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DIAGNOSTICS OF PRODUCTION PROCESSES USING SELECTED LEAN MANUFACTURING TOOLS

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Abstract

Modern manufacturing companies should adapt to the needs and requirements of customers, and the products manufactured should meet the needs of customers. Meeting these requirements is the key to maintaining an appropriate position on the market. In production systems, an important element of the efficient functioning of the production process is production logistics, therefore the aim of this publication was to diagnose logistics and production processes and propose improvements in this area. For this purpose, selected tools of the Lean Manufacturing concept were used: the SMED (Single Minute Exchange of Die) method and Goldratt's Theory of Constraints. SWOT analysis was used to determine the strengths and weaknesses of the company.

Keywords: production processes, production logistics, Lean Manufacturing, SMED technique, Theory of Constraints

List of Symbols/Acronyms

C/O – Changeover Time [s]
C/T – Cycle Time [s]
HT – hardening trolley
I – investments [PLN]
m – mass [kg]
NP – Net Profit [PLN]
OE – operating expenses [PLN]
P – net price [PLN]
pcs. – pieces
Q – quality
q - quantity
ROI - Return On Investments [%]
SME- small-medium enterprises
SMED - Single Minute Exchange of Die
T – throughput [PLN]
TA – Throughput Accounting
TOC – Theory of Constraints
TTp - total throughput [PLN]
Tu - throughput per unit [PLN]
TVC - total variable costs [PLN]

1. INTRODUCTION

Change is undoubtedly a key element in the development of an enterprise, and its desired effectiveness is supported by the use of tools that improve enterprise management [4, 34, 40]. One of them is the concept of Lean Manufacturing, which was created by the Toyota brand - a Japanese automotive giant engaged in the production of cars [8, 9]. The key to this philosophy is to eliminate all waste ("muda" in Japanese) [24, 31].

Lean Manufacturing implementation at an enterprise can cause many limitations. For example, it requires the employment of an experienced specialist involved in the implementation of this type of tools by the companies [1, 29]. However, the most important thing is the concern for employee involvement and their motivation to introduce changes [2, 19]. The financial element is also important. Each newly implemented change may require large financial outlays, such as: the purchase of modern machinery or the employment of specialists [10, 21, 23]. Nevertheless, the benefits of implementing Lean Manufacturing include: shortening process times, increasing productivity and eliminating all waste occurring in the company [11, 28, 37]. Proper management of the decision-making process [15, 35] and management of the machine park [25, 32, 39] are crucial.

One of the tools used for this purpose is the Theory of Constraints (TOC), created in 1970 by the Israeli physicist Eliyahu M. Goldratt [16, 30]. It is based on the belief that every system has at least one limitation and assumes that [27, 38]:

a) each system contains a specific purpose;
b) each system must improve the achievements that are related to the purpose;
c) achievements are limited.

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In this publication a diagnosis of logistics and production processes at the examined enterprise was made using the above theory, and then improvements in selected areas were proposed and evaluated. The changes proposed by the authors are not complicated and do not involve many factors related to the functioning of the company that should be taken into account in real conditions, but the aim of the presented considerations was primarily to demonstrate the validity of using Lean Manufacturing tools and the simplicity of their implementation.

The concept of Lean Manufacturing is widely discussed around the world, in relation to various industries. For example, the application of Lean Manufacturing in the SME sector is presented in [33] based on Indian companies, while in [2] the study was conducted among entrepreneurs from the United Arab Emirates. In [18] an example of the implementation of selected Lean tools is presented in the Indonesian wooden furniture industry. Research in the value chain of the enterprise from the USA dealing with fish processing and marketing was presented in [22], and in [26] the Lean tools were used in the chemical industry. There are many examples of such implementations, as there are many of them in world literature. This is due to the universality of this method, as well as the ability to provide a high-quality product while optimizing costs, increasing operational flexibility and market share [17]. However, this causes the need to constantly explore its principles and analyse these issues, using the example of various types of enterprises and markets. This assumption is also consistent with this article, in which the subject of the study is a Polish company from the construction industry.

The article consists of several sections. Following the introduction, the methods and the company characteristics applied in the study were presented. Then, the company's condition was diagnosed using SWOT analysis and the bottlenecks in the process were located, for which improvements were later proposed, these changes were assessed, final conclusions were formulated, and directions for further research were indicated.

2. MATERIALS AND METHODS

2.1. Selected elements of the Lean Manufacturing concept

As already mentioned, one of the tools used in the Lean Manufacturing concept is the Theory of Constraints and the related Process of Ongoing Improvement (POOGI). Its essence is to focus on the effort that will allow to obtain the best result by implementing “The Five Focusing Steps” [13]:

1) Identification of the constraint – locating the bottleneck that exists in the system;
2) Exploiting the constraint – using the limitation as much as possible;
3) Subordination – ensuring that the remaining stages of the production process function in a manner adapted to the identified limitation;
4) Elevation of the constraint – considering the possibility of increasing bottleneck efficiency;
5) Return – repeated analysis of the entire system, because the change may have caused another limitation to appear in the system.

In order to determine whether the proposed increase in bottleneck capacity is effective and efficient, Eliyachu Goldratt proposed in his Theory of Constraints, Throughput Accounting (TA) and specific measures that are presented below [5, 14]:

a) Throughput - T - the rate at which an enterprise creates money from the sale of specific goods or services provided. This should be understood as all the money obtained by the company, minus the costs paid to suppliers. In the case of processing, a distinction is made between unit throughput (Tu) and total throughput (TTp):

$$T_u = P - TVC \tag{1}$$

where:
Tu - throughput per unit, P – price, TVC - total variable costs.

$$TT_p = T_u \times q \tag{2}$$

where:
TTp - total throughput, q - quantity – number of pieces of the product sold.

b) Operating Expenses - OE – financial resources intended to increase throughput, other than truly variable costs (e.g. wages, utilities, taxes, etc.).
c) Investments - I – financial resources related to physical items, e.g. production inventories in progress, finished products, production machines and equipment, buildings.

The aim should be to achieve an increase in throughput while reducing operating expenses and investments. The support in the final decision regarding the appropriateness of introducing a given improvement are also [5, 14]:

a) Net Profit - NP – an indicator that shows the difference between throughput (T) and operating expenses (OE):

$$NP = T - OE \tag{3}$$

b) Return On Investments - ROI – an indicator that describes the ratio of net profit to investments. It greatly supports the decision-making process:

$$ROI = \frac{T-OE}{I} = \frac{NP}{I} \times 100\ [\%] \tag{4}$$

Another popular Lean Manufacturing tool used in production plants is SMED (Single Minute Exchange of Die). Its essence is to shorten the time of changeover machines and distinguishes three basic groups of activities related to it [6, 7]:

a) Internal work – activities that are performed when the machine is out of production;
b) External work – activities that are performed when the machine can operate without unnecessary interruptions;
c) Unnecessary work – activities that are unnecessary.

Changeover time (C/O) is wasteful from the point of view of Lean Manufacturing, so efforts should be made to keep this process to a minimum [15, 36]. Stages of procedure, in case of introducing the SMED method in the company are as follows [6, 7]:
Stage 1 - identifying all necessary work needed to changeover the machine, and then dividing this work into internal and external;
Stage 2 - since internal work requires stopping the machine, internal work must become external work;
Stage 3 – carrying out the improvement of all work that was identified in stage 1;
Stage 4 - implementation of organizational activities related to the machine changeover process.

2.2. Characteristics of the production process at the „Silikaty-Białystok" company

This article examines a production and trade company from the construction industry, producing lime-sand products used to build structural, curtain or partition walls. Currently, the company produces a wide range of silicate materials and is one of the most important producers of this type of materials in Poland. It is the only entity in the country that specializes in coloured and processed facade products, which, thanks to their unique texture, successfully compete with other facade materials. The general diagram of the production process for producing silicates is shown in Figure 1.

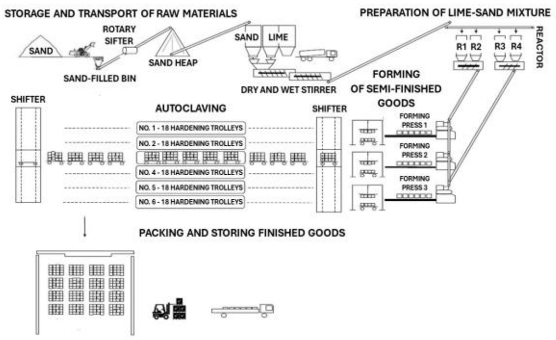

Fig. 1. General diagram of the silicates production process [20]

The entire production process consists of thirteen stages.

Stage I - storage and transport of raw materials. Its main goal is to obtain raw materials needed for production - sand and lime. The sand must be sieved to separate large fractions or impurities, and then it is stored in a heap, from where it is delivered to the production tank, which is done using a truck tractor with a special silo semi-trailer. Unloading takes place pneumatically into two tanks. Already at the first stage, the company checks the supplied raw materials by testing the lime slaking time and activity.

Stage II - preparation of the lime and sand mixture. This stage is completely automated. Weighed amounts of lime and sand are initially mixed dry using a twin-shaft mixer. In the second mixer, water is added and mixing is continued to achieve a uniform mass. Then, after moistening, the moisture and activity of the mixture are analysed. After obtaining the appropriate parameters, the mixture is transferred to steel tanks, which are called reactors, where the lime is slaked, i.e., the so-called maturation.

Stage III - forming semi-finished products. The mixture is directed to the presses via a conveyor belt (three forming presses can operate at the same time). Depending on the product being manufactured, the shaping form is changed. The cycle time (*C/T*) of the forming press is 9 seconds. There are 25 rows of semi-finished products on the belt between the machine and the stacker. Number of pieces of semi-finished product in one press cycle depends on the type of final product. In this article, Silicate N12 will be analysed (Fig. 2). One press cycle produces 5 pieces of semi-finished products.

Fig. 2. Analysed Silicate N12 [20]

It is worth emphasizing that the product forming stage generates the largest number of damages to the semi-finished product immediately after leaving the forming press, which constitutes approximately 15%. In other processes, damage practically does not occur. The most likely cause of the defect is the instability of the mixture in the reactor when the production series is started.

Stage IV - placing the semi-finished product on the hardening trolley (HT). It takes place after the forming stage is completed, when the receiver places the products on the conveyer and moves the elements under the stacker. The stacker grabs 4 rows simultaneously (the so-called stack), which is then placed on a hardening trolley. The number of semi-finished products taken by the stacker and placed on the hardening trolley depends on the type of product manufactured - for N12 silicate it is 240 pieces. The average cycle time of the stacker is 37 seconds. There are 12 pieces on one hardening trolley. The loading time of the entire hardening trolley takes on average 7 minutes 24 seconds. The operator changes the position of the last stack of the semi-finished product on the ready-made hardening trolleys formed by the stacker. It creates the so-called crown, which is required to maximize the use of the volume (load) of the autoclave.

Stage V – internal transport of the hardening trolley. The hardening trolleys are moved to the autoclave tracks by internal transport using an gantry crane. Two trolleys are moved on the crane at the same time. The time for loading two hardening trolleys onto the crane is 51 seconds, while the time for unloading them from the crane is 1 minute 53 seconds. The longest transport time of trolleys on the gantry crane (from the first forming press to the last autoclave) is 4 minutes 34 seconds. The average transport time is 4 minutes 17 seconds, while the average one-way travel time of the crane is 45 seconds.

Stage VI – stop before hardening. Each of the six autoclave tracks can accommodate 18 hardening trolleys. The estimated time to fill the entire track is approximately 1 hour 30 minutes. This is the time during which the buffer before the hardening process is filled by the operation of one press forming semi-finished products and an gantry crane transporting hardening trolleys.

Stage VII – hardening. The plant has a total of 6 autoclaves. Each autoclave holds 18 hardening trolleys. The hardening time of the semi-finished products takes 7 hours. The autoclave is unloaded and loaded at the same time, which lasts 2 minutes. The process of opening the unloading door of the autoclave takes 2 minutes and the loading door takes 1 minute and 20 seconds. The autoclave loading door closes on average 1 minute 23 seconds.

Stage VIII – preparation of pallets. This process takes place in parallel with hardening. While the products are hardening, the employee places the pallets manually in a special zone of the plant. Pallets are stacked in rows of at least 3 in each row. This is due to the fact that one hardening trolley, after unloading, takes up 1.5 pallets. It takes 20 seconds to stack one pallet. This is the time including picking the pallet and moving it and correct arrangement in a row.

Stage IX – removal of the crown. It takes place depending on the type of product manufactured. This operation can be performed while unloading the autoclave. However, in some cases, the uppermost finished products are placed only on a pallet so as not to damage them during transport by the gantry crane. The time required to remove the crown for three operators, for all hardening trolleys from one autoclave, takes 6 minutes and 22 seconds. The next activity performed by employees is moving the hardening trolleys apart and pushing the first row of the finished product together. This is related to the need to ensure that the crane lifting grip carrying finished products can freely pick up the products.

Stage X – placing the finished product on pallets. This stage is performed by three employees. The first employee is the operator of the crane that moves finished products from the hardening trolley to the pallet. The second employee helps manually set the crane lifting grip so that it does not damage the product during picking up. The third employee's task is to correct the alignment of pallets and stick on product specification cards to each pallet. The time required to collect the volume of one hardening trolley (1.5 pallets), place the contents on the pallet and return the crane takes a total of 2 minutes and 10 seconds.

At the plant, observations were made of placing finished products on 162 pallets, which corresponds to 108 hardening trolleys. Of all the pallets, 13 were noted to have incorrect alignment. Based on this it can be concluded that this represents approximately an 8% error in the positioning of the products. Summing up this stage, it can be concluded that the operations related to placing finished products on pallets are machine-manual in nature. This results in inaccurate positioning of products on the pallet.

Stage XI – taping up and installing the foil. The employee performs horizontal and vertical taping up manually. Then he applies the foil to secure the cargo during transport. The time to perform these activities for one employee is 2 minutes 10 seconds. The operation is performed by a total of 2 employees.

Stage XII - placing the product in the storage area. It involves picking up a pallet load unit using a two-pallet forklift, and then moving it to a previously prepared storage area. The time needed to load the pallet onto the trolley, place it in the appropriate storage area and return of the forklift is 1 minute 13 seconds.

Stage XIII – loading onto the truck. Loading onto the tuck is done using a forklift. The operator picks up a pallet load unit from the storage area and moves it towards the vehicle and then places it on the vehicle's loading surface. The company does not have its own fleet of vehicles for transporting manufactured goods, so it uses the services of external transport companies.

3. POSSIBILITIES FOR IMPROVING PRODUCTION AND LOGISTIC PROCESSES – CASE STUDY

3.1. SWOT analysis

For the initial diagnostics of the company, a SWOT analysis was used, which allows to assess the internal and external factors occurring in the organization that shape its position on the market. The former take into account all the elements over which the company has control, i.e. strengths and weaknesses. However, external factors should be interpreted as those over which the company has no control - opportunities and threats [2, 3, 12] (Table 1).

Based on the SWOT analysis, the examined company should choose an aggressive strategy (maxi - maxi), because the analysis is dominated by strengths, while the environment is dominated by opportunities. The company should use its assets, i.e. strengths and emerging opportunities in the environment in the expansion of a new product and increasing production capacity, which translates into the company's development. Having modern technology and increased production potential, the plant can invest in new products and expand its sales market [2, 12].

Table 1. SWOT analysis of the surveyed company

STRENGTHS	WEAKNESSES
A well-known brand with extensive experience in the construction materials market (over 60 years of activity).	The company operates mainly in the local area. (mainly in north-eastern Poland).
The main product - silicate is ecological and relatively cheap. Depending on the type of material, using silicates allows for 20-30% savings during construction.	Obsolescence of machines and equipment may affect the quality of goods.
Experienced and permanent staff, which eliminates excessive staff turnover.	The need to modernize the machinery, which involves huge investment outlays.
A favourable image of the company, confirmed by numerous certificates and awards.	High production costs due to low automation of the production process.
Managers' excellent knowledge of trends in the construction market.	Relatively strong competition in the industry
The production process does not cause environmental pollution (air, water and soil).	
A diversified product offer, that takes into account the size and colour of the product - about 15 types of products on sale.	
Very good quality of the finished product - durable colour, high heat retaining factor, high strength, frost resistance, fire resistance, resistance to biological corrosion.	
Professional approach to customer needs.	
Locational concentration of manufacturing activity.	
Large base of regular customers and intermediaries - more than 35 sales partners.	
OPPORTUNITIES	**THREATS**
Rapid development of the construction market.	Increased competitiveness on the building materials market.
The state's credit policy is favourable in obtaining widely available housing loans (7.3 % more mortgage loans were granted in 2023 than in 2022).	A huge increase in the prices of raw materials (coal, lime) caused by the outbreak of the war - even up to 20% compared to the pre-war period.
Offering specialized building materials (coloured blocks), which distinguishes the company from the competition.	Changes in the construction regulations may reduce demand and, consequently, increase production costs and affect the sales price of the products.
Increased demand for apartments and office premises.	Market instability – sudden increases and decreases in the demand for building materials.
Wage increase and continuous economic development of Poland.	Dependence of the company's economic performance on the prosperity of the construction market.

3.2. Locating bottlenecks – time-consumption and productivity

The study was conducted for a sample batch of N12 silicate, i.e. for production of 108 hardening trolleys in a system of 6 autoclaves, with the operation of 3 forming presses. The starting point is to determine the time-consumption of all identified stages of the production process. First of all, the so-called model "clean processing times", which refer only to the time necessary to complete a given operation, without taking into account unnecessary interruptions. Then, the time-consumption "Q" is calculated, taking into account defects arising during the process, in this case related to the unacceptable quality of the formed semi-finished products. Defects in the forming process extend the total production time by 0.648 h, or about 39 minutes, therefore by this time the operation of each press is extended. The last case to be considered is time-consumption taking into account quality (“Q”) and changeover times of production machines (C/O). Replacing the mold is necessary due to the nature of production, and it is also a very important element that affects the market success of the company and the diversity of its products. Changeover time of a forming press is from 4 to 8 hours, depending on the mold. For the purposes of the study, 6 hours were assumed. Production time-consumption with 6 autoclaves and 3 forming presses operating taking into account various wastes is presented in Figure 3. The longest process is hardening. Its duration is approximately 7 hours 40 minutes. As already mentioned, the problem with quality and defects in the production process mainly concerns the forming process, and for the rest it is negligible, therefore it was omitted from the analysis.

The study covered one calendar month (April), during which a total of 6,401 hardening trolleys were produced. During the analysed month, the mold was changed 3 times, i.e. there were 3 changeovers of the press. As a result, it took an average of 0.05 changeovers, or about 18 minutes, to fill 6 autoclaves (108 HT). Taking into account the quality ("Q") and changeover times (C/O), the forming process time is extended by approximately 57 minutes compared to the model situation, so the entire process of forming semi-finished products will take a total of 5 hours and 16 minutes in this case.

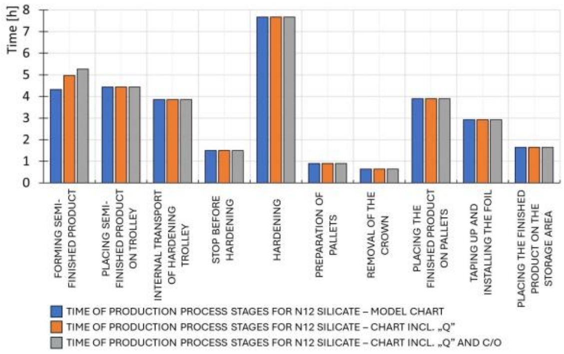

Fig. 3. Production time-consumption with 6 autoclaves and 3 presses operating

Figure 4 shows the productivity of the forming process of one forming press per one working shift, taking into account factors that reduce the potential of this process, and compares theoretical values with the actual implementation of the process. In this case, the model value concerns the number of hardening trolleys during one working shift, on one forming press, assuming reference production and is 66.67; the value taking into account the quality "Q" is the number of hardening trolleys taking into account the defects that arise, which is equal to 57.95; while the value taking into account the quality "Q" and the changeover time of the C/O forming press is 54.65. The maximum number of hardening trolleys, average values (monthly and for individual changes I/II/III) represent actual values, calculated on the basis of empirical data in relation to one forming press.

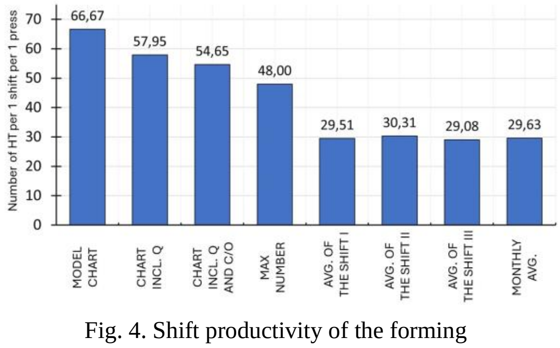

Fig. 4. Shift productivity of the forming process

Figure 4 shows that the plant produces fewer hardening carts per shift on one press (29.63 HT) than the current production capacity allows (54.65 HT), therefore there is unused production potential in the forming process. Assuming that the level of production of hardening trolleys in one shift, by one forming press, if all waste were eliminated, could be at the level of 66.67 HT, the degree of utilization of the potential of the forming press is 44%. Figure 5 in a similar way, shows the productivity of the hardening process in one shift in relation to the autoclave.

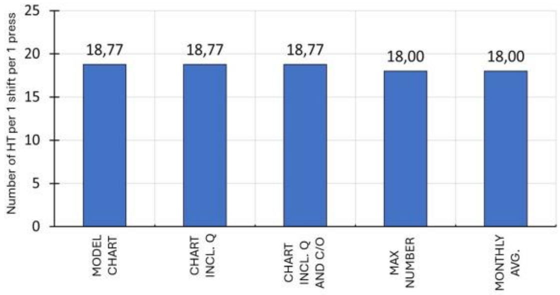

Fig. 5. Shift productivity of the hardening process

Factors occurring in the forming process, such as quality ("Q") and changeover time (C/O), do not affect the hardening process. The average value of the number of hardening trolleys hardened in one shift by one autoclave is 18. The company tries to ensure that before every start of the hardening process, each autoclaves was 100% full, i.e. by 18 HT.

3.3. Identification of bottlenecks and proposals for improvement

3.3.1 Forming process

Current possibilities of the forming process within one week, assuming 6 working days, are:

$$29{,}63\ \times 3\ \times 3\ \times 6\ = 1602\ [HT] \tag{5}$$

Whereas the possibilities of the hardening process are:

$$18\ \times 6\ \times 3\ \times 6 = 1944\ [HT] \tag{6}$$

This means that the plant is capable of producing during the hardening process, 342 more hardening trolleys than in the forming process, so the first bottleneck is the forming process. To eliminate this limitation, Goldratt's Theory of Constraints and the SMED method were used. In accordance with previously accepted arrangements, the down time of the machine from availability to production as a result of changeover is on average 6 hours. As an improvement, it should be considered that the plant is able to shorten the time of machines unavailability to production, due to changeover, by half of the assumed time, i.e. to 3 hours. The assumption can be considered realistic and achievable in a relatively short time. Taking into account the quality factor ("Q"), it is assumed that zero errors will be achieved on the forming press.

In the studied month there were manufactured 6401 HT, while the forming press was retooled three times. Thanks to this information, it is possible to calculate the number of hardening trolleys in one working shift on, one forming press after eliminating the quality factor ("Q") and reducing the changeover time to 3 hours. The average production series until retooling is:

$$\frac{6\ 401}{3} \approx 2\ 133{,}67\ [HT] \tag{7}$$

Number of working shifts needed to complete a typical production series:

$$\frac{2\ 133{,}67}{66{,}67} \approx 32{,}00 \tag{8}$$

Number of hardening trolleys in one working shift on one forming press after eliminating the quality factor ("Q") and reducing the changeover time to 3 hours:

$$\frac{2\,133{,}67}{32+\left(\frac{3}{8}\right)} \approx 66\ [HT] \tag{9}$$

Based on the above calculations, it can be concluded that the number of hardening trolleys that the system is able to produce in one working shift, on one forming press, after eliminating the "Q" factor associated with a significant number of defects to the semi-finished product immediately after leaving the forming press and shortening the changeover time up to 3 hours is 66 HT. After improvement, the current capacity of the forming process in one week is:

$$66\ \times 3\ \times 3\ \times 6\ = 3564\ [HT] \tag{10}$$

Whereas, the number of hardening trolleys that the plant is able to harden in the 3-shift system operation within 6 working days, by 6 autoclaves is:

$$18\ \times 6\ \times 3\ \times 6\ = 1944\ [HT] \tag{11}$$

The next stage should focus on creating a Throughput Accounting. To perform the calculations correctly, it is necessary to determine the unit throughput (*Tu*). Based on the data collected, it can be concluded that the production of one ton of the finished N12 product requires the consumption of lime worth PLN 42.08 and sand worth PLN 17.74, therefore the total variable cost (*TVC*) of the product is assumed to be PLN 59.82. The net price (*P*) of the most popular product, N12 silicate, is PLN 3.30, and the weight of 1 piece is 9.50 kg. The value of unit throughput (*Tu*) for one HT was calculated based on formula (1):

$$240\ [pc.] \times 9{,}50\ \left[\frac{kg}{pcs.}\right] = 2{,}28\ [t] \tag{12}$$

$$2{,}28\ [t] \times 59{,}82\ \left[\frac{PLN}{t}\right] \approx 136{,}39\ [PLN] \tag{13}$$

$$240\ [pc.] \times 3{,}30\ \left[\frac{PLN}{pcs.}\right] = 792{,}00\ [PLN] \tag{14}$$

$$T_u = 792{,}00 - 136{,}39 = 655{,}61\ [PLN] \tag{15}$$

Then, the actual production volume and the production volume that the system will achieve after introducing the improvements were calculated. The volume of actual production in the analysed month is 6,401 HT. Production volume after introducing changes in forming process, while taking into account the current possibilities of hardening (during the analysed period, the company worked a total of 24 working days) is:

$$18\ \times 6\ \times 3\ \times 24 = 7776\ [HT] \tag{16}$$

As a result, the change in total throughput (ΔTTp) calculated based on the formula (2), with the simultaneous elimination of the quality factor ("Q") and shortening the changeover time (C/O), will be:

$$\Delta TT_p = (7\,776\ - 6\,401) \times \times 655{,}61\ = 901\,463{,}75\ [\,PLN] \tag{17}$$

The calculations take into account the unit throughput (*Tu*), which should be regarded as constant for subsequent improvements.

Considering the current situation of the hardening process production capacity, it should be noted that one forming machine is completely unused. Whereas, the second press is out of production only during the third working shift. Each shift requires 8 employees. However, hiring a new employee costs PLN 4,000. In the case of three-shift work, this gives total savings of 4 production employees, which translates into reduced operating expenses (ΔOE):

$$\Delta OE = -4 \cdot 4000 = -16\,000\ [PLN] \tag{18}$$

Another very important aspect in the Throughput Accounting is investment outlays (*I*) and, above all, their change (Δ*I*). In the case of the modification proposed, investments involve increasing the level of inventories in the course of production. In order to obtain increased production capacity of the bottleneck in the forming process, the company should incur costs related to the removal of the quality factor ("Q") and training related to the introduction of the SMED method. All items listed are investment outlays (*I*). It was assumed that the cost of training one employee in the context of the SMED method would be PLN 3,500. The total number of employees servicing the presses is 5. The calculations assumed that the total costs incurred for training employees related to SMED and the elimination of "Q" will amount to approximately PLN 40,000. Additionally, a three-day inventory rotation was adopted for simplification. The change in investment outlays (Δ*I*) will therefore be:

$$\Delta I = (1\,375\ \times \frac{3}{7} \times 59{,}82\ ) + + 40\,000\ = 75\,251{,}07\ [PLN] \tag{19}$$

The proposed improvement of the bottleneck in the forming process leads to a large reserve of production capacity that can be largely used to improve other constraints in the system. In the case of expansion of the machinery park, the proposed modification is necessary.

3.3.2 Hardening process

Another bottleneck that appeared in the analysed company, is a product hardening process. The currently used capacity of the production system in the form of six autoclaves causes deficits there in terms of hardening. Two possibilities were proposed to eliminate the existing limitation.

The first proposal is to introduce 11 working shifts (five days of two shifts and one day of one shift) for the forming process and 21 working shifts (seven days of three shifts) for the hardening process. This will compensate for the difference in the number of hardening trolleys produced between the two main stages of the production process. In one week, the forming presses will be able to produce a total of 2,178 HT and all autoclaves will be able to harden 2,268 HT. Production capacity allowing full use of the production capacity of the hardening process means that each forming machine is capable of producing 726 HT in 11 working shifts. This will allow to use production potential held in 100%. As part of the improvement, a reserve of production capacity is created at the level of 90 HT, which results from the fact that the plant is able to harden a larger number of carriages than it can produce in the forming process. It is worth noting, however, that this is an acceptable situation because each press is used to the maximum.

Taking into account the new production capacity after improvement implementation, it can be seen that the company would be able to produce 234 HT more within 7 working days. Therefore, it can be assumed that the change in throughput (ΔTTp), due to changes in production, will be:

$$\Delta TT_p = 234 \times 655{,}61 \times 4 = = 613\,650{,}96\ [PLN] \quad (20)$$

The proposed improvement is related to a change in the plant's operation, which involves extending the hardening process to 7 working days, i.e. 21 working shifts, and in parallel shortening the forming to 11 working shifts. As a result, a different number of employees will be needed for each shift (Table 2).

Table 2. Number of employees on each working shift on individual days of the week

		Day of the week						
		Mo.	Tu.	We.	Th.	Fr.	Sa.	Su.
Shift	I	8	8	8	8	8	8	5
	II	8	8	8	8	8	5	5
	III	5	5	5	5	5	5	5

It was assumed that the first shift works from Monday to Saturday. The second one is from Monday to Friday and will perform the forming and hardening process. Therefore, it will be necessary to provide on these days 8 employees on each work shift. However, when only the hardening process is carried out, only 5 workers are needed. This requires the employment of an additional 4 people who will ensure the operation of all forming machines during each work shift. Hiring a new employee costs PLN 4,000, so the change in operating expenses will be:

$$\Delta OE = 4 \cdot 4000 = 16\,000\ [PLN] \quad (21)$$

Another very important measure is investments (I). Bearing in mind that on weekends (especially on Sundays) there will be no sales of finished products, a three-day inventory rotation has been assumed. In addition, newly hired employees should undergo training in the field of the SMED method. It was assumed that the cost of training one employee would be PLN 3,500. Therefore, the change in investment outlays (ΔI) will be:

$$\Delta I = (936 \times \frac{3}{7} \times 59{,}82) + + (3\,500 \times 4) = 37\,996{,}37\ [PLN] \quad (22)$$

Table 3 summarizes all four measures of the Theory of Constraints (TOC) and assesses whether the proposed change is attractive for the analysed company.

In the analysed case, the proposed improvement involves certain operational and capital expenditures. But in relation to the change in throughput achieved, this share is not great. Therefore, the proposal should be considered attractive due to the increase in total throughput and a very high return on investments.

Table 3. List of efficiency measures in the bottleneck in the hardening process (proposal 1)

Measure	Value [PLN]	Assessment
Total throughput change (ΔTT_p)	613 650,96	Large change of total throughput
Required operating expenses (ΔOE)	16 000,00	Low operating expenses
Needed investment outlays (ΔI)	37 996,37	Low value of investments incurred

As a second solution to eliminate the limitation occurring in the hardening process, it was proposed to purchase additional autoclaves and extend the plant's operating time. So far, the hardening process was carried out 7 days a week, with three working shifts operating simultaneously. The suggested improvement proposes that all processes were carried out in the same period (from Monday to Sunday). Moreover, in order to implement this proposal, it will be necessary to implement a four-team system, in which three shifts work actively around the clock and the fourth shift rests - all on a rotating basis. Increasing production capacity of the hardening process is also possible by purchasing an autoclaves. Since, following the introduced improvement in production process, the company is able to produce a total of 66 HT during one work shift, the production capacity of the forming process within 7 days for 3 working shifts, including 3 forming presses, amounts to 4,158 HT. The maximum capacity of one autoclave within 7 working days is 378 HT, so to harden 4,158 HT a total of 11 autoclaves needs to be used. Therefore, it is justified to purchase another 5 autoclaves. This way, the production capacity for one work shift will amount to a total of 198 HT, and the production capacity of 11 autoclaves in 7 days in the case of a four-team system will amount to 4,158 HT. Production occupancy for each of three forming presses will then be equal to 100%. It is worth emphasizing that thanks to this solution, there is no excess production capacity, as before, i.e. the number of hardening trolleys produced by the presses is precisely adjusted to the processing capacity of the autoclaves. For the calculation of basic efficiency parameters according to the throughput accounting, the increases from the state occurring in the first bottleneck were taken into account. The calculations were made for one month. If one autoclave is able to harden 18 HT in one work shift, 5 autoclaves will produce, in one month, 7,560 HT. Therefore, the change in throughput (ΔTTp) will be:

$$\Delta TT_p = 7\,560 \times 655{,}61 = 4\,956\,411{,}6\ [PLN] \quad (23)$$

Due to the need to employ an additional team, it is necessary to employ four more people to operate the forming presses. The change in operating expenses(ΔOE) will therefore be:

$$\Delta OE = 48\ 000\ \text{[PLN]} \tag{24}$$

The next measure, i.e. investments (I), is the cost of purchasing five autoclaves. Its price, based on the average market value, was assumed to be PLN 500,000. Inventory turnover is invariably 3 days and, similarly to before, each newly hired employee is obliged to participate in training. Therefore, the change in investment outlays (ΔI) will be:

$$\Delta I = \left(7\ 560 \times \frac{3}{7} \times 59{,}82\right) + 2\ 500\ 00 + \\ + 42\ 000 \approx 2\ 735\ 816{,}80\ [PLN] \tag{25}$$

Table 4 summarizes all four Theory of Constraints (TOC) measures and assesses whether the proposed change is attractive to the analysed company.

Table 4. List of efficiency measures in the bottleneck in the hardening process (proposal 2)

Measure	Value [PLN]	Assessment
Total throughput change (ΔTTp)	4 956 411,60	Very large change of total throughput
Required operating expenses (ΔOE)	48 000,00	Significant operating expenses
Needed investment outlays (ΔI)	2 735 816,80	Very large investment outlays

The proposed improvement should be considered attractive to the company and recommended for implementation. Despite very large investment outlays, it must be emphasized that the change in throughput is very high.

4. DISCUSSION OF THE RESULTS - EVALUATION OF THE PROPOSED CHANGES

To evaluate the proposed solutions, the indicators proposed in Goldratt's Theory of Constraints were used, allowing the final decision to be made, which of the proposed changes would be optimal. These are Net Profit (*NP*) and Return on Investment (*ROI*). Table 5 shows the improvement results for the two main stages of the production process - forming and hardening.

Each of the proposed improvements is profitable because for all of them Net Profit (*NP*) and Return On Investment (*ROI*) are positive and do not generate losses.

In the case of forming process, where the proposal to improve the first bottleneck is to solve problems related to quality and machine changeover times, a very high Net Profit (*NP*) of PLN 917,463.75 should be taken into account. Moreover, the Return on Investment (*ROI*) is also beneficial for the company as it is 1219%. This value should be considered attractive and interesting from the plant's point of view. Eliminating this bottleneck will increase production capacity in the forming process.

Table 5. Summary of Net Profit (NP) and Return on Investment (ROI) indicators

Process	Proposal for improvement	NP [PLN]	ROI [%]
Forming	Solving the quality problem and shortening the changeover time	917 463,75	1219
Hardening	Extension of working time	597 650,96	1573
	Purchase of autoclaves	4 908 411,60	179

In the case of the hardening process, the first proposal, i.e. extending the working time, generates lower Net Profit (*NP*) compared to the second proposal, by PLN 4,310,760. These values suggest that the improvement by purchasing additional autoclaves may be more beneficial in terms of profits and production results. Moreover, it is an investment in the future of the company, which will allow the company to develop and increase its market share. However, making decisions at a strategic level requires in-depth analyses and taking into account additional factors, that were not taken into account in the presented study. The authors' intention was only to present the possibilities of using selected Lean Manufacturing tools in the company in order to diagnose it and assess the possibility of introducing changes.

4. SUMMARY AND CONCLUSIONS

The aim of this article was to diagnose logistics and production processes presented using the example of a selected company and to propose improvements in processes that were considered crucial to the further development of the company. The main intention of the authors was to present a method enabling the implementation of this adopted goal, using selected tools of the Lean Manufacturing: the SMED (Single Minute Exchange of Die) method and Goldratt's Theory of Constraints. Additionally, In order to determine strengths and weaknesses of the company a SWOT analysis was used.

Based on the analysis and evaluation of the processes implemented and the calculation of the time-consumption of each stage of the production process, bottlenecks were found that limited the company's production capabilities. Then, specific improvements were proposed that significantly increased the efficiency and effectiveness of the company examined. The developed proposals were supported by the Throughput Accounting of Eliyahu M. Goldratt's Theory of Constraints along with an index assessment of the proposed solutions. The changes proposed are straight-forward and do not take into account many factors regarding the functioning of the company that should be taken into account in real conditions. However, this was not the intention of the authors, who primarily wanted to demonstrate the validity of using Lean Manufacturing tools and the simplicity of their use.

As shown, implementing methods to evaluate and improve the production process in an enterprise can be a source of effective changes that allow for generating greater profits. Return on Investment (*ROI*) in every case was impressive. In the situation of such a good position on the market, the examined company should decide to expand its machine park, which will increase the potential to generate higher profits in the long run, despite much higher operational expenses and investment outlays. As mentioned, such solutions require an in-depth and detailed analysis and consideration of many additional factors. When making a decision to further develop machine park, one should consider whether the proposed change will not have to involve the spatial expansion of the production plant itself. In this case, a Return on Investment (*ROI*) may not be as attractive as taking into account the free space for adding autoclaves. Detailed analyses in the presented scope will be the subject of further studies by the authors.

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