TOC implementation in a medium-scale manufacturing system with diverse product rooting

Wieslaw Urban
Faculty of Engineering Management, Bialystok University of Technology, Bialystok, Poland

ABSTRACT
Although the Theory of Constraints (TOC) is a widely known management concept, it warrants further research, particularly in terms of its application. The study investigates TOC implementation in a medium-scale manufacturing system with diverse products. The instrumental case study methodology is employed in this study, and the conceptual studies assess the case. The study helps to elucidate the methodology of TOC implementation in a manufacturing system. Instead of the five-step sequential approach that exploits constraints one after another, the cycles of system productivity target points are proposed, where each improvement cycle simultaneously considers several constraints. The proposed methodology is visualised, several implications and suggestions for constraint identification are provided, and a new method of bottleneck identification is elaborated in this study.

1. Introduction
The manufacturing world constantly follows new management ideas and emerging methodologies. The Theory of Constraints (TOC) (Goldratt, 1997; Goldratt & Cox, 1992) is not an especially new one, but to date, it has not been widely researched by scholars, particularly with respect to the peculiarities of its implementation. TOC tempts managers due to its simplicity, which can be summarised as follows: find a constraint of your system and improve the throughput of it, thereby improving the productivity of the entire system. This idea, which suggests focusing attention and improving efforts only on the constraints, is highly attractive because it brings a promise of high efficacy and obtaining great results with the smallest possible outlay. Finding a system constraint and improving it has wide applicability in many human activity fields, and it can be characterised as common sense.

Although several manuals on TOC application are available (Chowdhary, 2009; Cox & Schleier, 2010; Dettmer, 1998; Scheinkopf, 1999), which see TOC as a separate management methodology, there is still a lack of empirical research on the practical issues of TOC implementation in manufacturing systems. There are not many studies in which the introduction of TOC to a real manufacturing system is incrementally investigated. Such studies could determine the many challenges...
coming from manufacturing systems’ complexity and sophistication and provide guidance along with theory building generalisations.

The study conducts an in-depth investigation of the implementation of TOC in a manufacturing system that has the characteristic of diverse products. The research concept recognises the current state of investigated manufacturing systems and then elaborates a concept of TOC implementation through series of further studies of the research object. However, the research concept does not presuppose to follow the guidance of TOC implementation from the literature but attempts to investigate how to implement TOC idea in the most appropriate and convenient manner with respect to the studied manufacturing system. Introduced research approach leads to renewed insights into TOC implementation methodology and solves other obstacles that are faced when implementing TOC. The observations that are made are discussed, and some implications for the existing theory are drafted. The investigation is focused on the strategic manufacturing decision level, rather than on operational techniques.

2. Theory of constraints in the literature

Operations are of main interest in every company because they determine the revenue stream. Gupta and Boyd (2008) suppose that TOC is a kind of unified theory for operations management. Effective, less costly and faster production flows are a key factor in every organisation. TOC gives a generic idea of how to deal with it. The TOC approach may serve as a broad theory integrating a great many operations management concepts and studies (Boyd & Gupta, 2004). Some authors argue that TOC is very closely related to process thinking (Pacheco Lacerda, Cassel, & Rodrigues, 2010; Pereira Librelato, Pacheco Lacerda, Rodrigues, & Veit, 2014). Others demonstrate that TOC is inherently implemented in the main Lean Manufacturing diagnostic tool – Value Stream Mapping (Pereira Librelato et al., 2014).

TOC, which is also known as Goldratt’s theory, is plainly elaborated and justified by its author with respect to the central idea (Goldratt, 1997; Goldratt & Cox, 1992; Goldratt, Schragenheim, & Ptak, 2000). There are also application proposals, such as managerial methodologies (Chowdhary, 2009; Cox & Schleier, 2010; Dettmer, 1998; Roser, Lorentzen, & Deuse, 2015; Scheinkopf, 1999). As Mabin and Balderstone (2003, p. 570) state, Goldratt theory’s distinctive feature is the recognition that there are always limitations to system performance, and despite the complex set of factors influencing it, there are a very small number of elements in the system, usually only one that Goldratt terms the ‘constraint’, which directly restricts performance.

The five steps of improvement are a basic TOC cycle. These steps are as follows (Goldratt & Cox, 1992): (1) identify the bottleneck, (2) decide how to exploit the identified bottleneck, (3) subordinate everything else in the system to unblock the bottleneck, (4) elevate the bottleneck, and (5) monitor if the bottleneck has been broken and return to the beginning. Other researchers add to the fifth step a remark to avoid inertia while following other bottlenecks (Aguilar-Escobar, Garrido-Vega, & González-Zamora, 2016). The literature also adapts the elementary TOC methodology to be wider than the organisational and system levels, such as the sectoral level (Oglethorpe & Heron, 2013). Oglethorpe and Heron (2013, p. 1362) suggest that when applying TOC to food sector supply chains, one should start with the identification of operational
competencies, then identify the best practices, implement new practices or systems and, when they work, measure the benefits and impacts upon the core competencies. Then, the cycle should be started again.

Blackstone (2001) points out that TOC is mostly associated with manufacturing, even though it has been applied to other areas, such as performance measures, supply chains, marketing, and sales. Mabin and Balderstone (2003, p. 570) mention that the TOC approach epitomises systems thinking. In other words, TOC is a philosophy that recognises that the whole is much more than the sum of its parts and that a complex web of interrelationships exists within the system. Okutmus, Kahvecib, and Kartaş-Ova (2015) present a study of TOC in a furniture plant. Zivaljevic (2015) presents how to reduce highway congestion due to applying TOC. Pereira Librelato et al. (2014, p. 927) report on the TOC applications of a number of giant business and non-business organisations/institutions, namely, the following: 3M, Amazon, Boeing, Delta Airlines, Ford Motor Company, General Electric, General Motors and Lucent Technologies, the British National Health Service, the United Nations, NASA, the US Department of Defense (Air Force, Marine Corps and Navy), and the Israeli Air Force. However, a peculiar field of TOC application is to mix product optimisation with the Throughput Accounting methodology (Alsmadi, Almani, & Khan, 2014; Corbett, 1998; Wojakowski, 2016).

Although the TOC concept is relatively simple and straightforward, the application of this idea is not easy or simple (Pegels & Watrous, 2005, p. 302). Despite vast research experience, the authors suggest that there is still a need for further studies on TOC applications and application methodologies. According to Gupta and Boyd (2008, p. 1007), TOC needs more empirical tests. In particular, TOC should be adapted to a wider variety of operational concepts and issues. The TOC literature frequently refers to the constraints relating to generic issues surrounding managers, supervisors, executives, stakeholders, and teams, but there is still a lack of implementation, specifically in particular industries (Oglethorpe & Heron, 2013, p. 1349). The Drum–Buffer–Rope method (Bhardwaj, Gupta, & Kanda, 2010; Blackstone, 2001; Golmohammadi, 2015; Scheinkopf, 1999) seems to be one of the leading techniques related to TOC. However, there is a need for many more methods (Blackstone, 2001), including practical solutions supporting constraint identification and searching for appropriate solutions for significant bottlenecks. Studies of examples of TOC applications provide a better understanding and build precious practical knowledge (Watson, Blackstone, & Gardiner, 2007).

3. Research method

The idea of this study is a deep and wide exploration of TOC’s application in a manufacturing system with given characteristics. Actually, case study methodology is very often exploited in studies of manufacturing systems (e.g. Aguilar-Escobar et al., 2016; Pereira Librelato et al., 2014) because it allows for a comprehensive and broad view of complicated issues in highly differentiated environments. The case study is a qualitative method facilitating the exploration of a phenomenon within its context by using a variety of data sources. The study implies that an issue is examined through a variety of lenses, which allows for multiple facets of the phenomenon to be revealed and understood (Baxter & Jack, 2008, p. 544). In a case study, the researcher’s attention is focused on one particular
phenomenon that is chosen from many (Denzin & Lincoln, 2005). A case study method should be considered when a study is focused on answering the question of ‘how’ (Yin, 2003). Among the many types of case studies, an instrumental one is employed in this study. According to Stake (1995), the instrumental case study provides insight into an issue or helps to refine a theory. It differs from other types because it plays a supportive role as a facilitator and it helps an investigator to pursue an external interest. The instrumental case study methodology is supplemented by conceptual works based on a teamwork approach that engages managers from the investigated manufacturing system.

One of the components of the case study is research questions (Yin, 2003). This study poses the following question: how can TOC be implemented in a manufacturing system that is characterised by diverse (irregular) product routing? The implementation process will be addressed and taken from the current literature. Along with this main question is another one regarding the poorly guided problems and challenges that occur when TOC is implemented in a manufacturing system with the given characteristics.

Following suggestions by Yin (2003) and Stake (1995), several data sources have been exploited in this investigation, namely, the direct observation of the production process and the material flow throughout the system; the historical records of many types of process characteristics; direct interviews with managers, owners and operators; and finally, participant observation when a researcher is involved as a participant in the researched phenomenon, i.e. workshops with managers. The investigation of a company involved a number of visits and collected data from the abovementioned sources. During each visit, several unstructured interviews with managers and observations always occurred. The diagnosis and solutions that were determined were systematically compared with managers’ views, suggestions, and opinions. The undertaken diagnosis and the applied concepts are reported in the following sections of the study.

4. Object of investigation: the manufacturing system

The investigated manufacturing system provides printed bulk packaging made of thick corrugated board that is intended for the food processing industry and other fast-moving consumer goods manufacturers. The system performs medium and small production series. The manufacturing system is organised as typical batch production; there is no continuous flow, even partially; and the production orders (batches) are as large as one hundred thousand items. The investigated manufacturing system is composed of six basic processes, namely, (1) gluing cardboard, (2) printing on thick substrates, (3) lamination, (4) die cutting, (5) folding and gluing, and (6) folding. However, it should be emphasised that even though the latter two processes are similar, they are different from each other. Each abovementioned process is performed using advanced machines.

The time of the production cycle, which is called the C/T (Cycle Time of a process) in Lean Manufacturing, is presented in Table 1 below. All the processes that are presented in the Table are also renamed to simpler forms as A to F for easier further elaboration. The C/Ts that are presented below are calculated as the times that are devoted to performing a given operation on a whole batch divided by the number of items in a batch. The data were gathered during one month of typical work of the studied manufacturing system. However, some recalculations were performed because of product structure that differs at the production stages. At some stages, a product is divided into a few, and so the C/T is
calculated for a single output product. The figures in Table 1 referring to C/Ts are rounded to the first decimal place.

However, all of the processes from A to F can form, with several exceptions, the technological stream, starting with cardboard gluing (Process A) and finishing with folding without gluing (Process F). Nevertheless, the production sequence never covers the whole process. The longest ones are production orders covering four processes, and the shortest ones are of one process – but it can be any of them. The process is called a diverse production characteristic because production orders have different paths and lengths while moving through the production processes. This is a peculiarity of investigated manufacturing system, that production paths are composed of dozens process combinations, one cannot point out reasonably the most common (frequent) process sequence. The numbers of production orders of different lengths (consisting not of the same processes) are presented in Table 2 below. As shown, the orders that are served by only two processes outweigh the others (not always the same).

Having initially diagnosed the manufacturing system, it is possible to proceed to the next step, which recognises where the bottleneck occurs. According to Pegels and Watrous (2005, p. 303), using the TOC process, the production process should be improved to a point where the system’s constraint is outside the production area.

### 5. Bottleneck identification

Goldratt’s theory implies the beginning of an improvement process with the recognition of where a bottleneck exists in a system (Goldratt & Cox, 1992). A bottleneck is a restriction of a system that limits the production flow. The constraint may be a physical one, such as a machine with a limited capacity or a raw material, but it can also be policy or behavioural constraints (Mabin & Balderstone, 2003, p. 570). Three ways of identifying bottlenecks are applied to the manufacturing system that was presented above.

#### 5.1. C/T as a way of determining the bottleneck

The C/T in each manufacturing process is different, which implies different capacities for each of them. Figure 1 below presents the hourly productivity that is calculated for

### Table 1. Cycle Times of processes.

| Process                  | Process symbol | Cycle Time, C/T [sec.dec] |
|--------------------------|----------------|---------------------------|
| Cardboard gluing         | A              | 00.2                      |
| Printing on cardboard    | B              | 01.1                      |
| Lamination               | C              | 01.6                      |
| Die cutting              | D              | 02.7                      |
| Folding with gluing      | E              | 02.4                      |
| Folding without gluing   | F              | 04.6                      |

### Table 2. Number of processes in production orders.

| Number of processes in an order | 1% | 2% | 3% | 4% |
|---------------------------------|----|----|----|----|
| Number of production orders in one typical month | 14% | 53% | 18% | 15% |
each of the six processes. The hourly productivity is expressed as the volume of output products, as noted by the system characteristics in Table 1.

As indicated in Figure 1, productivity significantly varies between processes. It is clear that Process A is high-productive with approximately 18,000 items per hour. The lowest productivity occurs in Process F with more than 700 items per hour. Process F has the lowest productivity; therefore, this process limits the flow of the system. This process could be considered to be the bottleneck of the investigated manufacturing system.

5.2. Inventory before a process as a sign of a bottleneck

The production flow within the manufacturing system is directly linked to the production that is in progress and is waiting for consecutive processes. A high stock level is a sign that in front of this stock is a bottleneck that significantly affects the waiting inventory. Some authors suggest detecting production bottlenecks by observing inventories during a bottleneck assessment (Roser et al., 2015). Figure 2 presents the inventory wait for each process in the studied manufacturing system. The data were gathered by directly counting the waiting pallets in the production hall and in warehouses. The calculations were performed on one day.

The data show particularly high stock levels before Process A and Process D. The volume compared to the processes’ daily demand informs us that the stock times are, respectively, 30 and 22 working shifts. However, the material (cardboard) for Process A is supplied from the outside based on specific rules. The material is bought from external manufacturers. The investigated company keeps a huge stock of materials due to safety reasons. ABC analysis showed that half of the inventory indexes had no turnover in the last six months. The conclusion is that Process D but not Process A is probably a system bottleneck. Furthermore, it is noticeable that bottleneck identification according to inventories does not always give unambiguous results. Moreover, these findings provide no clue regarding the relative scale of the bottleneck, i.e. on the scale of the scarcity of productivity in relation to other processes.

5.3. C/T corrected by process engagement as a basis for bottleneck identification

The investigated manufacturing system has the characteristic of diverse products. The production sequences differ greatly from each other with respect to production orders,
and, as a result, process engagement also differs greatly. To approximate the processes’ engagement, the volume size of each process is compared to the whole output of the system. Table 3 presents the process engagement that is calculated according to this method. If, for example, engagement equals 1, it means that each ready-made product is processed in this process. None of the processes are fully engaged in the production of the whole product. Process A has the highest engagement. 91% of the volume flowing throughout the system is processed by this step.

Due to knowing the individual engagements of processes, it is possible to calculate the adjusted process C/Ts. Table 2 presents the process C/Ts that are corrected using the process engagement (figures referring to C/T are rounded to the first decimal place). The C/Ts after the correction symbolically reflect the time that is necessary to produce a product that serially passes through all the processes. For instance, Process B is engaged in approximately half of the production volume, and so its corrected C/T is half of what it truly is (real 1.2 sec. and corrected 0.6 sec.). Figure 3 presents the hourly productivity of processes, taking into consideration their real contributions to the whole produced product mix.

According to the presented data (Figure 3), Process A does not have the highest capacity, as indicated in Figure 1, but rather Process C does. The most important observation coming from the chart (Figure 3) is that the lowest capacity is Process D (not Process F) and that this is the bottleneck of the investigated manufacturing system. The capacity of Process D explains the extraordinary production stock waiting before this process (see Figure 2). The truth is that in today’s structure of production orders, this system works at the pace of Process D, which means that $C/T = 1.2 \text{ sec.}, 3,100 \text{ it./hr}$. The calculation of the corrected C/T indicates which process is a bottleneck.

Table 3. Engagement and corrected process Cycle Times.

| Process | Engagement | Corrected C/T [sec.dec] |
|---------|------------|-------------------------|
| A       | 0.91       | 00.2                    |
| B       | 0.51       | 00.6                    |
| C       | 0.11       | 00.2                    |
| D       | 0.43       | 01.2                    |
| E       | 0.26       | 00.6                    |
| F       | 0.10       | 00.5                    |
and shows the scale of the lack of productivity in relation to other processes, which is of key importance when planning bottleneck improvements. Of course, the calculated C/T and productivity reflect the real production/order structure at the moment of the manufacturing system’s diagnosis.

6. Exploitation strategies of identified bottleneck

The second step that was given by Goldratt and Cox (1992) is to determine how to exploit the bottleneck. However, as the experience of the investigated manufacturing system demonstrates, there are a dozen potential improvement options. Moreover, improvement projects that are focused on bottlenecks are usually highly interrelated with other processes of the system. Therefore, before the decision on ‘how?’ is made, potential improvement options should be developed. Additionally, an increase of a bottleneck flow should be simulated considering the whole system, i.e. other processes. This increase is closely related to Goldratt’s third step implying the subordination of everything else in the system to increase the bottleneck (Goldratt & Cox, 1992). This increase should be considered as early as possible when developing solutions for bottleneck exploitation. The three most promising solutions for increasing the system throughout are presented below.

6.1. Abrupt production capacity increase

Production capacity is a determinant of customer response times. Furthermore, inadequate capacity is responsible for waiting times and excessive inventory levels (Rajagopalan & Yu, 2001). One of the first thoughts for managers, if a company is traditionally managed, is just to install a new manufacturing unit when it is suffering from capacity shortages in a process. Indeed, this option incrementally improves production capacity. Process D, which is the bottleneck of the system, can double its productivity thanks to the new production unit. Figure 4 below presents the process productivity when Process D’s productivity is doubled.

Figure 3. Hourly productivity of the processes that are calculated based on the corrected C/Ts [it./hr.].

It is clear that there is a new bottleneck in another process – Process E – with an hourly productivity of 5,800 items. The proposed change would increase the whole system flow by 2,700 items per hour (5,800–3,100, which is an 87% increase). The rates of other processes
would also increase. However, this is a costly change. It requires an investment of approximately 200,000 euros in a machine.

6.2. Continuous process improvement

Everyday improvements in the value stream are a mantra of Lean Manufacturing (Ohno, 1988; Womack & Jones, 2003). Every employee is encouraged to improve operations and machines on an everyday basis. The Lean approach claims that at least one other factory is hidden as waste within a company (Womack & Jones, 1994). This metaphor gives an idea of how much can be improved by Kaizen actions in a manufacturing system. This forces us to consider continuous improvement actions in order to increase the flow through a bottleneck. The approximation of the potential improvement in a bottleneck process is an essential issue, and it should start with what is known about the process at the starting point. Table 4 below shows the measured statistics of Process D’s work cycle.

First, it is clear that this crucial process of the system has extreme variability, since the standard deviation of the data is 70% of the average C/T. The target of improvement (the Kaizen target) might be to reach the productivity level of the process closest to the bottleneck. If the C/T (realistic, not corrected) of Process D was 1.5 sec., the productivity (corrected) would reach that of Process E. This finding means that Process D and Process E would have the same productivity for a given order structure. In other words, Processes D and E would have a balanced production flow assuming that the order structure is as given above.

The minimum observed C/T is 1 sec., but the first quartile is 2.1 sec. Therefore, achieving a C/T of 1.5 seems to be rather a big challenge for this organisation, although it is not impossible. Any improvement of the process stability and the median of the C/T will benefit the system because this is a bottleneck. It is probable that if a company runs an intensified improvement programme, the C/T can realistically and credibly be diminished to below the first quartile, which gives a corrected productivity of approximately 4,000 items per hour. However, it is clear that for continuous improvement to be effective, it requires the strong determination of managers and must cover the whole manufacturing process, not only one workstation.
6.3. Changes in the structure of orders

Seeking favourable product scheduling and an optimum product mix are quite often the studied goals of TOC implementation (Linhares, 2009; Plenert, 1999). However, in the case of the investigated manufacturing system, the issue is that the diverse products unevenly affect the loads of individual processes. Therefore, in this case, the goal is to seek a product structure that would result in a balanced flow throughout the system’s processes.

It should be noted that the studied manufacturing system consisted of six processes, and it executes orders comprising a maximum of only four processes. Furthermore, there are many orders that are performed by a single process (see Table 2 above). The current structure of the production volumes that is conducted by particular processes is presented in the second column in Table 3 where the engagement figures represent the percentages of volumes that are performed by the processes. If the engagement structure would favourably change, the production loads would be balanced in all processes if this structure is realistic. Table 5 presents the target engagement. Additionally, the second row shows the current engagement.

The idea of a balanced flow in TOC relies on having simultaneously fully exploited the potential of each process and established an equitable flow between them. Aiming at this state, it is necessary to start with the process with the highest productivity. This means starting with Process A since it has the shortest C/T (see Table 1 above). If this process is fully exploited, it sets the rhythm for the whole system, which is at the level of 18,000 it./hr. (corrected productivity). This finding means that all the production volumes flow through this process (A). In order to fully exploit the other processes in the system, the other processes’ engagement should be as presented in Table 5 (first row).

As presented in Table 5, the current process engagement and the target one differ very much. It would require a total change in the order structure, which, according to the managers from the company who have been informed about the target, is definitely not feasible. For example, there are many buyers who cooperate with the company because they have offered to conduct Process B and Process D, which are suggested to have noticeably lower engagement. Furthermore, managers are pretty sure that some

| Processes | A  | B   | C   | D   | E   | F   |
|-----------|----|-----|-----|-----|-----|-----|
| Target engagement (x.yy represents the % of the production volume) | 1  | 0.18| 0.12| 0.07| 0.08| 0.04|
| Current engagement | 0.91| 0.51| 0.11| 0.43| 0.26| 0.1 |
| Corrected hourly productivity [it./hr.] | 18,000 |
| Market strategy | ↑ | ↓ | ↑ | ↓ | ↓ | ↓ |
corrections in the order structure are certainly possible. The lowest row in Table 5 presents the market strategy for each process. The sign ‘↑’ represents an increase in this process engagement (understood as the percentage in volumes) and ‘↓’ represents a decrease. These might be obtained by adjusting the offered prices and the intensity of the marketing activities.

7. Which solution should be applied to the system?

As presented above, at least three solutions for increasing the flow in the studied manufacturing system are possible. All of them are different. One is the installation of a new production unit. Another is introducing a Kaizen project, which cannot be performed without a wider continuous strategy in the company. The third one depends on changing the production order structure, and this one is probably one of the highest risks in terms of noticeably increasing the system’s production flow. In Table 6, three improvement solutions are evaluated. Four evaluation criteria emerged during the in-depth interviews with managers. They are as follows: (1) effectiveness (probability of success); (2) the investment scale (finance engagement); (3) the efforts needed to perform the improvement (by managers and the whole staff); and, finally, (4) difficulty, which reflects how much the skills of managers and other employees are needed (required knowledge and professionalism).

There is no doubt that the installation of a new production unit would eventually increase the productivity (the solution is effective) at the identified bottleneck. However, it is associated with a large expense. The two other options are less certain with respect to increasing the production flow in a short time. However, if they are systematically and persistently introduced, they could bring an even bigger increase than a new production unit.

TOC proposes several measures. The basic ones are (1) the throughput in monetary terms, (2) the inventory in monetary terms, and (3) operating expenses (Goldratt & Cox, 1992). TOC’s measures are perceived as being opposite to those of the traditional accounting system that offers a global view of a company (Mabin & Balderstone, 2003; Mehra, Inman, & Tuite, 2005). The measures are aligned with the strategic objectives of the company (Draman, Lockamy, & Cox, 2002; Smith, 2000). They are often practically employed in the company’s product mix optimisation (Alsmadi et al., 2014; Corbett, 1998; Gupta, Ko, & Min, 2002). The abovementioned measures are suggested to be used while making decisions that affect the main goal of a company (Goldratt & Cox, 1992). The investigated manufacturing system does not operate on its own products but serves the printing operations of many readymade goods manufacturers. Additionally, the marginal levels are comparable in all processes, and any increase of throughput, in money or volume, benefits the company. Therefore, the calculation of the typical TOC measures was determined to be unnecessary. Furthermore, the evaluation that is presented in Table 6 was perceived as supportive for making improvement decisions.

Table 6. Evaluation of the developed improvement solutions.

| Solutions                  | Effectiveness | Investment | Effort   | Difficulty |
|----------------------------|---------------|------------|----------|------------|
| #1. New production unit    | High          | High       | Moderate | Moderate   |
| #2. Continuous improvement | Moderate      | Low        | High     | High       |
| #3. Order structure change | Low           | Low        | Moderate | High       |
As the data show (Table 4), the bottleneck process is very uncertain. Its stabilisation can bring many benefits, but it should also be emphasised that process stabilisation cannot be performed just on one process. The whole system should be improved in this regard. Additionally, the actions that are aimed at a better order structure need a long-term selling strategy and a long time to result in noticeable effects. Each of the developed solutions does not exclude the others, and the managers from the studied company are sure that all of them should be introduced simultaneously. If so, the system needs to have a clear target. Table 7 below includes the calculation of the target production for each process that is assumed to be achieved after a year of hard work on the improvement. The three sources of productivity growth (improvement solutions) are specified in the table. The target production level is a reflection of the managerial decision what kind of improvement is seen as possible and undertaken for implementation.

The second column (Table 7) contains the current productivity of the processes that are calculated based on the C/Ts, as presented in Figure 1. This is a starting point for the improvement predictions. The next column presents the process productivities when the corrected productivity reaches the level of full exploitation of Process F (see the visualised corrected productivity in Figure 4). It provides balanced flows in four of the existing processes in the system (Processes B, D, E, and F) with respect to the previous order structure. The productivity deficiencies will be covered by a new production unit (col. 4) and continuous system improvement (col. 5). The assumed levels of productivity growth (in col. 5) are considered to be feasible thanks to the Kaizen actions. Additionally, due to the large unused productivity in Processes A and C, it is assumed that additional orders will be gained just for these two processes (col. 6). Finally, the last column (col. 7) presents the target hourly production that has to be reached within the assumed improvement cycle. The production system will still not be fully balanced. Two processes will account for a significant portion of the unexploited productivity, but this issue will be an objective for improvement after reaching the set goals.

The presented analytical logic shows that the decision on how to exploit a bottleneck considers many variances and goes beyond a bottleneck by considering the whole manufacturing system. The above meets the expectations of the second (decide how to exploit the bottleneck) and third (subordinate everything else to unblocking the bottleneck) steps that were mentioned by Goldratt and Cox (1992) and goes even further.

Table 7. Target production level for improvement actions.

| Process | Current productivity | Prod. for corr. produc. | New production unit | Continuous improvement | Additional orders | Target production levels |
|---------|----------------------|--------------------------|---------------------|------------------------|------------------|-------------------------|
| A       | 18,000               | 7,125                    |                     |                        | 1,000            | 8,125                   |
| B       | 3,273                | 3,993                    | 721                 |                        |                  | 3,993                   |
| C       | 2,250                | 861                      |                     |                        | 500              | 1,361                   |
| D       | 1,333                | 3,367                    | 1,333               | 700                    |                  | 3,367                   |
| E       | 1,500                | 2,036                    | 536                 |                        |                  | 2,036                   |
| F       | 783                  | 783                      |                     |                        |                  | 783                     |

[items per hour]
8. Discussion

The above investigation of the manufacturing case allows for the discovery of several peculiarities of TOC implementation. With respect to the constraint identification, the case shows that a number of possible methodologies can be employed at this point. The machine productivity that is calculated using the processing time can be an appropriate method when the product stream flows through all the processes. In the studied system, when based on the C/T, Process F seems to be a bottleneck. However, further calculation showed that a bottleneck is located in another process. The crucial for bottleneck identification was the inequality of the process engagement in the production stream. It allows us to find the real system bottleneck, which is Process D.

The study confirms what has been observed by some researchers (Roser et al., 2015) that inventories are a good marker of bottlenecks in a system. However, one should address inventories using a deep understanding of the production flow. In the studied case, the higher inventories were before Process A (see Figure 2), which in fact is not a bottleneck, but they were caused by different factors than the limitation of production flow in this process. The study shows that the issue of constraint identification is very important and needs further research and much more practical guidance. The system's bottleneck is not obvious and needs to be clearly identified considering the individual system characteristics and circumstances.

While planning bottleneck exploitation, a wide view of the manufacturing system is necessary. Improvements in the bottleneck and other 'next level' constraints should be considered. The investigated case shows that the linear-cyclical approach, i.e. exploiting one bottleneck after another, would be a kind of loss due to inaction in the sphere of other possible improvements that additionally applies improvements as the set it is perceived as jointly supporting. Therefore, synergistic effects are expected. As such, the improvement target is not to catch up to the flow level of the next process, but rather to some level of the system’s production flow that is possible considering the existing constraints, the applicable improvement actions, and the ability of the company to implement them. Similar optics emerge from the study by Pegels and Watrous (2005) who argue that manufacturing and external constraints should be simultaneously considered. Moreover, they demonstrate that several solutions should be collectively applied to the bottleneck problem.

The manufacturing case study focuses on the application of TOC to a manufacturing system, starting with the first activities. The collected insights allow us to record the process (methodology) of TOC implementation that emerges from this case. Figure 5 presents this as a flow chart. First, it is very clear that the identification of the location of a system’s bottleneck is not easy, and many methods can be employed by a company. It must be preceded by the identification of all processes along with the basic characteristics, such as the process times (e.g. C/Ts, C/Os – changeover times). As in the studied case, if a production system is characterised by diverse products, the engagement of each process must be taken into consideration. Supposedly, each manufacturing system needs to have an individual methodology of calculating and determining the bottlenecks.

The determination of a bottleneck is a crucial step, and another important one is the calculation of the flow limitations in other processes (next level constraints), both manufacturing ones and others that determine the production flow. For dealing with bottlenecks, it is necessary to know (in quantitative terms) and understand the different capacities.
between processes. When understanding a bottleneck and its differences from other processes with respect to its capacity, a company can determine a solution for how to increase the flow through the bottleneck. However, other processes always have to be taken into consideration. Usually, many solutions can be implemented, and some of them can be alternatives, which is why there is a need to evaluate them, enabling us to make a reasonable choice between the possible solutions. Eventually, Throughput Accounting (Mabin & Balderstone, 2003; Mehra et al., 2005; Smith, 2000) is one of the possible supportive methodologies in this matter. Finally, the mix of improvement solutions should be determined, along with a target point in terms of the production flow and/or productivity for the whole manufacturing system. While introducing the solutions, such as leveraging the production flow rate at the operational level, many techniques from the TOC arsenal can be implemented. For example, the Drum–Buffer–Rope technique can prevent the accumulation of inventory (Bhardwaj et al., 2010; Scheinkopf, 1999). After selecting a plan for improvement, it should be introduced and monitored. When achieving the previously set goals, a company should start with a renewed understanding of the existing constraints.

9. Conclusions

According to the study by Pretorius (2014), the five-step sequential nature of TOC implementation is one of the most important shortcomings of this management methodology. Similarly, the research that is presented in this study argues that accurately following the
TOC’s steps by focusing on the constraints one by one is also not appropriate. A deep exploration of the studied manufacturing system revealed that the practical requirements of the different approach, which were presented above, are the most suitable. The system’s constraints should be exploited as a set, and the outcome is a new level of the whole system’s productivity. To meet a new level of productivity, the manufacturing system needs to have adopted an improvement solution mix that is composed of a variety of means and methods.

According to the studied manufacturing case, the improvement solutions cannot only be focused on a bottleneck. They also require a comprehensive understanding of the production flow through all processes and other potential constraints. Improvement solutions should be reasonably selected considering many criteria, such as the company’s business strategy, skills, knowledge assets, financial potential, risks, etc. The manufacturing system is a complex and multi-dependent one. Therefore, a reasonable improvement plan should go along with the decided ‘balance point’, which is the new level of global productivity of the manufacturing system.

The studied manufacturing system is characteristic of diverse products, and so production consumes processes’ capacity differently. In order to determine a bottleneck and to understand the different capacities between processes, the calculation of process engagement was necessary. This is a new method that is not present in the existing literature, which provides a solution to a real problem with respect to constraint identification. It must be underlined that some irregularities in products and in process utilisation frequently occur in manufacturing systems. A large number of producers suffer from these issues, especially when a company produces a wide range of products. With respect to this point, the proposed approach for bottleneck identification might have wide potential utilisation in the manufacturing industry and elsewhere. Presumably, proposed methodology is very suitable for improvement of manufacturing systems with fully automatic production procedures.

The study also indicates that the manufacturing system is highly interrelated and uniquely complex such that while applying TOC to it, a highly individualised approach to bottleneck/constraint identification and improvement design is necessary. This view is coherent with Gupta et al. (2002, p. 928) in that the real-world manufacturing environment is much more complex than that presented in the literature. Consequently, the bottleneck constraint and other potential constraints should be collectively considered when determining the target productivity for a system improvement. This study contributes to production management theory by proposing a new method for TOC implementation and a method for bottleneck identification that considers the irregularities in processes’ capacity utilisation.

The study has employed a qualitative approach. This allowed for an in-depth investigation into the studied manufacturing system and possible TOC implementation methods in it. In-depth studies are precious due to the generic observations and close contact with an investigated object. Furthermore, the case study methodology provides weak evidence, which does not allow wider generalisations. Therefore, the proposed TOC implementation methodology is not a revealed guideline, but is rather just another view on this viable issue. Even though this is fragmented research, it shows the scale of the challenge when implementing TOC in a manufacturing system.

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