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Methodology for bottleneck identification in a production system when implementing TOC

Wieslaw Urban
Patrycja Rogowska*

ABSTRACT
For TOC (Theory of Constraints) implementation in a production system, the determination of the system's bottleneck is a crucial step. Effective bottleneck identification allows setting priorities for the improvement of a production system. The article deals with a significant problem for the manufacturing industry related to the location of a bottleneck. The article aims for a detailed analysis of methods for bottleneck identification based on a comprehensive literature review and the design of a generalised methodology for bottleneck identification in the production system. The article uses two research methods, first, the combination of a narrative and scoping literature review, and second, the logical design. Several methods for bottleneck identification are reviewed and compared, finding some being similar, and others giving new insights into the evaluated production system. A methodology for bottleneck identification is proposed. It contains several detailed methods arranged in coherent steps, which are suggested to be followed when aiming for the recognition of a production system's bottleneck. The proposed methodology is expected to be helpful in the practical TOC implementation. The presented methodology for the identification of bottlenecks in a production system is a practical tool for managers and experts dealing with TOC. However, it is still a conceptual proposal that needs to be tested empirically. The proposed methodology for bottleneck identification is an original concept based on the current literature output. It contributes to the production management theory as a practical managerial tool.

KEY WORDS
Theory of Constraints, TOC, production improvement, bottleneck identification, constraints

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Patrycja Rogowska

Bialystok University of Technology, Poland
ORCID 0000-0002-1156-5176

*Corresponding author:
e-mail: p.rogowska@pb.edu.pl

Wieslaw Urban

Bialystok University of Technology, Poland
ORCID 0000-0002-8240-381X

Introduction

A determined primary objective is a prerequisite for the proper operation of a business. It is often believed that the mission of a business is to manufacture and sell products, enter new markets, and use the latest technologies. However, those are nothing but means to influence the ability of a business to succeed in achieving its real objective: making money. A business must take the required steps to reach its objective as efficiently as possible and eliminate unproductive activities. To achieve this aim, the throughput must be improved by changing factors which constrain the

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production system. A critical step is to identify and focus on the constraints, the improvement of which would better the entire production system.

The traditional approach to management claims that constraints of a system should be reduced or even eliminated (Skołud, 2006; Skołud, 2009). Proper management of constraints requires appropriate methods and tools (Łopatowska, 2008). One of them is the Theory of Constraints (TOC).The Theory of Constraints was formulated by the Israeli physicist Eliyahu M. Goldratt. According to TOC, one cause may lead to many harmful consequences. A cause is identified as a constraint of a system that requires attention (Trojanowska & Koliński, 2015). The underlying assumption of TOC is that the capacity of the entire production system of a business depends on the capacity of the constraint. The Theory of Constraints focuses on the identification of constraints in production systems and their proper management to achieve the maximum throughput (Łopatowska, 2017).

A constraint is the most important element in the TOC method. It determines the capacity of the production system and limits its success. There are three types of constraints. The first type is the resources. A manufacturing company has a greater capacity than it thinks. An excess of production capacity is characterised by a surplus of stock of finished products and work in progress. Constraints related to resources may be present within a business, e. g., bottlenecks of the production system, that is production capacity limited by an insufficient number of employees or work time of a machine, or outside of the business, e. g., an inappropriate marketing strategy or changing demand. Another type of constraints is materials. This constraint is rather infrequent. An example is a problem with suppliers of universally available materials. The last type of constraints is related to the policy of a business. This includes all measures, principles, factors, and paradigms that define the ways used to manage the business and that influence the development of its policy. They are the cheapest and most frequent subject to remedy. An example of such a constraint is minimum employment, which does not always bring advantageous results (Woeppel, 2009; Koliński & Tomkowiak, 2010).

The identification of a constraint is the basis for improvement of a production system. The presence of constraints, that is, factors that limit the ability of a business to increase its profits leads to the use of tools that enable the improvement of business efficiency. "Five Focusing Steps" is a systematic constraint management method and a continuous improvement process suggested by Goldratt, which is based on five stages: the identification of a constraint, the exploitation of the constraint, subordination, the increase of the throughput of the constraint and the return to the first step. The objective of this method is to transform the weakest links of a production system into efficient and effective resources (Ikeziri et al., 2018). A procedure conforming to the five stages is shown in Fig. 1.

The recognition of constraints in a production system is of key importance. Therefore, the first step is to determine the exact location and to indicate the resource that limits the capacity of the production system to the greatest extent. To find a problem, it is necessary to identify its root cause. According to TOC, improvement of other elements of the system does not affect the efficiency of the entire system (Lisiecka, 2013).

The next step is the maximum exploitation of the constraint. This consists of the elimination of all things that result in a time deficit in a resource that constrains

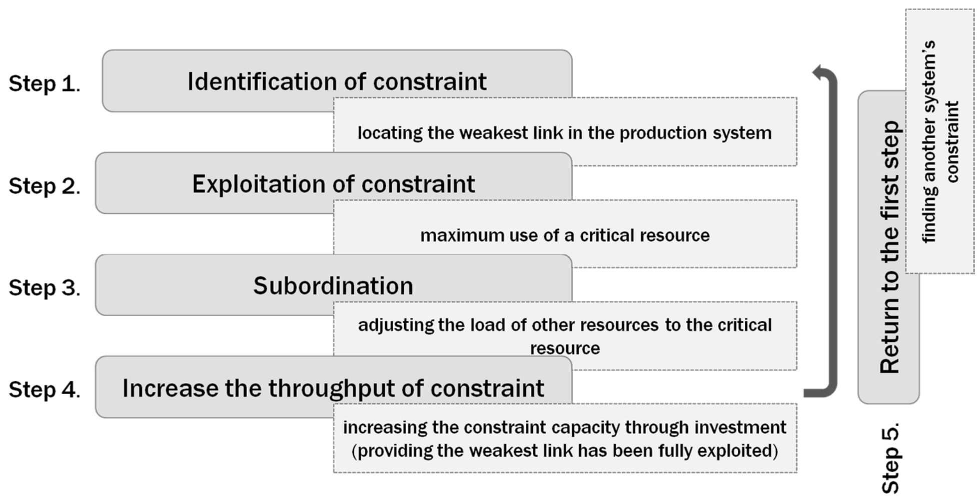

Fig. 1. Five Steps Cycle

the production system. Actions must be taken to ensure the continuous operation of the constraint to improve the efficiency of the system without incurring any additional expenses.

The third step is the subordination to the decision made in Step 2. This consists of the adaptation of the work pace of other resources to the work pace of the resource that constitutes a constraint. The remaining resources should not produce more than the constraint is capable of processing, and whatever is supplied must match the needs of the constraint (Wrodarczyk, 2013).

The fourth step is to improve the efficiency of the constraint. This stage makes it possible to improve the functioning of the constraining factor by way of possible investments. However, before this step is taken, the weakest link must be fully exploited. It must be remembered that the elimination of a constraint in one place leads to the occurrence of other constraints. It is important to constantly improve the production process by searching for and overcoming constraints (Li et al., 2010).

The research of manufacturing constraints and their appropriate identification is the key to improving production capacity and stability. Constantly developing companies that seek for continuous improvement have a stronger competitive edge in the market. The literature does not offer comprehensive and practical solutions and guidance supporting constraint identification in companies. The knowledge of the bottleneck allows increasing the throughput by streamlining a single process. The study by Urban (2019) showed that the bottleneck in the production system was not obvious and required to analyse the system as a whole. As methods used by the author showed various bottlenecks, this step in constraint management requires further research and practical guidance. Clear guidance is needed on how to identify a bottleneck.

The article aims for a detailed analysis of methods for bottleneck identification based on a comprehensive literature review and the design of a generalised methodology for bottleneck identification in a production system. The proposed concept of bottleneck identification aims to meet managerial needs for clear guidance regarding the practical recognition of a bottleneck location in a manufacturing system.

The study has the following structure. The first chapter presents the results of the comprehensive literature review concerning methods of bottleneck identification. Several methods for bottleneck identification are reviewed and compared. The next chapter describes the research methodology. In the third chapter, the authors of the article present their methodology for bottleneck identification in a production system, which can be helpful for production managers and experts implementing TOC. The final part analyses results and conclusions. A number of solutions and guidelines for applying the developed methodology in practice are proposed.

1. Literature review

The identification of a bottleneck is the first and most important step towards the improvement of a business production capacity. It is the key stage of the continuous improvement process. It is also the first step in constraint management according to the Theory of Constraints. The literature on this topic identifies many methods for the identification of bottlenecks in a production system. Table 1 shows a summary of bottleneck identification methods.

The Process Time method focuses on the measurement of the material flow time in processes. This approach indicates the maximum efficiency of a process in the tested conditions (Roser et al., 2014).

The Average Active Period and Active Period methods focus on the time when a machine is active continuously. The activity of a machine is defined as the time of operation of a machine, waiting for another machine, repair, or tool replacement. The aforementioned methods identify bottlenecks as processes with the longest average active time or temporary bottlenecks as processes with the longest instantaneous active periods. These methods use extensive process data (Roser et al., 2002).

The Longest Waiting Time method focuses on measuring the utilisation of machines in the production process. The machine which is utilised to the greatest extent is considered to be the bottleneck. In this method, accurate results require longer observations and measurements. This method is limited to stationary production processes (Law & Kelton, 2000).

Another recommended method is the Longest Queue method which analyses the length of a queue or the waiting time of machines in a production process. A machine with the longest queue or the longest waiting time is considered to be the bottleneck. This method is able to detect instantaneous bottlenecks (Betterton, 2012).

The Inactive Period method is an approach that determines a bottleneck in a place where the shortest time is spent in the inactive status.

The Utilisation method is also known as an effective process time method. It is used in mass production where the number of parts is the same at each station. A bottleneck is detected by calculating the utilisation

Tab. 1. Bottleneck identification methods

Name	Approach	Reference
Longest Queue	length of a queue analysis or a measurement of the waiting time of machines	Lawrence and Buss (1994)
Longest Waiting Time	rate of utilisation of machines measurement	Law and Kelton (2000)
Utilisation	rate of utilisation of machines measurement	Hopp and Spearman (2000)
Average Active Period/ Active Period	measurement of the machine activity continuously	Roser et al. (2001/2002)
Process Time	material flow time in process measurement	Delpf et al. (2003)
Queue Time/ Average Waiting Time	the waiting time before the process measurement	Faget et al. (2005)
Inactive Period	inactive time of machine measurement	Sengupta et al. (2008)
Turning Point	observation of blocking and waiting of processes	Li et al. (2009)
Bottleneck Walk	observation of processes and the level of inter-process resources	Roser et al. (2014)
Flow Constraint Analysis	takt time and the resource cycle time comparison	Sims and Wan (2017)
C/T Corrected	cycle time and the degree of utilisation of each process measurement	Urban (2019)

of each resource. A station with the highest degree of utilisation is considered to be the bottleneck of the production system (Dongping et al., 2014).

The Bottleneck Walk method consists of the observation of processes and of the level of inter-process resources. This method does not require measurements, calculations, or statistics. According to this method, if a process waits for parts, then the bottleneck is somewhere upstream of that process. On the other hand, if a process is blocked because it cannot hand over parts to another process, then the bottleneck is located downstream of the blocked process. Another source of information is inter-process buffers. If a buffer between processes is full, then the bottleneck is located further in the production processes; if a buffer is empty, the bottleneck is located upstream of the buffer. If a buffer is half full, the bottleneck can be on either side. These assumptions indicate the direction where the bottleneck can be found. During observation of the production process, the direction of the bottleneck must be noted. A bottleneck is located between arrows that face each other (Roser et al., 2014).

The Turning Point method consists of the observation of mutual blocking and waiting of processes. The turning point is a process whose share of the work time is the largest of all the neighbouring processes. A turning point is not present when the process waiting time is longer than the blocking time. If the waiting time of each process is longer than the blocking time, the bottleneck is considered to be the first process. Otherwise, the bottleneck is the last process.

The Queue Time method, also referred to as the Average Waiting Time method, consists of measuring the waiting time before a process. A process upstream with the longest average waiting time is considered to be the bottleneck (Yua & Matta, 2016).

The Flow Constraint Analysis method is an approach that evaluates customer demand. A bottleneck of a production process is identified by comparing the takt time and the resource cycle time in a production system. If the cycle time of a machine is longer than the time required to perform an order, then this resource is the bottleneck of the production system. Another approach of this method is the indicator of the utilisation of the spare capacity of a machine. Spare capacity is the difference between the cycle time and the takt time. A bottleneck in a production system with different cycle times is identified by the highest utilisation of a resource (Sims & Wan, 2017).

The Corrected C/T method focuses on measuring the cycle time and the degree of utilisation of each process in the production stream. The product of C/T and the process utilisation indicator is the actual time needed to make a product. The calculation of the efficiency of processes by the corrected C/T indicates the process that constitutes a bottleneck (Urban, 2019).

Other methods of bottleneck identification can be considered as some of the various mathematical approaches. Dongping et al. (2014) suggested an algorithm for the detection of bottlenecks in complex assembly lines. Chiang et al. (2002) analysed the impact of machines on bottlenecks.

In conclusion, different bottleneck identification methods are available in the literature. Some of them are remarkably similar, e. g., the Longest Waiting Time and Utilisation, and some are different, e. g., Process Time and Bottleneck Walk. Some methods provide a fresh look at the production system being evaluated, e. g., C/T Corrected. Most of the available methods can be considered having at least one or more disadvantages, e. g., in terms of their use in different production systems. Some methods require extensive process data that are not always available; long term data collection; detect temporary bottlenecks, or are only applicable to selected types of production systems. Many available methods use machine data. In this case, the accuracy of the bottleneck finding may be related to data variability. This variability can be caused by unplanned machine downtime, setting machine parameters, repairing or changing process times. Therefore, bottleneck identification based only on data can be incorrect and unreliable.

The literature provides bottleneck identification methods that are separate, single methods. The production manager can choose an appropriate method and apply it. However, the chosen bottleneck identification method does not guarantee the real result of the bottleneck in the process. It is, therefore, considered that the problem should be approached comprehensively. Therefore, the authors attempted to develop a bottleneck identification methodology, which would facilitate the search for the bottleneck and could be used in practice. The proposed methodology is expected to be a practical tool for TOC implementation.

2. Research methods

Aiming at a detailed analysis of methods for bottleneck identification, the systematic literature review methodology was employed. The review of the publication was based on the EBSCOhost database. The selection of the database was based on the availability of full-text content and size database. Publications were collected based on the wording “bottleneck identification in production”. The selected phrases were searched in titles, abstracts and keywords of publications. The time frame of the analysed period covered ten years, from 2009 to 2019. Additional conditions limiting the search were full version text and published in scientific journals. The obtained set of publications was subjected to content analysis. The largest number of publications directly related to the production system were obtained in the following journals:

- International Journal of Production Research,
- Mathematical Problems in Engineering,
- Robotics and Computer-Integrated Manufacturing,
- Logistics Research,
- Production and Manufacturing Research.

The substantial part of the literature review is presented above; however, it also contributes noticeably to the conceptual design referred to in the following parts. The second research work stream is on the design of the methodology for the bottleneck identification in a manufacturing system. In this task, the conceptual design approach was employed. The conceptual design method is widely practised in many fields of problem-solving, such as engineering, product development and manufacturing systems (Christophe et al., 2014; Thompson, 1999; French, 1999). The literature mentions the conceptual design as modelling by using precise and neutral concepts coming from needs or ideas (Christophe et al., 2014). According to Thompson (1999), a design concept defines and describes the principles and features of a system. In this particular task, the conceptual design is about the elaboration of the way of proceeding when determining the system bottleneck according to TOC. This design of a procedure applicable to any manufacturing system is based on already known methods and techniques, which were presented in the literature.

3. Bottleneck identification methodology

Bottleneck identification is a key element in the examination of production systems, which has the greatest impact on the efficiency of the entire system. Fig. 2 shows the proposed bottleneck identification methodology. The methodology is a collection of bottleneck identification methods. Some of those methods are available in various publications on this topic.

The first step to be made in the detection of a bottleneck in a production system is an analysis of the production flow and division into processes (#1). Direct observation of a process must be conducted. When determining the processes performed in a business unit, one must focus not only on production processes. A bottleneck can be found in logistics operations, warehousing operations, and even the information flow. Therefore, it is important to perform an accurate and detailed analysis of the production flow and the mutual relationships between the processes.

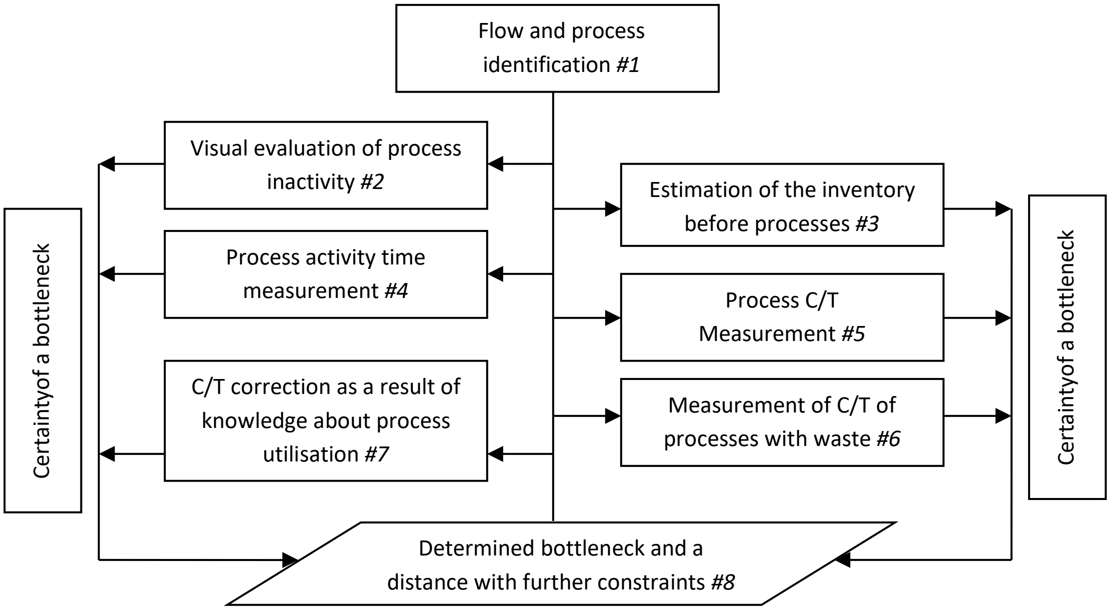

Fig. 2. Bottleneck identification methodology in the production system

The next suggested step is a visual evaluation of process inactivity (#2) based on observation. This enables the identification of processes that are inactive. Process inactivity can preliminarily exclude processes that are not the bottlenecks in the production system. It is important to think during observation why a specific process is inactive. If the operator is absent from a workstation, the possibility must not be excluded that the relevant process is not a bottleneck. Based on one observation, it is impossible to identify processes that are not bottlenecks.

The next suggestion is to estimate the inventory before processes (#3), in other words, stocks. This technique corresponds to the recommendation made by Roser et al. for the Bottleneck Walk method (Roser et al., 2014) and is very similar to the Longest Queue method mentioned by Lawrence and Buss (1994). It requires observation of the stock created between processes and their optimum level. If necessary, the stock size needs to be counted systematically and/or taken from the IT system. The issue is not the largest stock in numbers but the "longest" stock that is measured by the process occupation. A large quantity of stocks indicates that the bottleneck of the production process is located downstream of the stock. To confirm the presence of a bottleneck using inter-process stocks, it is recommended to conduct at least two observations with some time between them. The observations must be conducted in two directions: down and up the process line.

To identify a bottleneck, the process activity time (#4) can be measured. Publications on this topic describe multiple methods that utilise this indicator. These are the Average Active Period, Active Period (Roser et al., 2002), and Inactive Period (Dongping et al., 2014). The process activity time can be measured depending on the available data. The first approach consists of data-taking from the machine monitoring system. Another approach consists of the observation and measurement of the process work time for a period that ensures acceptable credibility. The process that has the longest active time is the bottleneck.

The next suggested step is the measurement of the cycle time of each process (#5). This indicator makes it possible to determine the real-time between the production of successive products in the process. Depending on the division of the flow into processes, this can also be, e. g., the loading time or the transport time. The process with the longest cycle time is considered to be the bottleneck.

The next method is the measurement of the cycle time of the process considering the waste (#6) occurring in the process. The consideration of all waste present in a process indicates the real availability of a process. Waste present in a process includes conversions, repairs, and setting of machines, non-productive time, and products that do not meet applicable quality standards. Like in the previous method, the process with the longest cycle time is considered to be a bottleneck.

The next suggested step that enables the detection of a bottleneck is the use of the corrected C/T (#7) method recommended by Urban (2019). This method requires to know the production structure and measure the process cycle times and the individual utilisation of a process in the manufacture of a product. The product of cycle time and the process utilisation indicator constitute the actual time needed to make a product. A process with the lowest efficiency (highest process cycle time) is the bottleneck of a production system.

The recommended methods provide tips regarding methods for the detection of a bottleneck in a production system. The identification of flows and processes is the key stage in the identification of bottlenecks. In the case of other elements, the use of all methods is not necessary. If only several methods have enabled the identification of a bottleneck and the calculation of the distance to the next constraint, it is not necessary to perform the remaining steps. According to Urban (2019), the detection of a bottleneck and the implementation of improvement actions result in the improvement of the efficiency of a production system. However, the calculation of the distance to the next constraint is an important element. The distance to the next constraint is the scale of the lacking efficiency compared to the next process. It is required to know the scale of the necessary actions to exploit the bottleneck.

4. Discussion of the results

Goldratt claims that each system has at least one bottleneck, which effectively constrains the full exploitation of the company's production potential. Therefore, their identification becomes crucial because only then will the system's throughput improve. The analysed literature shows that this step is not a simple and obvious task. The bottleneck identification methods proposed by other authors are stand-alone methods. However, the use of a single (often random) method will not provide a reliable answer as to the location of the actual bottleneck and the suitability of the method for this type of the production system. It is expected that the proposed methodology for the identification of a bottleneck in a production system will be a practical tool in the TOC implementation for managers and experts. The methodology provides several tips and possible steps that can be taken by production managers. These steps are not random but rather indicate a coherent approach to the production system. They allow assessing the system as a whole and getting to know in detail.

The observation of the flow and its division into processes are the key stages in the detection of bottlenecks in production systems. Once a bottleneck has been identified using the discussed methods, it is important to understand why a given process is a bottleneck. A recommended tool that can be used to find the cause of the problem is the 5-Why method. The identification of the cause of the problem makes it possible to implement effective corrective measures that will result in improved efficiency of the production system.

In step #6 (the measurement of the cycle time considering waste), a division of the waste can be used that is present in the OEE indicator. Waste is classified based on three parameters: availability, efficiency, and quality. When analysing waste in a process, particular attention must be paid to (1) events that cause production downtime, e. g., breakdowns, conversions, setting of machines, and production changes; (2) factors that cause the production process to be slower than the maximum efficiency of the process, e. g., start-up of machines; (3) events that cause loss of quality, e. g., the reduced efficiency of a machine during start-up.

In addition to the identification of a bottleneck, it is also important to calculate the distance from the identified bottleneck to the next constraint. The calculation of the distance to the next constraint requires to at least measure the process C/T (#5) or the process activity (#4). The detection of a bottleneck and its difference from other processes with regard to efficiency enables a company to take appropriate steps to increase the flow through the bottleneck.

An additional issue is the production system that uses the Lean Manufacturing approach, where the principle of the pull system (Womack & Jones, 1996) is toughly introduced into the manufacturing flow, where the material flow is controlled by Kan-Ban system (Puchkova et al., 2016) and where, e. g., a substantial part of the production flow is organised according to the One Piece Flow method (Eaidgah et al., 2016). The Kan-Ban system relies on pulling small production batches (containers of limited capacity). In such a system, the level of the stock between two cooperation workstations is determined by the number of Kan-Ban cards admitted to the system. If the number of cards determines the stock, the system bottleneck cannot be recognised by the level of waiting/queuing material. However, the bottleneck will be manifested by inactivity at work stations that are not bottlenecks, and the bottleneck will be fully loaded. So, the Process activity time measurement (#4) and the Process C/T measurement (#5) mentioned in Fig. 2 can be fully applicable in these cases. It must be underlined that one important purpose of Kan-Ban, like One Piece Flow, is to balance the manufacturing flow, which implies discovering bottlenecks in the manufacturing value stream and their resolution (Rother & Shook, 1999; Liker, 2004; Hino, 2006). It may be concluded that bottleneck identification is immanently tied to the Lean Manufacturing approach.

The literature also mentions the appearance of a shifting bottleneck (Thürera & Stevenson, 2018) in the manufacturing system. It means that a bottleneck changes its place in the manufacturing systems due to different circumstances. Is such a case, potentially each of the presented bottleneck identification methods can be used; however, production managers need to have convenient methods prepared to quickly find the answer to the question "Where is the current bottleneck?"

Conclusions

The identification of bottlenecks is important to every company. Bottlenecks have the greatest impact on efficiency because they dictate the pace of the entire production process. The article presented a detailed analysis of methods for the identification of bottlenecks in production systems based on a comprehensive review of publications on this topic. The methods can be divided into two groups. The first group of methods is based on at least one indicator related to the operation of machines or inter-process stocks. The second group of methods is mathematical algorithms.

A method for the detection of bottlenecks in a production system has been developed and constitutes a collection of the bottleneck identification methods that have been described in various publications on this topic. The key stage of this method is an in-depth analysis of the production flow and its division into processes. This makes it possible to understand and evaluate the current status of the system. The recommended method does not require the performance of all the suggested steps. A search for a bottleneck must continue until certainty is reached that a given process is a bottleneck in the system and until important parameters are calculated, based on which it is possible to determine the distance to the next constraint. The recommended method is a flexible tool that can be used for a broad range of production systems.

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