

Real time production monitoring system in SME

Aleksei Snatkin^a, Kristo Karjust^a, Jüri Majak^a,
Tanel Aruväli^a and Tanel Eiskop^b

^a Department of Machinery, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; {aleksei.snatkin, kristo.karjust, juri.majak, tanel.aruväli}@ttu.ee

^b Estonian Entrepreneurship University of Applied Sciences, Suur-Sõjamäe 10a, 11415 Tallinn, Estonia; taneleiskop1@gmail.com

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Abstract. Real time production monitoring systems (PMSs) is an alternative to manual data collection and captures most of the required production data without human intervention. The general objective of the current study is to analyse PMSs and to offer particular solutions for small and medium sized enterprises (SMEs). The subtasks to be solved in the case of each particular PMS include determining relevant parameters, designing PMS and development of the data analysis and prognosis model for short term and long term planning. The selection of suitable PMS components and relevant parameters and the development of lathe cutting unit measuring system are described in the case study. Defendec Inc. and National Instruments Corporation wireless components were adopted to implement a part of the PMS.

Key words: production monitoring, remote monitoring, real time information, manufacturing execution system, wireless sensor network, maintenance planning.

1. INTRODUCTION

The objective of the paper is to give an overview of the advantages and possible drawbacks of a PMS before starting to implement such a system in a specific manufacturing SME. SMEs are more flexible comparing to larger companies and can faster implement a new way of doing business. Also the result of changes can be seen earlier, which simplifies the research and offers quicker feedback.

Nowadays, in an open and competitive market, companies cannot afford the waste of time and resources to perform work that can be done in a better and faster way with advanced solutions. One of the advanced solutions can be the real time PMS. It is a production tool that collects and distributes necessary data

when various events occur in the shop floor. The main aim of a PMS is to prevent small disturbances having large effects. In this way, a PMS will decrease the number of unscheduled production stops, improve cost-efficiency and simplify the production planning.

The task of a PMS is to collect and distribute real time data of events in the shop floor. This data must be understandable and useful for decision making. Monitored data should help the production team to respond timely to the events that may affect the desired result. Such system should also alarm and inform the respective department concerning all recognized faults.

PMS is not just display boards that show production data, it also has a reporting and administration module, where stored data can be analysed to find trends, estimations and projections for knowledge-based decision making and production planning. Proactively detected faults will decrease wasted time and improve overall equipment effectiveness.

Production monitoring and machine data collection is one of the manufacturing execution systems (MES) functions. Historically, each software editor had its own definition of the MES, which was generally based on the capacities of their own tools or on the expectations of their customers [1].

Several of the major automation providers offer now MES solutions, including Emerson, GE, Honeywell, Invensys, Rockwell and Siemens. MES integrates separate data collection systems. It is like a linkage between the shop floor and office. It should solve the problems of the lack of integration between the enterprise resource planning (ERP) systems and the control systems on the plant floor.

MES position in the factory automation system can be described in different ways. To understand on what enterprise automation level it is positioned, a pyramid diagram can be used (Fig. 1).

The standard of the International Society of Automation ISA S 95 describes the architecture of a MES in greater detail, explaining how to distribute functionality and what information to exchange internally as well as externally. MES is overlapping with the product lifecycle management (PLM) system in the production phase [2-4]. It means that changes made by MES during the production (machine adjustment, tolerance change etc.) may have influence on the

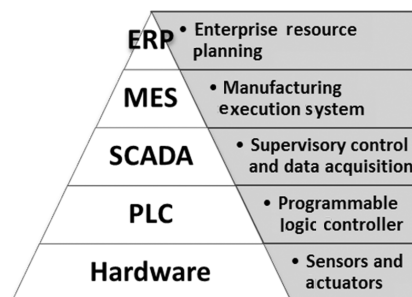


Fig. 1. Automation pyramid [2].

PLM workflow (changes in drawings and CAM). From the e-manufacturing point of view, a MES is the lower level of factory automation and communication systems [3].

The idea of a real time PMS is not to give some information simultaneously with the event but to provide the production team, as fast as possible, with the accurate and meaningful data. But there should be enough time to respond timely on these events. It will always take some time (seconds, minutes or even hours) to analyse monitored data and to respond to it. And the goal is to try to decrease this time.

Real time production monitoring information can be classified into two main groups. One group is related to the status of resources and another one to the status of jobs. Information on actual or potential disruptions may relate to resources or jobs. Machine breakdowns, material or tool shortages and longer-than-expected processing times give resource problems. Job related disturbances, arising from planning systems and customers, include changes in priority, reassignments of jobs to orders and the emergence of new jobs. Quality problems may relate to both resources and jobs [6].

Classification of real time information helps to understand how the desired PMS should be structured. The first step of real time data in the monitoring process is detection. Data can be detected by sensors, operators, barcode scanner, etc. Understanding the detection process will lead to effective use of real time data capture devices and to the removal of unnecessary and useless devices. Then data should be classified and identified; for example, transferred to respective department or handled automatically. The last step is diagnosis and analysis [6].

It is not reasonable to store all collected data (every single measurement) in a database. If the measurements are taken with high frequency (e.g. vibration) by using wireless sensor network (WSN), it is recommended to process an original data already in the WSN node, before sending the analysed data to the database. In this manner, WSN node energy can be saved, radio frequency channel can be held free longer time and database can be held more compact.

The trends of PMS solutions can be summarized as follows:

- Standardized plug & play connectivity;
- Real time performance;
- Wireless communication;
- Web-based architecture;
- Scalability and re-configurability.

It is evident that the amount of information, collected from control systems, increases tremendously with the degree of increased automation on the shop floor. Manufacturing systems grow because of the need for more complex processes to meet the needs of increased product functionality [1]. It means that PMS has to be connected to more equipment and it processes more data at the same time. In addition to these trends, there is a trend to self-learning decision making systems that maximally try to eliminate human intervention. General trend is to use PMS for improvement of the production processes by applying

statistical process control, mathematical modelling and optimization of the production process [7-11].

2. CONCEPT OF A PRODUCTION MONITORING SYSTEM

Production data, collected on the shop floor, may be incorrect, mostly due to human intervention or the improper production monitoring system. The human factor is more important in this case. That is why a PMS should capture most of the required data without human intervention.

When an unscheduled outage happens, time is spent for notifying support resources that a problem has occurred, time is spent for the support resource to respond to the issue, time is spent for troubleshooting and finally time is spent to resolve the problem. But predictive nature of continuous remote monitoring more often avoids unscheduled outages by addressing the issues before they affect machine operation and product quality [12].

The benefit of installing an efficient real time PMS is the immediate access to all required production related information by the relevant personnel. And there should be enough data to clearly identify the reasons of production stops, time loss, etc. At the same time, presenting too much information can confuse or even distract operators.

The most important requirements to any PMS are that the system must be economical, accurate and easy to set up on a production line. And it has to be capable of providing straightforward connection with switches, sensors, PLC outputs and other common industrial equipment. If the true production data can be automatically captured and presented in a simple, understandable way to the operators, they will become a more integral part of the improvement process [13]. Relatively simpler systems have greater potential for real-time control [14].

An effective production monitoring system should comprise at least five elements: collection, display, analysis, prognoses and data storage (Fig. 2). In the current development model, the prognoses module is added, which gives to the company additional flexibility that beside the short term planning (PMS system will automatically alarm, when some critical determined parameters reach the limit) we can make also long term planning to forecast future defects and tool life time. Using that information and prognoses module we can avoid the actual defects and plan the maintenance so that we will make the change of the wearing before it actually breaks.

Alarm system is also one of the basic capabilities of a PMS. Fault announcement should be properly understood by the personnel to act timely. An advanced PMS should provide the possibility to review the history of the alarms. Visualization of data can be made through displays, andon boards and mobile solutions, like smart-phones, etc.

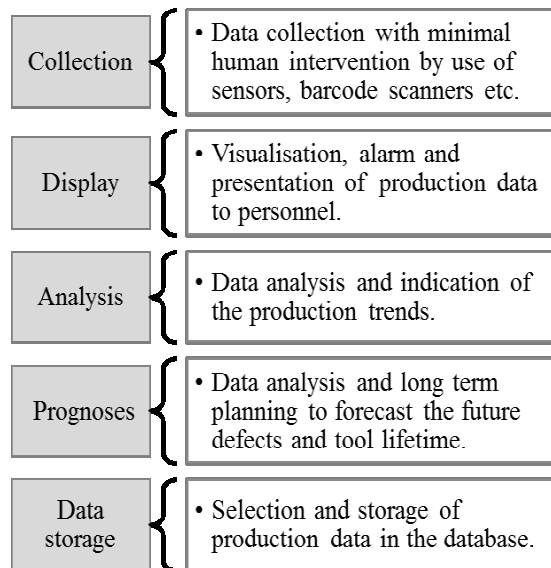


Fig. 2. PMS modules.

3. PMS INTEGRATION ON THE SHOP FLOOR

Because of the high cost of deployment of automated manufacturing systems, machines are not integrated on most shop floors [15]. Production industry still gathers most of the data on the shop floor through manual inputs.

Despite the fact that a number of automation providers offer MES solutions, such systems are mostly monolithic, insufficiently configurable, and difficult to modify. Installing such software and integrating it with current systems is found to be a challenging and costly undertaking [16].

Localized solutions can be more affordable and strengthen the advantages of automated production monitoring. Especially during the economic recession, companies more precisely weigh the pros and cons of investing money in a new production system. And a faster return on investments can be the decisive moment when choosing a production monitoring system, though alternative MES systems can offer a wide range of additional functions.

When calculating costs of a PMS, not only software and hardware investments should be calculated. Possible consultation and support costs must be taken into account. If a system is developed and integrated in cooperation with the production team, these costs can be decreased.

In case of modern manufacturing equipment, a monitoring system is assumed to be a part of the machinery. Installing wireless sensors (so-called “smart dust”) on machinery can be one of the solutions. Before that, models should be developed that reflect the correlation between the state of the machine and the monitored parameter. All these will enable the detection of failures and critical

modes of operation. Installing a monitoring system, based on wireless sensor nodes, is relatively cheap and it can be fitted to both old and modern manufacturing equipment [17]. Wireless sensors eliminate the cost of cables that also simplifies the installation. In real life wireless monitoring is used infrequently on shop floors [18].

4. A CASE STUDY

Monitoring systems have been designed for four machine tools at the Tallinn University of Technology (TUT) and for wood product manufacturing line in the private company JELD-WEN Eesti AS. The data collection and display modules are completed, but the development of the analysis module is in progress.

4.1. Monitoring system design based on sensors selection

Measuring devices will be assembled on a controlled machinery. That will provide early warnings of machine degradation or impending accident and will give input parameters to the prognoses module. The characteristics, chosen for monitoring and the measurement equipment, selected at TUT, are outlined in Tables 1–3, and at the private company JELD-WEN Eesti AS in Tables 4–5.

Table 1. Metal working lathes, 1K62B and 16A20

Need to know	Measuring	Sensor type
Machine tool is working/not working and with what load	Current in main cable	Clip-on ammeter
Spindle rotating speed	No of revolutions in time unit	Hall effect sensor
Work piece diameter	Distance from sensor to work piece	Optical sensor
Stability of spindle	Vibration in spindle	Acceleration/piezoelectric sensor
If tool is dangerously close to spindle	Carriage position	Magnet/Hall effect sensor
Bearing wearing rate	Bearing surface temperature	Thermocouple

Table 2. Milling machine DYNA MECH. EM3116

Need to know	Measuring	Sensor type
Machine tool is working/not working and in what load	Current in main cable	Clip-on ammeter
Spindle rotating speed	No of revolutions in time unit	Hall effect sensor
Stability of spindle	Vibration in spindle	Acceleration/piezoelectric sensor
Spindle engine pulley temperature	Belt friction point temperature	IR temperature sensor

Table 3. Wire-cut machine AGIE AC 50/120H

Need to know	Measuring	Sensor type
Machine tool is working/not working and in what load	Current in main cable	Clip-on ammeter
If coolant temperature is too high	Coolant temperature in storage reservoir	Temperature sensor
Coolant salt concentration	Water (coolant) salinity	Ultrasonic sensor/conductivity meter
Work table stability	Vibration in work table	Acceleration/piezoelectric sensor
Wire feed rate and breaks	Roller No. of revolutions in time unit	Hall effect sensor

Table 4. Planer line Weing 141

Need to know	Measuring	Sensor type
Input material quality, is it suitable or not	Material geometry	Optical sensor
Line speed and total length of material processed	Line speed	Rotary encoder
Stoppages, time machine is waiting for material	Material availability on the line	Optical sensor

Table 5. Painting line Makor

Need to know	Measuring	Sensor type
Total number of products feed to the line	Count of material from the in-feed	Optical sensor
Number of high quality products that need no additional repairs	Count of material reaching machine	Optical sensor

Thus, at TUT the milling, wire-cut and lathe machines are set up for monitoring.

In metal working lathe, cutting tool condition monitoring is highly important as the tool condition changes fast and it has direct impact to machining quality. Cutting tool producers give life expectancy for a tool from 15 to 90 min, depending on working parameters (mostly on cutting speed). Mitsubishi Materials give life expectancy for their steel (reference material: carbon steel, alloy steel 180HB) processing turning tools 15 min, if the cutting speed is 320 m/min. Decreasing the speed about 40% (depending on tool and work piece material), the tool life expectancy grows to 90 min.

Spindle rotating speed and work piece diameter are important parameters as they determine the cutting speed. Cutting speed can be calculated as

$$V_c = \frac{\pi D n}{1000}, \quad (1)$$

where V_c is cutting speed (m/min), D is work piece diameter (mm) and n is spindle speed (min^{-1}).

In the company JELD-WEN Eesti AS the input and output of the planer line and input of the painting line are designed and set up for monitoring (not machine tools). Currently four optical sensors and one rotary encoder are installed. The evaluation of the input material quality is performed automatically from measurements up to the selection of material for different products.

In this work, we focus on the metalworking lathe 16A20. Data collection and analysis module for other equipment is in progress.

4.2. WSNs components comparison

Two wireless sensor networks WSNs were adapted to metalworking lathe 16A20 to implement PMS. For these WSNs, different hardware and software were used, to compare their pros and cons. Main parameters of the adapted WSNs components and nodes are shown in Table 6.

The first WSN was designed to monitor the lathe front bearing temperature dynamics. The lathe front bearing temperature was measured at two points with J-type thermocouples. National Instrument (NI) WSN-3212 4ch 24 bit Thermocouple Input Node was used for real measurements. The first thermocouple was placed in contact with the spindle front bearing housing from inside the gearbox; the second thermocouple was placed in contact with the spindle front bearing flanged housing between gearbox and spindle (Fig. 3).

The data acquisition interval was 1 s and all the results were saved in real time in PostgreSQL database table with the following field layout:

- 1) timestamp – holding time of measurement,
- 2) sequence – measurement sequence No in the current test,
- 3) nodeID – ID of the measurement node (for saving measuring results of different nodes to one table),
- 4) value1 – actual measured value (the temperature of the first thermocouple),
- 5) value2 – actual measured value (the temperature of the second thermocouple).

Sample set of measurement values saved to PostgreSQL database are presented in Table 7. For further analysis, data from the database can be presented graphically. In Fig. 4, sample temperature dynamics is presented, using collected

Table 6. WSNs components used in monitoring

Type of components used	Bearing temperature monitoring	Lathe utilization (spindle speed) monitoring
Sensor	J-type thermocouples	Hall effect sensor
Node	NI WSN-3212	Defendec node
Node is programmable	No	Yes
Node maximum sampling rate	1 sample/s	More than 2000 samples/s
Gateway	NI WSN-9791	Defendec gateway
Database	RDBMS PostgreSQL	MySQL

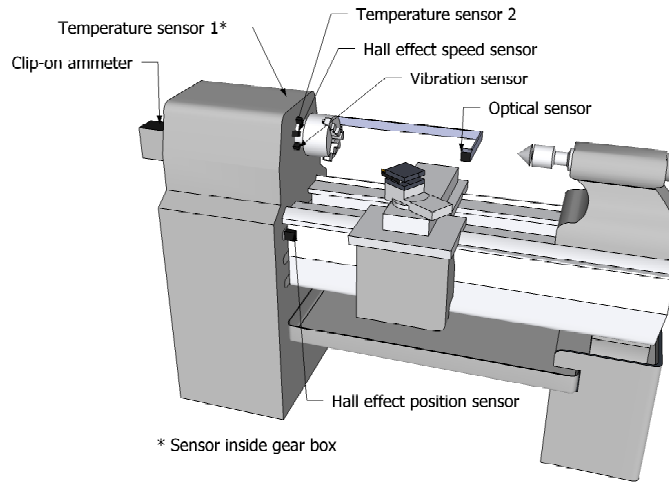


Fig. 3. Lathe cutting unit measuring system.

Table 7. Sample set of measurement values from the PostgreSQL database

Timestamp	Sequence	Node	Value1	Value2
15.10.12 10:55:06	0	2	29.048	30.107
15.10.12 10:55:07	1	2	29.032	30.103
15.10.12 10:55:08	2	2	29.015	30.098
15.10.12 10:55:09	3	2	28.615	30.014
15.10.12 10:55:10	4	2	28.492	29.988
15.10.12 10:55:11	5	2	28.299	29.981

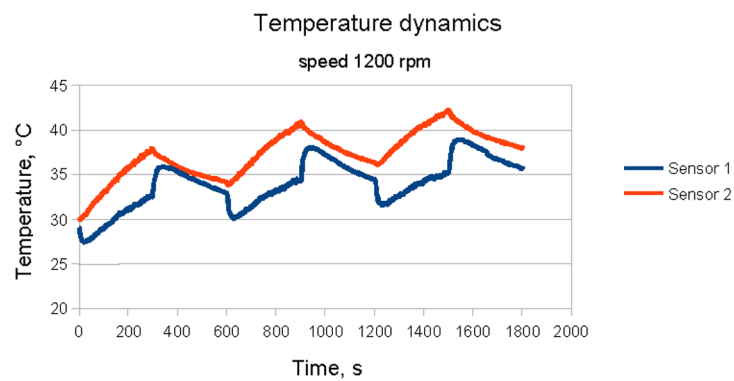


Fig. 4. Sample temperature dynamics graphic.

measurement data from the database. Temperature dynamics is collected by experiment, where 300 s free spindle running and 300 s spindle standstill were in turn three times.

The second WSN was designed to monitor the lathe utilization information. Utilization was determined by measuring the speed of the spindle. It was presumed that rotating spindle means that the machine tool is utilized. Hall effect sensor was placed between the gearbox and the spindle (Fig. 3) in the position, where spindle bolts were close enough to the sensor to influence it. Three spindle bolts were influencing the sensor, when they passed the sensor. It means, there were three times more sensing points than spindle turns. Defendec programmable node counted signals in one second and divided them by three to determine spindle speed. The node was programmed to send data, if the spindle speed was changed more than 10 rpm.

Defendec and NI hardware were used in the monitoring application. NI hardware and software LabView are easier to use than the Defendec node, as NI equipment is preinstalled and the programming environment is graphical. It is possible to graphically illustrate measurement results without using the database. It gives the advantage to create simple monitoring applications with illustrative graphics faster, but in a more advanced system, it has programming limitations. Current NI node was not programmable, but it is available as programmable for extra charge. The advantage of using Defendec nodes is wider opportunities in programming. Additionally, Defendec nodes permit to read high frequency measurements, more than 2000 samples per second. NI nodes allow reading one input per second. This excludes using NI nodes by measuring fast changing information as acoustic, vibrations and rotational speed. Nevertheless, it is sufficient for monitoring temperature, voltage and current. In an advanced intelligent WSN systems and in high frequency measurements the Defendec nodes are more suitable due to their flexibility; on the other hand, the usage of NI nodes is often more efficient in research. In adopted WSNs, both hardware components performed their tasks. NI components were measuring slow changing temperature and programming of nodes was not necessary. Defendec node was reading more than 10 impulses per second. In addition, program for rotation speed calculation and data transmission was used directly in the node. As PMS contains many measuring points, which need different sampling rate, it is preferable to use only Defendec components to create a homogeneous system.

Latest versions of MySQL and PostgreSQL database systems can be used as abstraction layer in PMS. Both database systems can be accessed via standard structured query language (SQL) statements, as it handles easily a large number of concurrent connections and solves data storage, replication, and backup challenges.

4.3. Machine tool (production line) components life-span forecast model

In order to provide safe manufacturing process and avoid working tool damages, there is a need to perform replacement or maintenance of the machine tools (production line) components timely. However, unique approach for estimating aging seems here not available, since the wearing (aging) of the

components depends on quite different factors like particular equipment, working time, regimes, temperature, loads, materials used, etc. The PMS allows gathering, storing and analysing information needed for estimating the wear of the components. Supported by data, collected by PMS, the forecast models with different complexity levels can be developed. First, it is needed to select most critical components of the machine tool (production line). Next, the key factors, affecting wear of the selected components, should be determined. Third step is collecting of necessary input and output data for the forecast model (the values of the determined key factors and wear parameters). Finally, the functional dependence between the input and output data (the forecast model) should be proposed.

In the following the above described cutting tool utilization is considered as an example. The simplest cutting tool wear forecast model is based on data obtained from the PMS and can be given in the form

$$T_R = T_0 - \sum_{I=1}^k T_{MI} \frac{T_0}{T_{VI}}, \quad (2)$$

where

$$T_{VI} = a * V_{CI} + b, \quad (3)$$

T_0 and T_R are the initial and remaining life expectancy time for a tool corresponding to cutting speed $V_{C0} = 320$ m/min, respectively. T_{MI} and V_{CI} are the length of the time interval I and cutting speed computed for this time interval using Eq. (1), k is the number of time intervals. The coefficients a and b in Eq. (3) can be determined from life expectancy data for a given tool: 15 min, if the cutting speed is 320 m/min, decreasing the speed about 40% increases the tool life expectancy to 90 min. Assuming linear relationship for life expectancy estimation, one obtains for the coefficients the following values: $a = -0.586$, $b = 202.5$.

Note, that the data, obtained from PMS, is not directly used for composing the model (2)–(3). Actually, the PMS data are considered in cutting tool wearing forecast model (2)–(3) through the cutting speed V_{CI} , which is computed by Eq. (1) and depends on the spindle rotating speed and work piece diameter – the key parameters for describing wear of the cutting tool, obtained from PMS described above. Also, the time intervals T_{MI} in Eq. (2) are not necessarily equal and depend on the spindle rotation speed (if spindle rotation speed changed more than 10 rpm then a new time interval is defined).

Obviously, the proposed analytical model can be considered as a simplified approach, which does not cover all complexities. The model (2)–(3) considers two key factors. There are lots of more complex approaches available for cutting tool wear forecast model development. One such approach is being developed also by the authors of the current study – a multilayer perceptron based feedforward artificial neural network model. As a rule, such models need much more

powerful dataset than currently available. The new factors, which can be included in the improved model, are the material of the tool and work piece, vibration of the spindle, temperature, etc.

5. CONCLUSIONS

The real time PMS systems, designed for TUT and JELD-WEN Eesti AS, enables to continuously acquire data from the shop floor with regard to efficiency, malfunctions and productivity. This leads to improved production capacity and cost-efficiency and helps to achieve desired production goals.

The developed prognosis module can be used in the short term and long term planning. It is tightly connected with the maintenance planning to prevent the critical components breaks and to help to increase the productivity and flexibility of the company.

Sample NI and Defendec wireless component based WSNs were adopted for their comparison. Both, NI and Defendec nodes can be used in WSN, but on different measurement frequency levels. Adopting them in PMS, Defendec components are preferable with their higher sampling rate.

Each production SME has differences in manufacturing processes, equipment, priorities and capital resources. That is why the following questions still need to be answered.

- Which data should be collected first?
- Which data have to be saved in the PMS database and for how long (filtering)?
- What is the easiest way to connect different data formats and communication interfaces?
- How to visualize the production data to make it clear to all personnel?

This leads to the general challenging question: is it possible to design a “plug and play” PMS solution that is suitable for most of the production SMEs? Answer for the latter question is open.

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Reaalajas toimiv tootmise seiresüsteem

Aleksei Snatkin, Kristo Karjust, Jüri Majak, Tanel Aruväli ja Tanel Eiskop

Uuringu eesmärk oli analüüsida reaalaja tootmise seiresüsteeme ja välja töötada paremaid lahendusi. Seiresüsteemi ülesanne on koguda, analüüsida ja jagada reaalajas andmeid sündmuste kohta, mis toimuvad tsehhis. Need andmed peavad aitama tekkinud olukorrale õigeaegselt reageerida. Seiresüsteemide raske juurutamine tootmisprotsessides sunnib uusi lahendusi otsima. Suhteliselt lihtsamad lahendused võivad sobida kõrgema potentsiaaliga reaalaja protsesside juhtimiseks. Käesolevas töös pakutud mudel võimaldab prognoosida võimalike probleemide teket tööpinkides.