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Comparative Simulation of the Production Flow with the Implementation of Kanban and DBR

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Abstract
Currently, we live in a culture of being overly busy, but this does not translate into efficiency, speed of implementation of the actions taken. Enterprises are constantly looking for methods and tools to make them more efficient. The most popular method of production management is Lean Manufacturing, less known is Theory of Constraints. This work is a continuation of the research on the comparison of these methods with apply a computer simulation, which the analyzed production process in the selected enterprise, after 24 hours and week. An attempt was made to simplify the comparison of the methods based on the obtained simulation in terms of costs. In analyzed case, more advantageous solution is to use the DBR method. To produce various orders that do not require 100% production on the bottleneck position, the use of Kanban is a frequent practice as it provides greater flexibility in order execution.

Keywords
Modeling for control optimization; Real-time control; Process control; Lean Manufacturing; Theory of constraints.

Introduction

We now live in an over-busy culture where it is good to be busy. During multitasking, we start many projects, but this does not translate into efficiency, speed of implementation of actions taken, initiatives, what is more, it causes pressure, which causes us to spend most of our time re-implementing the matter. The contemporary realities of work assume that a more effective approach to work is based on the principles of a sports relay race, which is when there is no work, the employee is not working, when there is work, the employee does it as quickly as possible, maintaining the appropriate quality (Trojanowska, 2011). Internal pressures occurring in enterprises to improve the efficiency of the functioning of enterprises, often requiring reducing operating costs, improving the use of resources, increasing throughput, process integration or knowledge management (Łopatowska, 2014)], make enterprises look for methods and tools that will make them more efficient and effective every day competitive.

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Over the years, many production management methods have been developed. Lean Manufacturing is the most common and most frequently used method of production management in enterprises. Lean creates the work culture of the enterprise in such a way that everyone involved is focused on continuous improvement. Currently, the Lean method uses several dozen complementary tools and techniques that simplify the production process, positively affecting the effectiveness of the entire enterprise (Woeppel, 2000). One of the methods is Kanban, which belongs to pull systems, which is based on production to order not to the warehouse. Kanban consists in synchronizing the need to replace or supplement the materials necessary for production. It allows to integrate the material flow with the workplace for all workstations, reducing the amount of work-in-progress by using visual signals. Lean assumes providing the customer with the highest quality products while minimizing waste. Another method of management and improvement is the Theory of Constraints, which was formulated by E. Goldratt, according to which the organization is as good as its weakest link. Goldratt proposes to remove or manage bottlenecks by using Drum–Buffer–Rope (DBR) Methodology (Goldratt, 1984). The key to its application is to identify this constraint, as it is the overall constraint that determines the capabilities of the process. The foundation of the theory of constraints is to concentrate all resources on a constraint, known as a "bottleneck", and then strengthen the constraint (Goldratt, 1984). The throughput of the production system is the same as a bottleneck, a limitation, which is the improvement of throughput depends on the weakest link (Łopatowska, 2011). The purpose of The Theory of Constraints is to help managers and organizations think about constraints, develop breakthroughs solutions, and implement them successfully (Rogowska, 2021). Both Lean and The Theory of Constraints strive to improve the use of resources as well as the operational results obtained, which increases the effectiveness of the organization's functioning (Łopatowska, 2013). Each of them, however, does it in a separate way.

The scientific aim of the article is to compare the effectiveness of the Kanban and DBR (Drum–Buffer–Rope) methods in the production process through computer simulation, using a selected company from the packaging industry as an example. The analysis will be conducted after 24 hours and after a week, and the results will be compared to evaluate the potential benefits and limitations of using DBR instead of Kanban. The article also aims to fill the research gap regarding the lack of access to relevant data in comparative studies of the effectiveness of these methods. The use of computer simulation in this work is novel, as it will allow for a thorough examination of the effectiveness of the Kanban and DBR methods in real working conditions in the packaging industry, providing more precise results than previous theoretical research. This study is also unique in that it is the first to compare the effectiveness of the two methods through computer simulation, whereas previous research has often involved theoretical analysis or real-world experiments which have not been as accurate.

The paper presents a theoretical introduction on Lean Manufacturing and TOC, and how Kanban and DBR methods have been improved. The methodology of work is presented. The results obtained from the computer simulation for both methods were subjected to a comparative analysis and discussion. The whole work was summarized and further research directions were indicated.

Literature review

Many production management methods have been developed over the years. The most popular method of production management is Lean Manufacturing, and Kanban in particular.

Lean Manufacturing – Kanban

Lean has evolved much. Among others, lean could be a way (Howell, 1999), a process (Womack et al., 1990), behavior-driven (Bicheno, 2016), a philosophy (Liker, 2004; Alukal, 2003; Shah and Ward, 2007; Goshime et al., 2018), a practice (Simpson and Power, 2005), a system (Womack and Jones, 1994; Hopp and Spearman, 2004), a manufacturing paradigm (Seth and Gupta, 2005), or a model (Alves et al., 2012). The main opponent of the production process is waste (Monden, 1993). "The goal of Lean Manufacturing is to be highly responsive to customer demand by reducing waste" (Bhamu and Sangwan, 2013).

Kanban has evolved from a production system developed by Taiichi Ohno in the 1950s to a method of managing projects and business processes. Many different forms of Kanban have been developed over the years. Kanban is a visual way to manage tasks and workflows, which utilizes a Kanban board with columns and cards. Thus, the overall situation of the project can be seen immediately, while the continuous flow of task cards indicates the progress of the project over time (Ikonem et al., 2011). It has been enhanced by the introduction of new tools and technologies, such as electronic Kanban boards and Kanban-based project management software. Kanban is enhanced by adding various methods and tools that allow for more effective management of projects and processes. Examples of these improvements include:

- Introducing Work In Progress (WIP) limits to control the amount of work simultaneously performed by the team, which allows for better use of resources and increased efficiency (Anderson, 2010).
- Using Flow Mapping to better understand and optimize business processes.
- Introduction of Service Classes to define quality levels and priorities for different types of tasks.
- Introduction of the Pull Policy to workflow management, which allows for more effective adjustment of performed tasks to the current needs of the project.
- The introduction of workflow visualization tools (Kanban Board) allows for easier project control and management. Despite the demand for visualization of the workflow there are no special guidelines about how to apply the content of the Kanban board (Nur, 2021). "Kanban board visualizes the activities of the development process and keeps WIP in control" (Alaidaros et al., 2016).

These and other enhancements allow for more efficient project and process management, as well as better adapting Kanban to different industries and business situations.

Additionally, its use has expanded beyond the manufacturing industry to various other fields such as IT, healthcare, and services. Nowadays, Kanban is often used as part of an agile methodology such as Scrum (Senapathi, 2020; Gaete 2021; Aurisch, 2021). "The beauty of the Kanban method is that it can be adopted immediately to the current state of the process. From there, we can evolve in small steps by recognizing bottlenecks, waste, and variability that affect the process performance" (Raju and Krishnegwoda, 2003).

Theory of Constraints – Drum–Buffer–Rope

The Theory of Constraints (TOC) by Israeli physicist Dr. Eliyahu Moshe Goldratt is a production management method that assumes that every company has constraints that can affect its performance and efficiency. The theory focuses on eliminating or appropriately managing constraints in a flow. In TOC material flow, it is essential that materials are available where they are needed, in the right quantity and at the right time. TOC assumes that the flow of materials should be as simple and effective as possible, and that it should be adapted to the needs of the customer.

Since its first publication, The Theory of Constraints has evolved and developed into an increasingly complex management tool. Currently, it is considered one of the most important and effective ways to improve the efficiency and effectiveness of business processes. The theory has been refined with tools such as Critical Chain Project Management (CCPM) and Drum–Buffer–Rope. (Goldratt, 1997; Goldratt, 1984) These tools allow for better identification and elimination of limitations, as well as better management of projects, production, and supply chain.

The main element of TOC Drum–Buffer–Rope is the concept of "drum", which represents the constraint that has the greatest impact on the entire production process. All production activities must be adapted to the speed of the drum. "Rope" is a tool that allows you to control the pace of production so as not to exceed the speed of the drum. It performs a signaling function to release inventory in the process, ensuring process throughput. It ensures the delivery of materials to the workstations of a limited resource, forcing the process to store only the material that is scheduled on the drum (Arora, 2004). This allows you to avoid overproduction and related costs. The "buffer" is a reserve of materials and time that allows you to absorb unplanned changes in the production process. The buffer is set before the (drum) limit and allows the drum rate to be followed even if there are unplanned changes in the production process (Tomaszewska, 2022).

Instead of focusing on labor cost reduction, the most logical way to increase the company's profitability was to increase throughput. The use of the constraint in conjunction with the equalization of the pace of work of all elements of the enterprise and the supply chain leads to improved production flexibility, shortening the time of order fulfillment, lowering costs, and improving customer satisfaction (Łopatowska, 2014).

Table 1 shows a comparison between Kanban and Drum–Buffer–Rope method.

Table 1
Comparison between Kanban and DBR method

Area	Comparison methods	
	Kanban	DBR
Idea	increasing profit by enhancing the added value of the product from the customer's point of view	increase your profit by increasing your throughput
Organization of the flow	continuous	compliance with constraint
Stimulation	the customer sets the pace	constraint sets the pace
Production enviroment	repeatable production	serial and unit production
Flow type	pull	pull
The sequence of operations	FIFO	FIFO
Methods implementation steps	5 Lean principles	POOGI
Inventory	elimination of all possible	managing enough quantity to maximize the flow of constraint
Component	supermarket, Kanban	buffer, rope
Result	lower production costs and prevention of waste	increased production capacity

Source: Tomaszewska (2022), Production flow between workstations using the Kanban and DBR methods – comparative study, Lecture Notes in Mechanical Engineering: Advances in Manufacturing III, pp. 225–236

The use of Lean is aimed at reducing the costs achieved by eliminating any type of waste and slimming the organization. On the other hand, the Theory of Constraints focuses on management through the full use of the possibilities of limitation, subordinating all resources to them, which translates into the maximization of the company's throughput. Both concepts draw attention to the need to engage employees and the importance of human capital in shaping and improving business. Both the TOC and the Lean concept emphasize flexibility of operation and adaptation to customer needs, using solutions that enable direct response to customer needs (among others Kanban system in the Lean concept, snare-buffer-rope method in TOC) and the delivery of small batches of various products. (Łopatowska, 2014).

Although Kanban and the Theory of Constraints are different management tools, they can be used together to improve production processes. Kanban can be used to visualize workflows and monitor progress, while the Theory of Constraints helps identify and remove constraints that may hinder the achievement of organizational goals.

Materials and methods

Constraints can be external or internal. It is easier for the company to manage internal constraints as they can be operator, machine, or company policy (Trojanowska, 2011). In the article, in connection with the continuation of the considerations, the existence of an internal limitation was assumed, which was identified based on the observation of the flow of material in the analyzed production process. The author used the elementary method of scientific work – the method of (direct) observation, which is exploratory in nature and is characterized by premeditation, planning, purposefulness, activity, and regularity. The work is based on a specific case study, defined in the literature as a detailed study of a single person, group, or event, in particular, to present and investigate the reasons underlying its principles.

The work methodology consists of several stages.

Theoretical introduction, which present the concepts and principles of the Kanban and DBR methods and their application in the manufacturing industry. Selection of a company for research – identification of a manufacturing company that already uses the Kanban method and a preliminary analysis of its production process. The case study was a company from the printing industry, dealing with the production of packaging. A fragment of the production process was analyzed, which included three successively occurring stations, the middle of which was indicated as a bottleneck. (Tomaszewska, 2022). Completion of a computer report: development of a simulation model based on data from the company and reports for both methods (Kanban and DBR). A computer simulation with the use of dedicated software was used to analyze the discussed case study. Simulation allows for efficient execution of experiments in which performing analytical calculations is too laborious, and sometimes even impossible. The simulation shows a specific process from start to finish and allows you to change the parameters and its course. On the other hand, the purpose of its application is not only to facilitate the understanding of the essence of the modeled phenomenon, the functioning of a specific process, but also to learn how to make decisions in specific conditions. (Raczyńska, 2010). Results analysis, which included a summary of the results for both methods in terms of results, indicators and other criteria. Presentation of test results and indication of test results.

An important aspect of the methodology is also the use of company data and a computerized report for Kanban and DBR analysis, which allows the results to be taken into account further than just initial consideration.

Results

The schedule for delivering the raw material to the first station is one pallet every half hour. In the following order:

- raw material A – 11 pallets of 3550 sheets,
- raw material B – 26 pallets, 3250 sheets each
- raw material C – 11 pallets with a non-standard number of sheets (2800, 2700, 3200, 3550, 2800, 2700, 3550, 2700, 3250, 3500, 2750).

According to the schedule, the raw materials are delivered to the storage field (Buffer) in front of the machine (M1), which processes them. Then the raw material is delivered to the buffer before the next station (M2), where 90% is delivered to the buffer before the third machine (M3), and 10% is waste. 95% of the product from third workplace is transported for shipment and 5% is waste. One employee is assigned to each machine, working in a 2-shift system. The model was generalized, and the working time was assumed 24/7, with a total planned break for a meal – 1 hour during the day.

The collective assumptions of the model are presented in Table 2.

To generalize the model, the following factors were not considered: special reasons disrupting the production process, the time of transferring changes, and employee training. Both shift changeover times and production preparation times are critical to the efficiency of the production process. To reduce downtime

Table 2
Assumptions of the model Kanban

	Assumptions of the model		
	M1	M2	M3
speed	16 500 sh/h to 10 500 sh/h	5 500 sh/h to 3 500 sh/h	10 000 sh/h to 8 000 sh/h
C/C	0.21 to 0.34	0.73 to 1.03	0.36 to 0.45
C/T	0.25	0.90	0.40
The size of the buffer before the workplace	max 7100 sh (that is 2 pallets after 3550 sh)	max 35500 sh (that is 10 pallets after 3550 sh)	max 7100 sh (that is after 3550 sh)
% amount of raw material	100%	90%	95%
workers	2	2	2

Source: own study

and increase productivity, the company employs various strategies, such as speeding up tool changes, using production planning tools such as the SMED method and Lean Manufacturing principles. Micro-stoppages have been included in the form of a cycle time interval for each machine, among others the cycle time for an M1 is 0.21–0.34. But also, the interval for the cycle time was indicated to make the work of the machines more realistic. Moreover, the model assumes that the order is performed in 100% by the machine marked as a bottleneck in the production process. Cooperation of orders that may be omitted in the process from second workplace was not considered. The production cycle is the time needed for a specific part of the raw material to be taken from the material warehouse, subjected to all processing operations and control activities, and transferred to the warehouse in the form of finished products (Trojanowska, 2011).

The author conducted a computer simulation of 24 hours and seven full days of the production process using the Kanban method. An exemplary statistical report was obtained showing the job occupancy after 24 hours (Fig. 1) and after a week of work (Fig. 2).

The simulation was also conducted using the DBR method instead of the Kanban method. Assumptions regarding C/C, C/T and the buffer capacity before positions have been changed and shown in Table 3.

Buffer size is a short-term problem because buffers can be modified and adapted to your company's circumstances and conditions. It is an individual matter for each process (Practice shows that if during

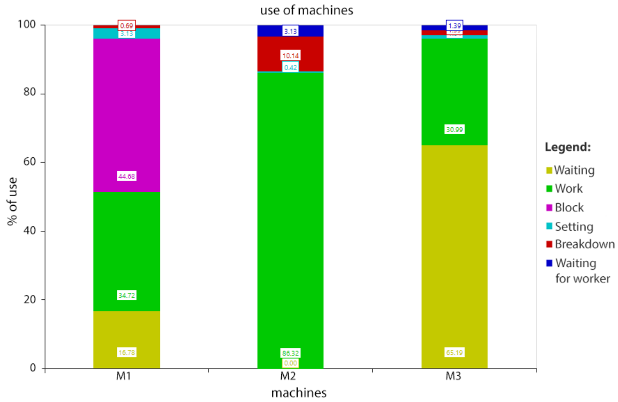

Fig. 1. Use of machines after 24 hours – Kanban
Source: own study

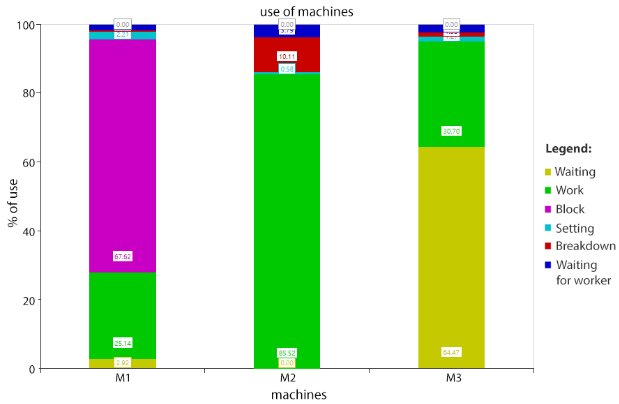

Fig. 2. Use of machines after 7 days – Kanban
Source: own study

Table 3
Assumptions of the model DBR

	Assumptions of the model		
	M1	M2	M3
speed	5 500 sh/h to 3 500 sh/h	5 500 sh/h to 3 500 sh/h	5 500 sh/h to 3 500 sh/h
C/C	0.73 to 1.03	0.73 to 1.03	0.73 to 1.03
C/T	0.90	0.90	0.90
The size of the buffer before the workplace	max 3600 sh that is 1 pallet	28400 sh that is 8 pallets	max 3600 sh that is 1 pallet
% amount of raw material	90%	90%	90%
workers	2	2	2

Source: own study

a month less than 5% of orders will go to the red zone, the buffer should be decreased by 15%. However, if more than 5%, the buffer should be increased by 15%.) (Trojanowska, 2011). "The buffer size is given as the total time of predicted processing times of operations that the buffer handles in." Park et al., (2007) proposed the buffer size setting method for DBR scheduling providing numerical model for the buffer size that was not shown for DBR scheduling – when production ordering is rapidly changed (Park et al., 2007). The buffer must be large enough for the resource being the constraint to work according to the schedule assigned to it during the corrective actions (Trojanowska, 2011).

An exemplary statistical report of the simulation using the DBR method instead of Kanban was obtained, specifying the occupancy of positions after 24 hours (Fig. 3) and after a week of work (Fig. 4).

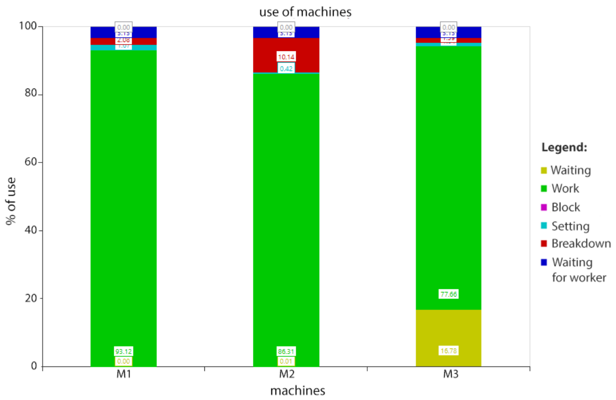

Fig. 3. Use of machines after 24 hours – DBR
Source: own study

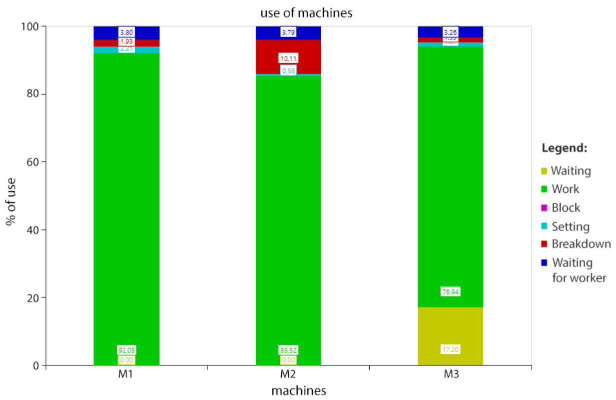

Fig. 4. Use of machines after 7 days – DBR
Source: own study

Moreover, a simplified simulation of the process costs during the application of the Kanban and DBR methods was performed.

The assumptions made are as follows:

- machine running cost per hour M1 = 50,
- machine running cost per hour M2 = 30,
- machine running cost per hour M3 = 20,
- cost per operation M1 = 0.75 (these can be the costs of 1 sheet passing through the machine, because then the sheets going to the "scrap" – waste will also be considered),
- cost per operation M2 = 0.25,
- cost per operation M3 = 0.5,
- revenue for product A = 25,
- revenue for product B = 20,
- revenue for product C = 40.

The cost of an employee's work can be included in the cost of the machine's work.

Based on the assumptions, the following simulation results obtained for each method are presented in the Table 4.

Table 4
Comparision assumptions of the models Kanban & DBR

	Comparision	
	Kanban	DBR
Profit after 24 hours	1 217 346	1 356 273
Profit after 7 days	8 869 357	9 022 202

Source: own study

The calculations did not consider operating outlays, such as energy, rental, and salaries, as well as investments such as stocks of materials and raw materials, other resources, such as buildings, land, machines. Too little specific information, therefore, there is no capacity calculation from the TOC.

Discussion

The table shows a comparison of the values of manufactured products A, B, C using the Kanban method and DBR instead of Kanban. Table 5 is a summary of the statistical report by week.

Based on the (Table 5) and the graphical presentation (Fig. 5) of the machines use simulation on the analyzed stations, it is possible to notice better process synchronization when using the DBR method, when all stations operate at the limitation pace. In the case of the (Ultimate Guide to Kanban, 2022) Kanban method, the raw materials issued according to the order schedule could not be issued above the buffer size limit in front of first station. Therefore, the simulation graphically shows the situation in the form

Table 5
Summary report – comparision methods

Area	Comparision methods	
	Kanban	DBR
% Of machine No. 1 work	27	92
% Of machine No. 2 work	94	92
% Of machine No. 3 work	34	83
Work-In-Progress A	18295	6244
Work-In-Progress B	5371	868
Work-In-Progress C	18936	0
Sigma Product Index A	2.563	2.566
Sigma Product Index B	2.561	2.557
Sigma Product Index C	2.558	2.562
Quantity produced – A	118 263	117 129
Quantity produced – B	249 049	227 537
Quantity produced – C	81 083	95 486
Sum of the quantity produced	**448 395**	**440 152**

Source: own study

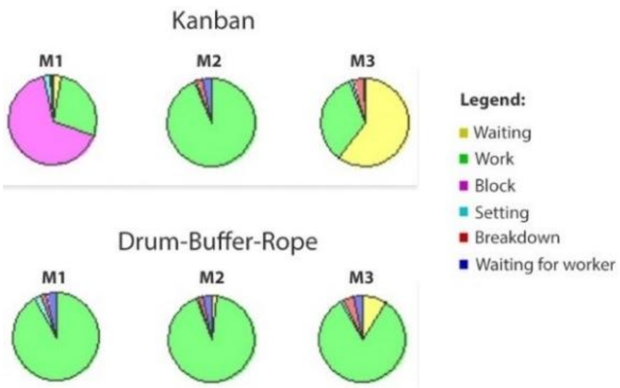

Fig. 5. Comparison methods Kanban & DBR – use of machines after 7 days. Source: own study

of a blockage marked with a purple color on the chart. This was due to reaching the buffer size limit before the second station, which was indicated as a bottleneck of the process because the work is performed the slowest. On the other hand, according to the assumptions, the third station works faster, which is why the yellow color indicates wastage in the form of waiting for a semi-finished product from second station. It is a simplified model, the execution of orders is based on the use of each station, does not include parallel work or cooperation.

In the long-term perspective, in the analyzed case of the week, the simulation shows that the use of the DBR method is more beneficial if the company wants to synchronize the use of machines. Estimated profit increased by 152,845 compared to the Kanban method. In the analyzed case, after the weekly simulation, there are 8,243 more products produced using the Kanban method. To produce various orders that do not require 100% production on a bottleneck position, the use of Kanban is widely practiced. Because it allows you to maneuver between different jobs, using other waiting machines while the bottleneck station is slower. This enables the execution of more orders.

Conclusions

Increasingly common is the modern approach to production management, which uses the use of computer simulation that maps the production process of the enterprise. Thanks to this, the management could analyze many variants of work in a virtual model, rather than in a living organism.

Both Lean and TOC focus on continuous improvement and control of material flow in the production hall. The continuous improvement process in the theory of constraints is the result of concentrating all efforts on the purpose of the system (Tomaszewska, 2022). This process is the basis of the theory of constraints, including the management accounting it postulates. Applying the theory of constraints positively influences the flow and increases the production throughput, and will also allow achieving long-term profits thanks to the proper management of constraints in the enterprise. Both methods are aimed at more efficient use of resources and improvement of operational efficiency (Forte, 2016). The use of Kanban is widely practiced, especially for the production of various orders that do not require 100% production by using the bottleneck position. Because it allows maneuvering between different tasks using other waiting machines while the bottleneck station works slower. This enables the fulfillment of a greater number of orders. Supporting the principles of the Lean concept with the TOC approach and tools will allow not only to minimize losses, which is the basis of the Lean concept, but also to improve throughput, and thus obtain greater revenues from the products sold. Thanks to the interaction of both solutions, it will be possible to obtain additional benefits, the synergy effect (Łopatowska, 2014).

Both methods have different applications, it is impossible to say clearly which of these methods will bring better performance, because it depends on the specifics of a given company and its needs. Kanban is effective in reducing inventory and improving production flexibility, which can help increase profits by reducing inventory costs and better tailoring production to customer needs. TOC, in turn, is effective in increasing the efficiency and effectiveness of the enterprise, which can contribute to increased profits by reducing waste and better use of resources. In both cases, it is important to understand the needs and goals of the company and choose the appropriate production management method that best suits these needs and goals. In the analyzed case, the company is focused on production flexibility by using the Kanban method, which is easier to implement than DBR. "Kanban can be implemented at a lower cost, as DBR requires a higher degree of information transparency and a solid contract between partners to align incentives." (Puche et al., 2019).

Further simulation studies should cover a wider range of parameters related to machine failure and human resource management. In addition, it will be important to perform a computer simulation of the production process with the variability of orders and a different distribution of% of their execution by the position being the bottleneck. As well as running simulations using cooperation or with a new bottleneck support machine and analyzing the results as to whether the buffers will be reduced or eliminated altogether. Through real-time simulation, enterprises will prevent predictions and will be able to implement flexible changes.

Many studies compare these methods based on their theoretical assumptions and indicate the potential benefits of their use, but there are no studies that would compare them in specific situations in real enterprises. To better understand the effectiveness of these methods and compare them with each other, further research is needed in different companies in different industries.

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