INFLUENCE OF TEMPERATURE BASED PROCESS PARAMETER COMPENSATION ON PROCESS EFFICIENCY AND PRODUCTIVITY

Wpływ kompensacji parametrów procesu w oparciu o temperaturę na wydajność i produktywność procesu

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Abstract: Conditions in the working environment related e.g. to dust, vibration or temperature may have a negative impact on both, the production process and the manufactured product. Inappropriate and unstable conditions can cause instability of the production process and deteriorate the quality of manufactured products. Moreover, this can induce time waste and decrease the efficiency and productivity. In this paper the problem of temperature influence on a manufacturing process is analyzed. Monitoring of the temperature is not enough to ensure the achievement of manufacturing goals. It is necessary to adapt the parameters of the production process accordingly so that no nonconformities arise due to changes in temperature values and no delays appear. This paper deals with the efficiency and productivity of a manufacturing system which work under unstable working environment. The authors prove that application of the manufacturing process parameters compensation can significantly improve both, efficiency and productivity. The values of efficiency and productivity were monitored within a fixed period of time for a manufacturing system, on where the manufacturing process is realized. Then, a procedure of process parameters compensation was introduced. Next, within a fixed period of time the data were collected and the efficiency and productivity values were compared with the values obtained before. Additionally, the authors propose to introduce the Overall Equipment Effectiveness (OEE) indicator and present information about ways of data collecting.

Keywords: Overall Equipment Effectiveness (OEE), Utilization, Efficiency, Productivity, Quality, Flexible Manufacturing System (FMS), CNC machine, Control of accuracy, Test of machines, Repeatability, Capability

Streszczenie: Warunki w środowisku pracy związane np. zapyleniem, wibracjami lub temperaturą mogą mieć negatywny wpływ zarówno na proces produkcyjny, jak i na wytwarzany produkt. Nieodpowiednie i niestabilne warunki mogą powodować niestabilność procesu produkcyjnego i pogarszać jakość wytwarzanych wyrobów. Co więcej, może to spowodować stratę czasu i zmniejszyć wydajność i produktywność. W artykule przeanalizowano problem wpływu temperatury na proces produkcyjny. Monitorowanie temperatury nie wystarczy, aby zapewnić osiągnięcie celów produkcyjnych. Konieczne jest odpowiednie dostosowanie parametrów procesu produkcyjnego, aby nie powstawały niezgodności wynikające ze zmian wartości temperatury i aby nie pojawiały się opóźnienia. Artykuł dotyczy wydajności i produktywności systemu produkcyjnego, który pracuje w niestabilnym środowisku pracy. Autorzy udowadniają, że zastosowanie kompensacji parametrów procesu produkcyjnego może znacząco poprawić zarówno wydajność, jak i produktywność. Wartości wydajności i produktywności były monitorowane w ustalonym okresie czasu dla systemu produkcyjnego, na którym realizowany jest proces produkcyjny. Następnie wprowadzono procedurę kompensacji parametrów procesu. Po czym, w określonym przedziale czasu zebrano dane i porównano wartości wydajności i produktywności z wartościami uzyskanymi wcześniej. Dodatkowo autorzy proponują wprowadzenie wskaźnika całkowitej efektywności wyposażenia (OEE) i w artykule przedstawiono informacje o sposobach zbierania danych dla obliczenia OEE.

Słowa kluczowe: Całkowita efektywność wyposażenia (OEE), wykorzystanie, wydajność, produktywność, jakość, elastyczny system produkcji (FMS), obrabiarki CNC, kontrola dokładności, test maszyn, powtarzalność, zdolność

Introduction

The efficiency and the productivity are important indicators to assess a manufacturing system. For the Flexible Manufacturing Systems (FMS) it is expected that the indicators will have high values. The main advantage of FMS is the fixed unit cost for the flow of both a multi-piece batch and a single batch. The most common disadvantages is the high cost of starting the line and high failure rate resulting from many components. However, when the work on FMS is well organized, prepared and planned the manufacturing process should goes on without significant problems. Usually, FMS are monitored since the production is launched to identify technical and quality problems. They are then analyzed to find and eliminate the source causes.

In this work a FMS operating in a company in which aviation parts, i.e. housings, are manufactured is analyzed. The FMS is monitored, first of all to avoid quality problems, which generate high costs. The material for the products is expensive and the manufacturing process is continued for approximately 20 hours for a part. Moreover, the skilled personnel taking care about the FMS and involved in technical preparation process is costly. When creating the technological process of the product processing, the technologist, fixture designer and

CNC programmer had to take into account all possible scenarios that will affect the quality and compliance with the requirements of the client.

Despite the implementation of various available methods to increase the quality of the process the problems kept coming up again. Implementation of measuring probes and automatic unclamping and clamping of parts during machining to eliminate stresses did not give the expected results. Nonconforming products appeared what causes downtimes, while the problems were solving. Machine geometry measurements and corrections performed by maintenance services as well as nonconformity analyzes significantly worsened productivity. This, in turn, affects the production flow and inventory levels (WIP - Work In Process).

Analyzes and tests have shown that there are many variable parameters that affect part quality. Two of them that have the greatest influence on the process are temperature fluctuations and machine repeatability.

In this paper the first factor is analyzed - temperature fluctuations and its influence on the efficiency and productivity. The article presents the results of efficiency and productivity improvement that were achieved after the introduction of innovative, fully automatic methods of compensation to minimize temperature fluctuations and machine repeatability.

Other indicator, used to assess a manufacturing system is Overall Equipment Effectiveness (OEE) indicator. This indicator combines information about quality of the products manufactured on a manufacturing line with time spent on the process. In the analyzed company the OEE is currently not calculated. Therefore, in this work it is also analyzed how OEE can be introduced in the FMS assessment process.

The next section presents the work methodology. Section 3 describes the analyzed flexible manufacturing system. Section 4 indicates data, which are collected in the system. In the section 5 efficiency and productivity are defined and their calculation procedure is presented. Next section describes a methodology of process parameters compensation. In section 7 the values of efficiency and productivity indexes calculated before and after compensation procedure implementation are compared. Section 8 presents a proposal of OEE implementation. The last section summarizes the work

The research goal and work methodology

The goal of the research presented in this paper was to prove that minimization of the temperature fluctuations by implementation on an automatic compensation of the manufacturing process parameters can significantly improve the efficiency and productivity of the FMS.

The work methodology was as follows:

- Step 1 – Collecting a manufacturing process data to calculate efficiency and productivity – the current state.
- Step 2 – Designing and implementation of the manufacturing process parameters compensation.
- Step 3 – Collecting process data to calculate efficiency and productivity after implementation of the process parameters compensation.
- Step 4 – Comparative analysis of the results – efficiency and productivity before and after implementation of the process parameters compensation.
- Step 5 – Proposal of a system that will allow to calculate Overall Equipment Effectiveness (OEE).

Presentation of the flexible manufacturing system

The Flexible Manufacturing System (FMS) analyzed in this paper consists of:

- Machines (5-axis milling centers) (M1-M4) in a linear or circular system connected with each other by a system of controllers and computers controlled by a central machine management system,
- robot (R1) for transporting pallets with semi-finished and finished products,
- loading and unloading stations (L1-L2),
- pallet warehouse (W1) with equipment for temporary storage of semi-finished and finished products,
- tool magazines (T1-T4) integrated with the machines.

The scheme of FMS components arrangement is presented in Figure 1.

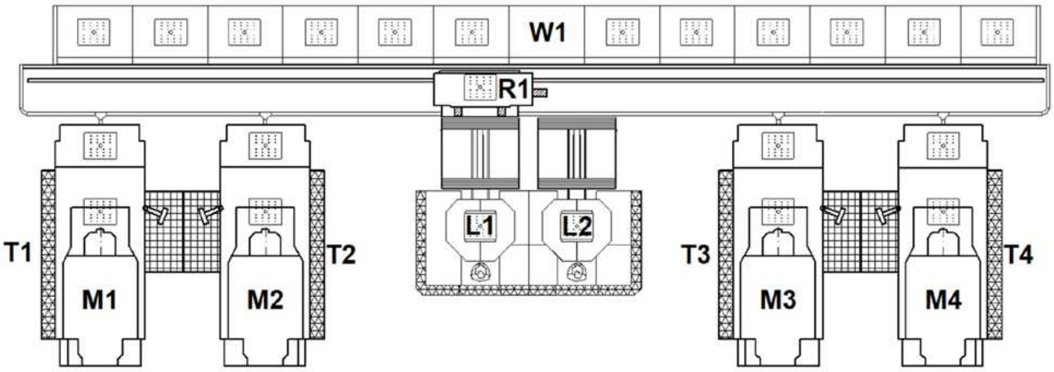

Fig. 1. A scheme of the analyzed FMS; M1 – machine 1, M2 – machine 2 M3 - machine 3, M4 – machine 4, R1 - robot, L1-L2 – loading & unloading stations 1&2, W1 - pallet warehouse, T1-T4 – tool magazines 1-4

The full flexibility of the line is achieved only when the parts implemented for production can be performed on each machine with the same efficiency. This is extremely difficult to achieve when machining large complex parts. The most common limitation is the capacity of the tool magazines. Then the only solution is to indicate specific machines for selected operations. In this case, it is possible to keep the benefits of the setup time reduced to zero. Unfortunately, any problem that appears disrupts flow. Line flexibility always limits the item with the lowest capacity. Most often it is a tool magazine, therefore, to ensure greater flexibility, central warehouses are used that support several or all machines.

Data collected from the analyzed FMS

On the analyzed FMS the following data are registered:

- production order number,
- product name,
- number of operation,
- work type (manual, automatic) – manual work is realized to attach the product to a fixture; automatic work is realized by CNC machines,
- product production start date – production of one product can continue for two days,
- number of products manufactured in a batch,
- standard time for operations, decided by a technologist,
- start and end time of the operations,
- real time of the operations – is calculated automatically taking into account start and end time,
- available time (so called Global Open Time – GOT) – it is usually 8 hours – this is time when employees supporting and working on FMS are available.

The presented data are used to calculate efficiency and productivity.

Efficiency and productivity calculation procedure

The **productivity** is one of the most commonly used Key Performance Indicators (KPIs) to monitor a plant's manufacturing excellence in the analyzed company. The productivity refers to the number of products that were produced in the available working time. In the analyzed company, to calculate the productivity, time units referring to the number of products are used. The productivity consists of two indicators – **efficiency** and **utilization**. In order to correctly calculate the indicators, reliable data should be recorded.

The **productivity** index is calculated by multiplying **utilization** and **efficiency** (equations 1).

$$\text{Productivity} = \text{Utilization} \cdot \text{Efficiency} \tag{1}$$

The **utilization** index is the quotient of the sum of the **real time** and the sum of the *Global Open Time* (equation 2).

$$\text{Utilization} = \frac{\sum \text{Real Time}}{\sum \text{Global Open Time}} \tag{2}$$

Real Time is the sum of time "consumed" for the execution of production tasks included in production orders. *Global Open Time* (*GOT*) is an available time, and it is calculated as the sum of time available to perform production tasks for a position or group of positions (production line, production department). It is often used to define the time available for an operator or group of operators who work on a specific production line.

The **efficiency** is an indicator that evaluates whether a production process is as efficient as expected. The efficiency index is calculated as the quotient of the sum of the *Standard Time* and the sum of the *Real Time* (equation 3). The indicator gives an information about the efficiency of a process and/or an operator. In the case of technological operations performed manually by a human, the quality of the indicator is determined by the so-called the discipline of *Real Time* registering and the accuracy of standardizing *Standard Time* activities. For technological operations performed in automatic mode, the real-time automatic registration is of key importance. In order to eliminate human error, automatic real-time measurement is increasingly being used. In cases such as the analyzed FMS line, automatic timing gives the ability to track the efficiency index in real time.

$$\text{Efficiency} = \frac{\sum \text{Standard Time}}{\sum \text{Real Time}} \tag{3}$$

Standard Time (*STD time*) is defined for each operation. The sum of operations standard times for all manufactured parts in a given period of time (day, week, month ...) is used to calculate the **efficiency**. All non-standard downtimes, such as breakdowns, quality stops, and missing production orders, reduce utilization and they are monitored with the productivity indicator. The non-standard downtimes cause that the lower number of products are manufactured.

The productivity can be also calculated as a product of the sum of *Standard Times* and the *Global Open Time*, as it is presented in (equations 4).

$$\text{Productivity} = \frac{\sum \text{Standard Time}}{\sum \text{Global Open Time}} \tag{4}$$

The quality of *Standard Time* determination has direct influence on the **efficiency** as well as the **productivity**. The accuracy of recording *Real Time* is of great importance in correctly calculating **utilization** and **efficiency**.

A common mistake companies make when calculating *Standard Time* is underestimating or overestimating *Standard Time*. In both cases, the **efficiency** calculated on its basis gives extremely different results, leading to decision errors. In the case of automated production processes, where work is performed by machines in conjunction with robots, determining the *Standard Time* is quite easy and often it is *Real Time* for the undisturbed performance of a set of procedures that make up a technological operation.

The FMS line, which is the subject of the research, is used for machining the housings of aircraft gears. Technical parameters (length, diameter, error of shape, position and surface roughness) made on machines are the final (drawing) dimensions. The basic material used (forging), high accuracy and complicated shape as well as large dimensions mean that even a slight disturbance of the process due to external factors causes the production of a non-compliant part. When a nonconformity is detected, the machine is always stopped in the FMS line in order to determine the cause. Any such stoppage results in lower **productivity**. The role of the **productivity** index is not only to indicate the state of the current situation, but also it gives the possibility of continuous and conscious control of production losses at the organization level through accurate tracking of partial indicators.

Methodology of process parameters compensation

As part of the research and implementation work carried out on the FMS line described in section 3 of this article, a system was developed and implemented whose task is control and calibration of geometric and kinematic parameters of the machine tool.

Due to the variety of manufactured elements, changes in ambient temperature, machine tool failures, it was necessary to periodic monitoring and calibrating machining centers for process suitability. Before the implementation of automatic process suitability control, measurements were performed manually with the use of dial indicator and artifacts. Qualified personnel were required to interpret the measurement results and correct the machine tool. To shorten the measurement time and reduce the involvement of production personnel, measurement procedures were developed using the part probe, temperature probe, master object in the form of a cuboid with the characteristic dimensions of 750x750 mm, and two reference spheres placed on the machining pallet (Fig. 2).

The individual stages of measurements were designed to reflect, as far as possible, the acceptance instructions contained in the standards (ISO 10791-1) [4] and the acceptance documentation of the machine manufacturer. The measurement procedure was divided into six steps:

- **Step 1** – Cuboid temperature is measured to compensate for the nominal geometrical values of the artifact. The temperature is measured by probe TP44.10 [3].
- **Step 2** – The analysis of the geometrical properties of the machining center using the RMP600 object probe [9] and measuring cycles [11]. Straightness measurements of individual linear axes are made in the YZ, ZX, XY planes. The angular relationships between the YX, YZ and XZ axes are also checked (See Fig. 2.a)
- **Step 3** – The assessment the correctness of the machine zero position (See Fig. 2.b), and verification of the error of parallelism of the rotation axis of the table B in relation to the Y axis in the ZY and XY planes. The assessment of these parameters is made by measuring the position of two artifacts in the form of reference balls whose position in space is changed by means of the rotation axis B in three characteristic positions (B0, B-90, B-180).
- **Step 4** – Correctness of kinematic vectors is tested (See Fig. 2. c), which are used to define 5-axis transformations (TRAORI, TCARR) [10]. The measurement takes place in such a way that with the help of the object probe three positions of the measuring ball are read for each of the two rotary axes (A, B) [11]. The results obtained in this way are compared with the current settings, and corrected if necessary.
- **Step 5** – If the tests are passed (measurements in specified tolerances), the machine zero position and kinematic vectors are automatically corrected by making change to the machine data.
- **Step 6** – Re-inspection of the machine tool is done in order to verify the correctness of the entered new machine data (step 3, step 4).

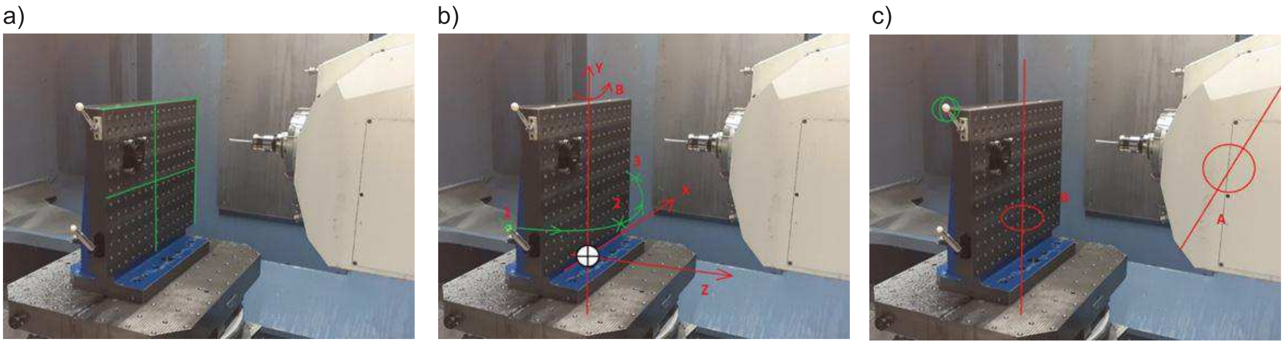

Fig. 2. View of the calibration master (two reference sphere's, calibration column), together with the RMP600 probe, inside 5-axis machine center: a) geometry measurement, b) machine zero measurement, c) kinematic vectors test

The acceptable deviations were adopted in accordance with the acceptance requirements contained in the purchase contract of the analyzed machining center and the requirements of the standard ISO 10791-1 [4]. In case of any of the measured parameters exceeds the assumed tolerances, the machine tool activates a sound and a light signal to call the operator to assess the situation.

All data obtained during the calibration procedure are recorded in the form of a text file. This allows data to be analyzed at any time in the event of problems during auto-calibration.

Assessment of efficiency and productivity

The data used in this analysis was collected in the period from 03-08-2020 to 29-04-2021 and consists of 809 records.

The data necessary to calculate efficiency and productivity are obtained from two sources – the ERP system and production. In order to correctly calculate the efficiency, a detailed analysis of the duration of the operations performed on the FMS line was performed. *Standard Time* (*STD*) has been entered into the ERP system and is used in calculations. *Standard Time* is defined by a process engineer in the stage of a new product implementation.

The second element for calculating the process efficiency is the *Real Time* of the operation. There are two methods of getting this time – automatic and manual. Both of them are used in the plant, however, for the presented case, the results of manual work time recording are presented. An FMS line employee sends a signal to the ERP system when an operation from a production order is started and ended. Based on the data the system calculates *Real Time*. This way has disadvantages as the reliability of the *Real Time* recorded depends on the discipline of the employees. The productivity index is calculated fully automatically, and the employee has no influence on it. Both, Standard Time and *Global Open Time* come from the ERP system.

The nine months of operation of the FMS line, for which the analysis was done, can be divided into three periods (Table 1):

- Period 1 – from August to December 2020 – the data come from the manufacturing line operations before the introduction of parameter compensation.
- Period 2 – January 2021 – the data come from the month when the innovative solution of process parameters compensation was implemented.
- Period 3 – from February to April 2021 – the data come from a operational system with fully automated parameter compensation.

Table 1. Data collected for the purpose of efficiency and productivity calculation for FMS

Year	Month	STD time [h]	REAL time [h]	GOT [h]	Efficiency [%]	Productivity [%]
2020	Aug	160.4	279.6	671	57.4	23.9
	Sep	309.1	527.0	693	58.6	44.6
	Oct	319.7	344.5	609	92.8	52.5
	Nov	81.4	108.4	548	75.1	14.9
	Dec	264.7	283.7	458	93.3	57.8
2021	Jan	416.2	419.9	544	99.1	76.5
	Feb	477.9	485.2	528	98.5	90.5
	Mar	641.1	648.4	737	98.9	87.0
	Apr	530.1	531.0	596	99.8	88.9

Figure 3 presents visual representation of efficiency and productivity in the mentioned periods of time. The warm summer months and the first cold autumn month are connected with large temperature fluctuations. The large volume of the production hall does not help to quickly stabilize the temperature with the existing air conditioning system. Maintenance service employees intervened many times during these periods. This influenced the quality of the manufacturing process, the stability of machines work and the products quality. This in turn caused production downtime what had a very big influence on the efficiency and productivity.

In the months, before the machines parameters compensation due to temperature fluctuations was introduced, the efficiency equaled from 57.4% to 93,3%. The productivity equaled from 14.9% to 57,8%. This

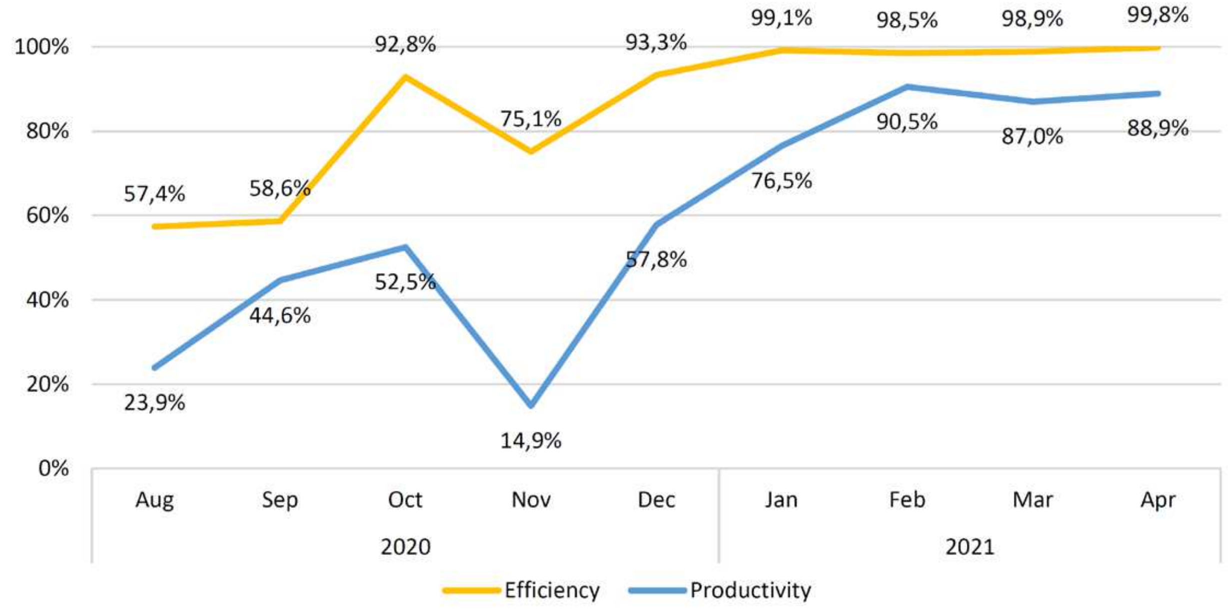

Fig.3. Efficiency and Productivity in the period before and after the introduction of process compensation

means that about half or more of the GOT was devoted to manual measurements of machine geometry and kinematics and analysis of the causes of non-compliance needed to be performed before production could be continued. Only after making sure that all parameters were correct, the machining process could be continued.

In these months, research was carried out on the impact of temperature fluctuations on the geometry and kinematics of machines in relation to the quality of parts. The result of these works was the implemented system of automatic compensation of machines parameters needed to be adjusted due to by temperature fluctuations, without the participation of maintenance services. Before the innovation was introduced, it was necessary to stop the work of the machine after each detection of nonconformity. Machine geometry measurements and corrections performed by maintenance services as well as nonconformity analyzes significantly reduced productivity. This was directly related to the reduction of the standard time (time really used for processing), which is the sum of all standard times of the parts produced. Automatic compensation of machine parameters minimizes the possibility of making a nonconforming part and thus machine downtime.

After introduced of innovation the efficiency was never lower than 98% and the productivity was equal or higher than 87%. The generated downtime has been reduced to a minimum and the quality of parts has improved significantly.

Currently, it is not calculated how much the number of nonconforming products influence on the manufacturing line effectiveness. The information of the nonconformities is registered, however they are not directly connected with operational time. Therefore, the implementation of the Overall Equipment Effectiveness (OEE) index is planned in the future

Proposal of Overall Equipment Effectiveness indicator implementation

Thanks to the implementation of OEE, it the indicator combining Quality, Performance and Availability in real time can be monitored. This will allow to react quickly if OEE will be below the assumed target.

OEE will help follow the process over a longer period of time by observing the trend. In the event that the currently used method of parameter compensation ceases to be effective, maintenance can start in advance. This can happen with different products, different materials, different technology, different times of the year or in case of problems with cutting tools. Always after achieving the maximum possibilities of machine parameters compensation, the service of specialists is inevitable if the introduced automatic parameter compensation did not solve a problem. Analyzing of partial OEE indicators, such as Quality, Performance or Availability, the root cause of OEE reduction can precisely determine.

Overall equipment effectiveness (OEE) is introduced by Nakajima [7] as a Key Performance Indicators (KPI) to measure the equipment productivity of a manufacturing system. The indicator is widely used in industry [8]. The published works present OEE application in the beverage industry [13], weaving industry [14], pharmaceutical industry [5], on the beerfilling lines [2], for a semiconductor manufacturing [1] and many others. All downtimes and even micro downtimes have significant influence of on OEE [15].

The OEE indicator is planned to be introduced into the FMS monitoring process. The way of OEE calculation will be adopted from [12] (equation 5).

The quality will be calculated from (equation 6). The utilization will be calculated from (equation 7). The availability will be calculated from (equation 8).

$$\mathrm{OEE} = \mathrm{Quality} \cdot \mathrm{Performance} \cdot \mathrm{Availability} \tag{5}$$

$$\mathrm{Quality} = \frac{\text{Time to manufacture all products} - \text{Time to manufacture all nonconforming products}}{\text{Time to manufacture all products}} \tag{6}$$

$$\mathrm{Performance} = \frac{\sum \text{Real Time}}{\sum \text{Global Open Time}} \tag{7}$$

$$\mathrm{Availability} = \frac{\text{Global Open Time} - \text{Unplanned downtimes}}{\text{Global Open Time}} \tag{8}$$

The performance component of OEE will be calculated in the way which is used currently to calculate productivity. The availability component of OEE will be calculated in the way which is used currently to calculate utilization. To calculate OEE the presented data need to be collected. It looks that not much additional work will have to be done to calculate OEE. The only problem is connected with currently used data bases and connections between them what have to be improved.

Conclusions

The presented paper explains how the manufacturing process parameters compensation can significantly improve both, efficiency and productivity. In the analyzed company it was discovered that temperature fluctuations influence the process and products quality through their impact on repeatability of the machines. The quality problems influenced the efficiency and productivity. Implementation of an automatic method for the process parameters compensations decrease the number of problems and interventions and improve efficiency and productivity indicators. Efficiency increased on average by 31.3% and productivity by as much as 129.3%. It was possible thanks to the maximum reduction of losses related to machine downtime. The process has stabilized at a satisfactory level. Efficiency and productivity remained at 99.1% and 88.8% respectively.

Although, the nonconformities influence the mentioned indicators it is not directly calculated what is the influence. The implementation of OEE indicator can more precisely indicate what influence the most of the manufacturing line effectiveness. This can be for example wrong planning process (availability component), technological problems (performance component) or quality problems (quality component). In the future work the connections between the problems existing on the analyzed FMS and OEE will be studied.

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