THE USE OF THEORY OF CONSTRAINTS TO IMPROVE PRODUCTION EFFICIENCY
– INDUSTRIAL PRACTICE AND RESEARCH RESULTS

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Abstract
The production activity of companies is dependent on both internal and external conditions in which they operate. Dynamically changing market requirements force companies to use different methods and management tools in order to improve their competitive position on the market. Today, business executives often decide to use the tools offered by the Theory of Constraints. In this paper the authors describe the theory of constraints and analyze the impact of application of this methodology on selected measures of production efficiency. Some industrial case studies are presented and obtained results, concerning application of theory of constraints, are discussed. Also some particularities, related with practical application of this methodology, are highlighted.

Keywords: Theory of constraints, efficiency, productivity, effectiveness, profitability, reliability.

1 INTRODUCTION
The production process is closely related to other processes significantly affecting the efficiency. For the customer, product value is the result of many processes in the supply chain, e.g. supply, production, and distribution, and the consumption of resources in these processes [1]. Many companies that aim for high operating efficiency find it difficult to define the course of the process that best achieves the adopted company strategy and eliminates actions that do not add value for the customer [2,3,4]. Production efficiency is therefore dependent on the value chain. Through its contribution to the creation of the product, the value chain requires that every action in the production process adds value to the result of the preceding action [5].

The issue of efficiency is widely described in the literature not only in relation to the production process but also, for example, transport [6]. Nevertheless, the efficiency of production process causes difficulties both in terms of literature, and in economic practice. It is difficult to perform a successful analysis of efficiency. This is due to the choice of the analytical tool, the level of detail of the analysis [7], and the risk of irregularities in the production process, which adversely affect the efficiency. Improving the production efficiency is therefore an important part of control actions supporting the process of managerial decision-making. The literature describes many applications of the dominance-based rough set approach to gaining insight into the manufacturing process [8], minimizing losses [9,10,11], verifying validity of measurement and inspection tools [12,13] or even economic conditions and personal features of the employee [14]. It should be noted, however, that the efforts aimed at maximizing production efficiency may create a number of risks. The most important traps in the maximization of production efficiency include [15]:

- contradictory operating objectives of different departments in one company,
- the risk of negative impact on the environment.

Note that efficiency increase of one department does not necessarily lead to improved efficiency of another department in the company. Only improving efficiency of key processes will boost the economic performance indicators of the company. It is also important to coordinate the operational and strategic objectives [3]. When strategic objectives are not exactly translated into operational objectives, it may lead to the generation of contradicting indicators, which adversely affect the efficiency of production management.

2 ASSESSING THE EFFICIENCY OF THE PRODUCTION PROCESS
In terms of economics, efficiency results from the company’s business activity, and it is the ratio of the achieved result and its cost:

$$E = \frac{r}{c}$$

where:

E – efficiency; r – results; c - cost

Efficiency is defined ambiguously, which causes major decision-making problems, both on the strategic and operational level. In the literature there are numerous notions wrongly treated as synonymous, such as efficiency, productivity and profitability. Essential differences among these notions were discussed in [16-18].

The APICS dictionary offers numerous definitions, which may be analyzed in terms of assessing the efficiency of the production process. Selected definitions of efficiency from the point of view of production management are discussed in [19].

Due to the complex nature of the efficiency of production processes, the ambiguity of definitions, and the wide range of tools both used in business practice and presented in
the literature, it is very difficult to successfully use efficiency analyses in companies.

The complexity of production management is combined with the large number of management theories that are implemented to improve the efficiency of the production process. According to formula (1), we should distinguish several methods of improving operational efficiency:

- reduction of expenditures while maintaining current results,
- reduction of expenditures while increasing the level of results,
- maintaining current expenditures and increasing the level of results,
- increasing the current level of expenditures, while drastically increasing the level of results.

The authors decided to carry out a rough analysis only on selected ratios, based on efficiency improvement methods using TOC, and taking into account the complexity of the task of developing a comprehensive system of ratios and measures of efficiency [20] together with methods of measuring the ratios. They ratios are listed in Table 1.

Table 1. Selected measures used for assessing production efficiency taking into account the specific nature of TOC tools.

<table>
<thead>
<tr>
<th>Name of measure</th>
<th>Description</th>
</tr>
</thead>
</table>
| 1. Employee productivity ratio | \[
  \text{net sales} - \text{salary cost} \times \% \]
| 2. Efficiency of order processing | \[
  \frac{\text{number of completed orders}}{\text{total number of orders}} \times \% \]
| 3. Production flow | \[
  \frac{\text{downtime in production process}}{\text{total worktime}} \times \% \]
| 4. Production capacity utilization | \[
  \frac{\text{used production capacity}}{\text{total production capacity}} \times \% \]

Source: Own study

The set of ratios given above takes into account the basic feature of efficiency, expressed by the formula (1). It has been further supplemented by the Overall Equipment Effectiveness (OEE) ratio. The use of the OEE analysis is justified by the need to include the production process in the analyses of operating efficiency. The OEE analysis is an aggregated indicator, and it makes it possible to monitor and control the production process, which shows the utilization of the production equipment and machinery capacity net of the impact of confounders. OEE ratio analysis is most often used to measure the efficiency of equipment and resources, based on the actual availability of resources and the quality of the product. The choice of ratios is motivated by the authors’ focus on comparing different companies which disclosed their data concerning the implementation of various TOC tools. The nature of all the companies also had a direct impact on the choice of ratios being assessed.

3 TOC TOOLS

The assumptions of the TOC, as introduced by an Israeli physicist Dr. Moshe Eliyahu Goldratt, were first published in the 1984 book The Goal: Excellence In Manufacturing which offered comprehensive solutions for production management. Application of the principles of TOC in practice requires a holistic view of the entire production system [21]. One of the three principles of TOC is concentration [22], i.e. focus on the most important issues. It means that all processes and positions should be supervised, although the non-critical may enjoy certain autonomy. Most attention should be given to tasks that are crucial from the point of view of the system as a whole. The main aim of every company is to increase the profit. According to this point of view, constraints are the main obstacles in achieving the aims of companies. In other words, anything that gets in the way of gaining more profit is considered a constraint [23]. The identification of the constraint is the basis for improving the production system. According to TOC the system consists of five steps. The steps are sequential and instruct concentration of efforts on the system component that is capable of producing the most positive impact on the system [24].

The process of ongoing improvement in TOC is shown in Figure 2.

![Figure 2. Process of ongoing improvement. Source: Own study based on [25].](source: own study)

The first step in the process of continuous improvement involves the identification and precise indication of the system component which hampers its global performance. According to TOC the introduction of changes must start from such a weak link, because improving other elements in the system and improvement of local efficiency will not affect the performance of the system as a whole. Each system has at least one constraint [26], and its identification is necessary for proper management [27].

The second step consists in the exploitation of the constraint: the change agent should obtain as much capability as possible from the constraining component. Each lost minute caused by the fact that the constraint is not working is a loss which cannot be recovered. Therefore, in this step the change agent should take the necessary action to ensure uninterrupted work of the constraint, in order to achieve maximum capability of the system constraint.

The third step involves subordination of everything else to the decision that was made, i.e. the adjustment of the pace of work of other system elements to the pace of work of the constraint. Otherwise, when other system elements will produce faster or produce more, the cost of production will grow, among others by the increase in work-in-progress inventory.

Steps 2 and 3 are very important in the TOC, because they contribute to the structuring of the system. There are still many other ways to increase throughput and improve the system. In the fourth step, described as increasing the
productivity of the constraint, TOC allows for investments which will contribute to improving the efficiency of the entire system by strengthening the constraint. If the constraint is overcome, which should happen as a result of the continuous improvement of performance as a result of step 4, it is necessary to find another component which restricts the capability of the production system.

Appropriate identification of constraints offers many opportunities for business improvement and it positively affects the performance indicators. Note that TOC was designed as a tool for managing constraints, and it is not synonymous with continuous liquidation. At the appropriate moment, it is necessary to purposefully leave the constraint in the company, and then, through proper management thereof, control the bottleneck of the production system.

A method of project management called Critical Chain Project Management (CCPM) was developed on the foundations of TOC. Critical Chain means that all the co-dependent tasks must take the longest path to complete, taking into account the constraints of system elements [28]. CCPM consists in planning, scheduling and maintaining the critical chain during the project in order to maximize the working time of the bottleneck, and to efficiently determine inventories for the fundamental steps of the project [29]. CCPM takes into account the ambitious task performance times and eliminates individual safety margins, adding a time buffer at the end of the project, which allows for smooth management and evaluation of project progress. The use of CCPM requires discipline and change in the habits of employees, but the use of the critical chain method results in significant improvement in project timeliness. Currently, software supporting CCPM is available, facilitating the process of project management.

Additionally, within the TOC a drum-buffer-rope (DBR) tool was developed for production management. According to [30]:

- A drum is a detailed production schedule of the bottleneck resources. Drum decisions include bottleneck recognition and bottleneck scheduling.
- A buffer is a protection mechanism to protect the bottleneck from starvation due to manufacturing fluctuation. It can be either a time buffer or a physical buffer.
- A rope is a detailed schedule of releasing raw material into a system to pull the system’s work pace synchronously to the drum.

![Figure 3. Production management by using DBR concept. Source: Own study](image)

The use of DBR in practice requires the development of a system calculating time buffers appropriate for the given organizational conditions and taking into account the dynamics of material flows.

### 4 THE IMPACT OF TOC ON MANUFACTURING COMPANIES - CASE STUDY

The main aim of this paper is to identify the impact of TOC tools on the efficiency of the production process. For this purpose, the authors decided to analyze case studies. The use of case studies makes it possible to determine the state of the studied phenomenon, which may be only suggested by the results of qualitative studies. Compared to other research methods, case study offers a broader scope of techniques and tools for data acquisition and analysis. Data may be gathered through observation, interviews, and surveys. Since there are various possibilities of data acquisition, the case study method is not methodologically limited in terms of data analysis. Case study should be seen as an individual and limited research process, its aim being a detailed analysis using many research techniques for a long period of time [32]. Research methods based on case study are not subject to evaluation of sample representativeness [33]. The aim of case study is to reveal relations between the phenomena occurring in the described processes. Quantitative methods, based on statistically representative samples, do not enable such analyses. The literature on the possibilities of dependency verification by means of case study offers various opinions on the number of variants which ought to be analyzed for the conclusions of the research to be of scientific nature. The dominant view suggests that four to ten case studies have to be completed [34,35]. Taking into account the nature of the production process efficiency, the authors concluded that they would be able to draw general conclusions from the results of analyses of the impact of TOC tools on performance ratios in four manufacturing companies. Enterprises selected for the analysis of TOC tools’ impact were either large or medium production enterprises from different industries, all using batch production.

The first of the analyzed enterprises was a planner manufacturing company from the advertising industry. The company has been on the market for over 20 years and employed nearly 400 people. The development and implementation of TOC took the company nearly a year. Since 2010, the company has worked on the basis of the TOC process, using the DBR for production management and CCPM for order management, seeing each of them as a separate project. The use of TOC in the analyzed company is difficult due to the seasonal nature of production, which results in seasonal change of the location of constraint: from internal to external. However, it does not affect the possibility of using batch production.

Table 2 shows selected production data and performance indicators (from table 1) before and after the implementation of TOC tools.

<table>
<thead>
<tr>
<th>Productivity [pcs/shift]</th>
<th>16000</th>
<th>23520</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of stocks of finished products [pcs/month]</td>
<td>10000</td>
<td>7500</td>
</tr>
<tr>
<td>Number of timely deliveries [per month]</td>
<td>18720</td>
<td>25800</td>
</tr>
<tr>
<td>Total number of orders [per month]</td>
<td>24000</td>
<td>30000</td>
</tr>
<tr>
<td>Production costs [PLN/shift]</td>
<td>5670.00</td>
<td>4762.80</td>
</tr>
<tr>
<td>Employee productivity ratio [%]</td>
<td>87</td>
<td>91</td>
</tr>
<tr>
<td>Efficiency of order processing [%]</td>
<td>78</td>
<td>86</td>
</tr>
<tr>
<td>Production capacity utilization [%]</td>
<td>67</td>
<td>79</td>
</tr>
<tr>
<td>Production flow [%]</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td>OEE [%]</td>
<td>76</td>
<td>81</td>
</tr>
</tbody>
</table>

Source: Own study
During one year the production flow ratio was reduced from 17% to 14%, which shows that downtime in the production process was minimized.

In the subsequent years the company improved their TOC tools, which led to further increase in the efficiency of the production process, although it was not as dynamic as in the implementation period. Figure 4 is a comparison of production data covering five years of the company’s activity. It shows results from before and after the implementation of TOC tools, and results achieved during the years directly following the implementation.

TOC tools were implemented in 2010, therefore the analysis focuses on such a period. Note that in spite of further improvement of the production situation after the implementation of TOC tools, the results only show the continuous improvement of the current situation.

The second analyzed enterprise was a company from the power industry involved in the production of accessories for overhead power lines. The company has been in the business for nearly 70 years and it has production facilities on five continents. The company spent less than a year to develop and implement TOC, the main aim being the reduction of lead time. The company has operated based on the continuous improvement process, and used DBR and CCPM since 2013. Table 3 shows selected production data and performance indicators (from table 1) before and after the implementation of TOC tools.

As a result of the TOC tools implementation, it was possible to reduce the stock of finished products. The company has worked based on the continuous improvement process and used DBR since 2011. Table 4 shows selected production data and performance indicators (from table 1) before and after the implementation of TOC tools.

The third analyzed enterprise was an entity from the household appliance industry, involved in the production of kitchen equipment. The company has over 70 years of experience and it has production facilities in a few European countries. The development and implementation of TOC took the company a year. The main aim was to reduce the stock of finished products. The company has worked based on the continuous improvement process and used DBR since 2011. Table 4 shows selected production data and performance indicators (from table 1) before and after the implementation of TOC tools.

### Table 3. Production data before and after the implementation of TOC tools – case study 2.

<table>
<thead>
<tr>
<th></th>
<th>before</th>
<th>after</th>
</tr>
</thead>
<tbody>
<tr>
<td>lead time [h]</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>the volume of stock of work in progress [pcs/month]</td>
<td>100</td>
<td>56</td>
</tr>
<tr>
<td>number of timely deliveries [per month]</td>
<td>25</td>
<td>32</td>
</tr>
<tr>
<td>total number of orders [per month]</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>production costs [PLN / shift]</td>
<td>160.00</td>
<td>100.80</td>
</tr>
<tr>
<td>employee productivity ratio (%)</td>
<td>68</td>
<td>80</td>
</tr>
<tr>
<td>efficiency of order processing (%)</td>
<td>83</td>
<td>91</td>
</tr>
<tr>
<td>production capacity utilization (%)</td>
<td>68</td>
<td>71</td>
</tr>
<tr>
<td>production flow (%)</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>OEE (%)</td>
<td>74</td>
<td>79</td>
</tr>
</tbody>
</table>

Source: Own study

### Table 4. Production data before and after the implementation of TOC tools – case study 3.

<table>
<thead>
<tr>
<th></th>
<th>before</th>
<th>after</th>
</tr>
</thead>
<tbody>
<tr>
<td>productivity [pcs/shift]</td>
<td>2000</td>
<td>2500</td>
</tr>
<tr>
<td>volume of stocks of finished products [pcs/month]</td>
<td>875</td>
<td>700</td>
</tr>
<tr>
<td>number of timely deliveries [per month]</td>
<td>278</td>
<td>362</td>
</tr>
<tr>
<td>total number of orders [per month]</td>
<td>320</td>
<td>400</td>
</tr>
<tr>
<td>production costs [PLN / shift]</td>
<td>1,506.00</td>
<td>1,265.04</td>
</tr>
<tr>
<td>employee productivity ratio (%)</td>
<td>89</td>
<td>93</td>
</tr>
<tr>
<td>efficiency of order processing (%)</td>
<td>87</td>
<td>91</td>
</tr>
<tr>
<td>production capacity utilization (%)</td>
<td>79</td>
<td>86</td>
</tr>
<tr>
<td>production flow (%)</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>OEE (%)</td>
<td>84</td>
<td>87</td>
</tr>
</tbody>
</table>

Source: Own study

As a result of the implementation of the TOC tools in the analyzed production process, it was possible to reduce the stock of finished goods by 20%, improve productivity by 25% and reduce production cost by 16%.

During one year production flow ratio was reduced from 14% to 11%, which shows that downtime in the production process was minimized. Figure 6 is a comparison of production data covering five years of the company’s activity. It shows results from before and after the implementation of TOC tools, and results achieved during the years directly after the implementation.
TOC tools were implemented in 2011, therefore the analysis focuses on such a period. The management of the company found the results unsatisfactory, which entails the need to expand the machinery and other logistics infrastructure.

The fourth analyzed enterprise was an entity from the household appliance industry, specialized in the production of cooling equipment. The company has been on the market for over 60 years, currently employing over 300 people. The development and implementation of TOC took the company nearly a year. Since 2012, the company has worked on the basis of the TOC process, using DBR for production management and CCPM for order management. Table 5 shows selected production data and performance indicators (from table 1) before and after the implementation of TOC tools.

Table 5. Production data before and after the implementation of TOC tools – case study 4.

<table>
<thead>
<tr>
<th></th>
<th>before</th>
<th>after</th>
</tr>
</thead>
<tbody>
<tr>
<td>productivity [pcs/shift]</td>
<td>2700</td>
<td>3450</td>
</tr>
<tr>
<td>volume of stocks of finished products [pcs/month]</td>
<td>1182</td>
<td>1000</td>
</tr>
<tr>
<td>number of timely deliveries [per month]</td>
<td>417</td>
<td>620</td>
</tr>
<tr>
<td>total number of orders [per month]</td>
<td>480</td>
<td>700</td>
</tr>
<tr>
<td>production costs [PLN / shift]</td>
<td>1,731.90</td>
<td>1,454.80</td>
</tr>
<tr>
<td>employee productivity ratio [%]</td>
<td>87</td>
<td>91</td>
</tr>
<tr>
<td>efficiency of order processing [%]</td>
<td>87</td>
<td>89</td>
</tr>
<tr>
<td>production capacity utilization [%]</td>
<td>81</td>
<td>87</td>
</tr>
<tr>
<td>production flow [%]</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>OEE [%]</td>
<td>88</td>
<td>91</td>
</tr>
</tbody>
</table>

Source: Own study.

As a result of the implementation of the TOC tools in the analyzed production process, it was possible to:
- reduce the stock of finished goods by 10%,
- improve productivity by 27%,
- reduce production cost by 16%.

During one year, the implementation of TOC resulted in the increase of the following ratios:
- employee productivity (from 87% to 91%),
- efficiency of order processing (from 87% to 89%),
- utilization of production capacity (from 81% to 87%),
- OEE analysis ratio (from 88% to 91%).

Also, production flow ratio grew from 15% to 19%, which shows that downtime in the production process increased, resulting from the minimized inventory of work-in-progress and increase in production capacity. In the discussed case the ratio was not an important part in the analysis of production process efficiency. Figure 7 is a comparison of production data covering five years of the company’s activity. It shows results from before and after the implementation of TOC tools, and results achieved during the years directly after the implementation.

Figure 7. The impact of TOC implementation on production process efficiency – case study 4.
Source: Own study.

TOC tools were implemented in 2012, therefore the analysis focuses on such a period. The management of the company found the results satisfactory. Due to the decline in the rate of improvement of the ratios and production data, it must be concluded that investments in additional machinery might be necessary to achieve further process optimization, and throughput and profitability increase.

5 CONCLUSIONS

The issue of efficiency evaluation is very important from the point of view of its practical application in companies. The analysis of production efficiency should be based not only on operational measures, directly related to the production process, but also on financial indicators. The goals and measures used in the analysis of production efficiency should result from the vision and strategy of the company [36]. The analysis of production efficiency may be considered complete when it refers not only to measures which reflect past results, but also to measures which allow us to monitor the aspects that shape future results.

While doing research in the companies, the authors noted that the implementation of solutions proposed by TOC had a positive effect on employee motivation. This may be due to the fact that TOC unambiguously defines a constraint as the most important element in the company. By giving the highest priority to the position defined as the constraint of the system, we give the employee precise instructions on what is most important at the moment. Clear rules and procedures positively influence the atmosphere in the workplace, which may result in higher motivation to work. Improving production efficiency ratios in the years following the implementation did not generate such spectacular, positive changes due to the fact that all the analyzed companies used the basic assumptions of throughput accounting [37]. It was also observed that the greatest challenge related to TOC implementation is employee resistance to change. Therefore, it is crucial to have honest discussions and organize training for employees to help them understand not only the principles of TOC, but most of all the benefits resulting from proper TOC application for all of them, as well as the importance of the role each employee plays in the success of the company. Another important aspect of efficiency evaluation is the identification of the alliance network between the individual logistic processes, that support the production process. The efficiency indicators developed and analyzed in the article, take into account the need to identify such alliances, but in economic practice this is difficult to analyze.
6 REFERENCES


