Research*, v. 31, n. 2, pp. 354-380, 1983.
- [60] T. L. Smunt; W. C. Perkins. "Stochastic unpaced line design: review and further experimental results." *Journal of Operations Management*, v. 5, n. 3, pp. 351-373, 1985.
- [61] S. R. Lawrence; A. H. Buss. "Shifting production bottlenecks: causes, cures, and conundrums". *Production and operations management*, v. 3, n. 1, pp. 21-37, 1994.
- [62] J. W. Patterson; L. D. Fredendall; C. W. Craighead. "The impact of non-bottleneck variation in a manufacturing cell." *Production Planning & Control*, v. 13, n. 1, pp. 76-85, 2002.
- [63] N. Nahas; D. Ait-Kadi; M. Nourelfath. "A new approach for buffer allocation in unreliable production lines". *International journal of production economics*, v. 103, n. 2, pp. 873-881, 2006.
- [64] S. S. Chakravorty; J. B. Atwater. "The impact of free goods on the performance of drum-buffer-rope scheduling systems". *International Journal of Production Economics*, v. 95, n. 3, pp. 347-357, mar 2005.