Proceedings of the Estonian Academy of Sciences,
2015, **64**, 4S, 567–580
doi: 10.3176/proc.2015.4S.04
Available online at www.eap.ee/proceedings

PRODUCTION
MANAGEMENT

Production monitoring system development and modification

Aleksei Snatkin*, Tanel Eiskop, Kristo Karjust, and Jüri Majak

Department of Machinery, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

Received 4 March 2015, accepted 7 April 2015, available online 2 December 2015

Abstract. Main attention of this paper is paid to the development of a simple, but efficient concept of a real time production monitoring system. The goal is to offer an effective concept, which will help to provide an accurate overview of the shop floor activities by diverse information appearance and improve asset management, machinery utilization, and production process stability. The subtask considered includes description of the design of a visual module for the proposed production monitoring system for a certain type of micro, small and medium sized enterprises.

Key words: production monitoring, remote monitoring, manufacturing execution system, shop floor visibility.

1. INTRODUCTION

Industrial systems are becoming more complex due to integration of new technologies. At the same time, it makes maintenance and monitoring activities more expensive and complicated to get the reliable data on time. This situation motivates the researchers to look for innovative ways of production monitoring and maintenance. Equipment performance and condition monitoring was always an essential part of the information systems used in industry to improve effectiveness and to minimize unplanned downtime [1]. The sector of SMEs takes considerable part of most economies. In business areas, where capital and entry costs are high, SMEs' share is small. But from the other point, SMEs can dominate in niche markets where larger companies are not so active due to low sales volume. This narrow focus can give good results while developing totally new products and solutions. The question arises: how to increase SMEs' productivity and efficiency with the lack of resources. And one of the solutions can be an affordable, easy to integrate production monitoring system (PMS) based on open source software and hardware. As many SMEs may not have the possibilities of expensive production monitoring tools, this alternative solution can help to increase productivity. SMEs often lack the financial resources to hire experienced specialists or acquire expensive machinery with integrated monitoring tools. In many cases, production equipment used, even for the same functions, is from different producers. All this complicates the integration of embedded monitoring solutions to one system and analysis of collected data. Trade-off should be found between an expensive system with extensive functionality and cost effective solution. The proposed PMS could help to overcome these challenges. And it should be considered not as a tool to control the operator behaviour, but as a tool to reduce burden on operators and simplify reporting.

In the first part of this paper, production monitoring system concept for SMEs is described that will provide the basic idea of the system structure. And the second part of the paper is focused on the case study of a visual module development.

2. PRODUCTION MONITORING SYSTEM

Production monitoring data can be classified into two major groups: status of resources and status of jobs [2]. Status of jobs is related to data of each completed operation, estimated production time, sequences, etc. It provides information about the order flow for improvement of production sequences. Real time overview of

* Corresponding author, aleksei.snatkin@ttu.ee

the production process supports paperless reporting approach. Thus, comparison of planned and actual production numbers is possible at any time and allows more realistic scheduling that will help to meet delivery deadlines.

The second group, the so-called status of resources, is closely connected to machinery, personnel and working environment monitoring (Fig. 1). Here the machine event monitoring shows machine workload, downtime, availability, and performance. If the machine is not working, operators know exactly why and can rearrange the planned operations on time, which saves time and cost. Such data give detailed real-time and historical information of what is/was happening on the shop floor with the machinery. Personnel monitoring covers optimal movements tracking; planned versus actual manpower data, etc. Different indoor positioning systems may be used for people and equipment location tracking [3] that is part of the global production effectiveness (GPE) concept [4]. Working environment is seen here as a part of the "status of resources" group, as it affects the personnel comfort and safety. That directly impacts production efficiency. Here the requirements for ventilation, intensity of light, noise level, CO_2 concentration, vibration, magnetic field, etc., are regulated and checked by the international labor organizations (e.g., C148 – Working Environment convention from 1977) and by local labour institutions.

Data about the status of jobs and resources groups support functions of material and resource planning systems and provide feedback from the workshop. Keeping all departments informed of what is going on in the workshop, helps to timely react on unplanned situations. Production monitoring system does not directly control machinery, but tracks it.

In many cases, data subsets from different groups, described above, should be reviewed as a single data set to identify, e.g., reasons of quality problems, unplanned downtime, low performance, etc. Detailed status on every machine in the PMS is supported by such key performance indicators (KPIs) as availability, performance, quality rate, and overall equipment effectiveness (OEE). For machinery fault diagnosis different strategies can be used:

- Preventive maintenance – periodically shut down services for manual inspection. One of the drawbacks of such strategy is that equipment should be normally out of operation during the inspection to detect problems.
- Condition-based monitoring – fault diagnosis by means of appropriate observations based on acoustic signal, temperature, electrical current, vibration monitoring, etc. Condition-based monitoring is a more preferable strategy due to automatic diagnostic and predictive nature.

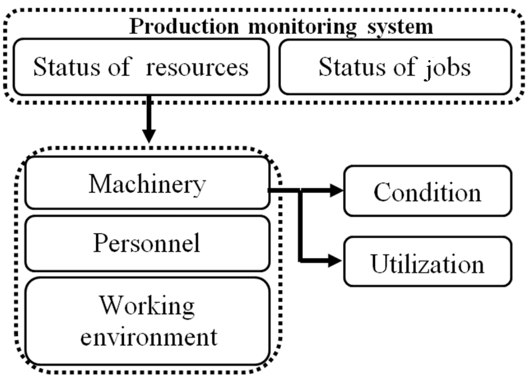

Fig. 1. Production monitoring system classification.

PMS systems can be seen as a subset of the Manufacturing Execution System (MES) that comprises the same functions as data collection and acquisition, maintenance management, resource status, product tracking, and production performance analysis [5,6]. However, machinery monitoring, which is one of the main functions of the PMS, is not the primary goal of the majority of MES solutions. The reason is that the initial idea of MES was to provide higher level systems, e.g., enterprise resource planning (ERP), with the required production status data from the workshop. To support the accurate production plan scheduling through material movement tracking and inventory management. There are several standards and regulations (e.g., ISA-S95) that ensure MES robustness and interconnection with other systems. Through that it may have influence on the PMS development.

At the same time, PMS is closely related to supervisory control and data acquisition (SCADA) systems that conventionally were mostly responsible for process monitoring and control operations, but nowadays come with more advanced functions like reporting and scripting capabilities, performance calculation, and integration with MES/ERP.

Numerous specific software products exist to manage production processes. They may be presented as MES, but functionality is varying depending on customer expectations or tools used (e.g., spreadsheets, comprehensive management applications). The basic functions of MES solutions, developed by the leading providers of industrial software and automation systems, are inventory management and collection of production state data with limited equipment state data with support functions like performance analysis and maintenance management (Table 1). The main focus of these solutions is on midsize and large companies, mostly in process (chemical, oil and gas, food and beverage) and automotive industries.

The main disadvantage of these solutions is investment costs (software purchase, customization, testing, implementation, maintenance, etc.). In some cases such

Table 1. Example of some of the advanced MES solutions provided

Vendor name	Product name	Core functions
ABB	cpmPlus Suite	Quality management, material and warehouse management, visualization, process optimization and decision support, electronic work instructions, production performance reports
Apriso	FlexNet	Warehouse, quality maintenance, labour activities, managing and executing production
Aspen technologies	aspenOne	Performance analysis, production resource management, production dispatching and execution
Emerson process management	Syncade	Production operations, inventory management, quality management, maintenance and machinery health management
Forcam	Factory Framework	Order data management, personnel data, production data management, machine data collection, process data management and traceability
iTAC software	iTAC.MES.Suite	Material logistics, quality management, production planning and management, production and machine data collection
IBS	IBS:MES	Operational data, machine data, tool administration, resource and service management
GE intelligent platforms	Proficy for Manufacturing	Order completion status, interactive schedule planning, material delivery management, maintenance management
Honeywell process solutions	Intuition Executive	Planning and scheduling, supply chain and operations management, equipment monitoring, performance monitoring
Invensys	Wonderware MES	Electronic work orders, operations management, performance management, quality management, product traceability, inventory
MPDV mikrolab	Hydra	Material and production logistics, machine and process data collection, tool management, quality assurance, personnel scheduling
Rockwell automation	FactoryTalk	Production management, asset management, quality assurance, performance management, control system connectivity, automation control programming
SAP	SAP ME SAP MII	Production management, product traceability, maintenance activities, labour tracking, production metrics, material tracking
Schneider electric	AMPLA	Asset utilization and performance metrics, material tracking, quality management, labour tracking, energy consumption tracking
Siemens	SIMATIC IT	Quality control management, product tracking, mapping of manufacturing processes, collaboration with R&D, process efficiency and utilization management

systems may have weak re-configurability or require expert knowledge of the system that may affect flexibility of the company, when every change in configuration (machines, materials, design, suppliers, etc.) must be prepared by the software supplier and imported to the system [7]. There is a lot of companies providing solutions with limited functionality and operating in a specific area (e.g., Evocon Line Efficiency, Wintriss ShopFloorConnect). Such solutions are normally designed to get the most basic inputs form the production line (machine): unit and flow speed counting, job list, downtime and quality reports, etc. Apart from that, many production companies are developing and implementing their own unique niche production monitoring solutions to suit their specific needs rather than to buy or rent one. Complete history of the work shop activities supports the ability to review quality problems on any life stage of the product that is one of the product lifecycle management (PLM) functions [8].

3. CONCEPT

Integral parts of PMS are data collection and analysis, prognostics, visualization, and storage (Fig. 2). Complexity of each component may differ according to customer requirements [9–11]. It means that the system is expandable: additional custom modules may be added to form one integrated platform.

PMS does not provide main functions of the production scheduling system and should work closely with

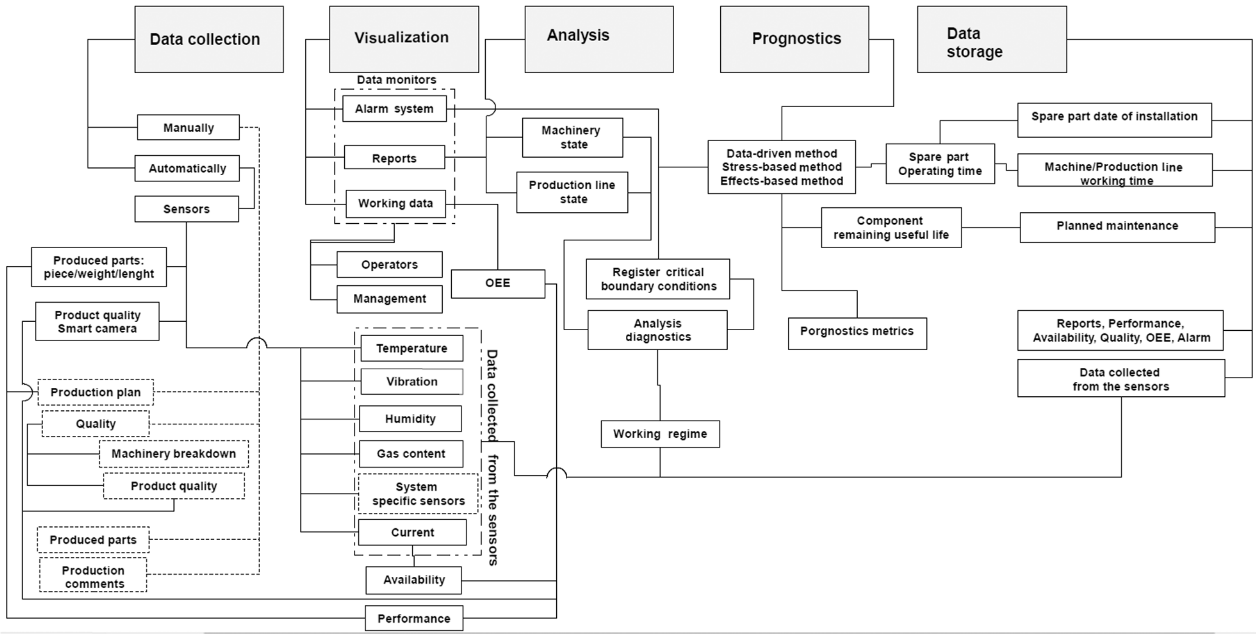

Fig. 2. Simplified concept of a production monitoring system [11].

production planning systems to exchange data (e.g., through MES, ERP, etc.). As an example, such data as the number of pieces to be produced and ideal cycle time to calculate machine performance should be inserted once and used in different systems. Standalone solution may require a number of manual inputs and have limited functionality.

The more sensors will be integrated in the system, the more data will be generated that should be handled. But processing this growing number of data through traditional database technologies will be challenging. This problem is directly related to the concept of Big Data. But the use of Cloud computing may help to simplify these data processing issues [12].

Preferably, a web based user interface, based on open source software, should be used to cut the costs. At the same time, custom open-source software may lead to the lack of qualified support and require more effort to integrate with existing equipment [13]. To mitigate these risks, integration may be supported by third parties (university research teams, private companies) and special dedicated online communities. Different motivation points for people to participate in such online communities are considered [14] (e.g., benefits from the work of someone else, making a research project, etc.). Despite some drawbacks, such software and hardware supports principles of open research and collaborative knowledge creation. The design of a PMS and its parts requires interdisciplinary research: to incorporate data mining, software, hardware, user interfaces, ergonomics, etc. As software architecture and engineering is not in the scope of this research paper, only basic software functions will be described.

3.1. Data analysis and prognostics

Different data analysis techniques are used to retrieve useful information from the collected data. And by the support of prognostics the most likely scenarios are determined with maximally eliminated inaccuracy and uncertainty. Here focus should be mostly on high value parameters. Along with that are additionally required developments in advanced sensor technologies and incipient fault detection techniques.

It is a real challenge to obtain samples of the failure progressions, as most of the critical systems are not allowed to run until failure and vital parts are replaced. So in this case limited analysis may be performed. Failure degradation of some systems takes a long time that complicates the research. Solution to that is to run experiments in a laboratory environment, to accelerate the aging. But studies conducted in research laboratories often neglect certain practical considerations from the real-life situations.

3.1.1. Data analysis

Together with different data mining techniques (e.g., neural networks, genetic algorithms, decision trees) to identify a possible problem, statistical process control (SPC) may be used to calculate upper and lower limits. That will help to inform operators about possible abnormal conditions. Such methods may be applied to construct control charts by use of data measurements on a continuous scale, e.g.:

- Shewhart control charts.
- Exponentially-weighted moving average chart (EWMA).
- Cumulative sum control chart (CuSum).

To construct an X-bar chart (control chart) or R-charts (range chart), the following steps should be done:

- Measure (subset) data points.
- Calculate mean and range.
- Calculate standard deviation.
- Calculate upper and lower limits (subset size determines the constant to be used in equation).
- Construct plots.

In a visualization module, where control charts are presented, collected data (e.g., temperature, current, vibration) are plotted in a time order. On these control charts, the central line for the average is shown together with upper and lower control limits. By comparing the real time data with the historical one, operator can draw conclusions whether the process is stable. Out of control signals should be marked. Chart axis scale should be automatically updated.

As an example, a subset of five readings are calculated using the following equations [14]:

$$\begin{aligned} &Central\_line\_\overline{\overline{X}} = \frac{(\overline{X}_1 + \overline{X}_2 + ...\overline{X}_k)}{k}, \\ &Central\_line\_\overline{R} = \frac{(R_1 + R_2 + ...R_k)}{k}, \\ &\overline{\overline{X}}\_UCL = \overline{\overline{X}} + A_2\overline{R}, \quad \overline{R}\_UCL = D_4\overline{R}, \\ &\overline{\overline{X}}\_LCL = \overline{\overline{X}} - A_2\overline{R}. \quad \overline{R}\_LCL = D_3\overline{R}. \end{aligned} \tag{1}$$

Here k is the number samples (subgroups). If subgroup size $n = 5$, values of the formula constants are: $A_2 = 0.577$, $D_3 = 0$, $D_4 = 2.114$.

Additionally, the area between limit controls and grand average can be divided into more regions:

$$\begin{aligned} &1/3\_UCL = \overline{\overline{X}} + (\overline{\overline{X}}\_UCL - \overline{\overline{X}}) * 1/3, \\ &2/3\_UCL = \overline{\overline{X}} + (\overline{\overline{X}}\_UCL - \overline{\overline{X}}) * 2/3, \\ &1/3\_LCL = \overline{\overline{X}}\_LCL + (\overline{\overline{X}} - \overline{\overline{X}}\_LCL) * 2/3, \\ &2/3\_LCL = \overline{\overline{X}}\_LCL + (\overline{\overline{X}} - \overline{\overline{X}}\_LCL) * 1/3. \end{aligned} \tag{2}$$

3.1.2. Prognostics

As prognostics is becoming more widely applied in different disciplines, all the definitions describing it are subject for further development and refinement. But most of the definitions agree on the prediction aspect. A prognostic is usually used to predict one of several related measures [15, 16]:

- Remaining useful life (RUL): the amount of time the component will continue to meet its design specification.
- Time to failure (TTF): the time a component is expected to fail.
- Probability of failure (POF): the failure probability distribution of the component.

According to various requirements, there are different approaches, from a simple (e.g. degradation trends) to relatively complex ones (e.g. physics-based model methods). The regression type (e.g. polynomial, linear, exponential) to be applied is determined by the knowledge of the physical process. And prognostics methods may be separated into three different groups: data-driven method, effects-based method, and stress-based method.

In *the data-driven method* the prognostic model is based on data, collected from the system. In general, it is an easy and fast method to implement. This method considers historical data to estimate the lifespan under normal usage conditions. One of the most popular parametric models for that is the Weibull distribution [16]. And the most general expression of the Weibull probability density function is given by the three-parameter Weibull distribution:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}, \tag{3}$$

where t is time; γ is the location parameter ($\gamma = 0$, yields the two-parameter Weibull distribution); $f(t) \geq 0, t \geq 0$ or $\gamma, \beta > 0, \eta > 0, -\infty < \gamma < \infty$; β is the shape parameter. If $\beta > 1$, the failure rate is increasing; $\beta = 1$, the failure rate is constant; $\beta < 1$, the failure rate is decreasing; η is the scale parameter.

Main disadvantage of such method is that operating conditions are not considered. Components operating under different conditions than modelled are going to fail earlier or later. And this method requires sufficient number of samples that were run until failure, but it is not always feasible.

The effects-based method considers degradation of a component. Degradation effect should be slow enough for the decision to be made. Degradation can be a function of several measured variables. Model development requires a thorough understanding of the system, in other words, clear understanding of the degradation mode (e.g., physical model). Typically, physics-based algorithms assume that new equipment is perfectly designed and produced.

The stress-based method, additionally to the data-driven method, also considers an environmental impact (vibration, temperature, humidity, etc.). This method can provide a more precise assessment of the RUL.

The simplest class of the stress-based methods uses an ordinary least squares regression model to predict the failure time. By use of such information as a component load, temperature or other working conditions, in addition to the time to failure data, a multivariate regression can be performed to predict the expected failure time. In this model, the slope is related to the stress, caused by operating conditions. Another approach is to use multiple data-driven models, which account for different working conditions. Or in special cases a single data model with a correction factor, which accounts for a stress based information [17]. It can even be a simple linear regression model that includes prior observations of explanatory variables and response variables as a failure time.

The proportional hazards model (PHM) [16,18] is often used to combine failure data with environment (stress) data. It uses environmental condition information as covariates to modify a baseline hazard rate function:

$$\lambda(t; z) = \lambda_0(t) \exp\left(\sum_{j=1}^{q} \beta_j z_j \right), \tag{4}$$

where $\lambda_0(t)$ is the arbitrary baseline hazard or function; z_j is a multiplicative factor, explanatory variable or covariate; and β_j is a model parameter.

Of course, a prognostic is not feasible in all cases. For example: getting dust into the bearing is an uncertain event and you cannot predict it. But if you measure the state of the bearing (vibration, temperature, etc.), you may be able to detect the upcoming failure and replace (take precautions) before it fails. You can also try to eliminate uncertainty by preventive/protective measures (e.g. dust seals), which you can take based on the root cause analysis from the machine stoppages explanatory data of a PMS system.

3.2. Data collection

Parameters of interest should be decided for each customer/case separately. Starting from analysing an enterprise, main problems may be mapped and relevant KPIs selected that are in line with the objectives defined. Indeed, comparing to larger companies with more complicated structure, the process of selecting, changing, and reviewing of KPIs inside SMEs could be more likely to be performed with relative ease. Different approaches may be used to select proper data to be collected and visualized (customer interview, questionnaire, etc.). As an example, questionnaires may describe such points as the definition of a problem or goal to be solved, minimum requirements to be achieved, equipment to be monitored, known limitations and restrictions, responsible individuals, etc.

As there is always a risk that the system may be rejected by the operators (e.g., because of intrusive data inputs), information should be maximally collected automatically.

In industry (and laboratories), to get a readable data from a sensor, signal conditioning module, analogue to digital converters and data loggers are used. Typically total cost of this equipment is quite big, but cost effective solutions are available, as, for example based on Raspberry Pi single board computers and Arduino single board microcontrollers. Raspberry Pi that can be used as a data logger (local host) does not have an analog-to-digital converter (ADC) and requires external ADC to allow sampling of an analogue signal. But in this case, care must be taken as Raspberry Pi is not running real-time operating system (RTOS). Therefore, Arduino board that has ADC may interface between the sensor and Raspberry Pi. There is also a ready combination of platforms like UDOO, Beaglebone and others available on the market.

Preferably, wireless solutions should be used, like wireless sensor networks (WSN) that help to reach difficult accessible locations, by maximally eliminating wiring for quicker installation. There is a number of ways how this network architecture may be implemented. Large networks can be decomposed into clusters, where cluster could have either single-hop or multi-hop communication [19], as well as a combination of wired and wireless technologies or only wired communication could be used in more data-intensive operations or stringent environments. Different energy sources may be applied using piezoelectric materials (e.g., energy harvesting from vibrations), thermoelectric converters, photovoltaic approach, etc. Also Field Programmable Gate Arrays (FPGAs) may be used to extend the functionality of WSN controllers [20].

3.3. Visualization module

The process of development of the graphical user interface (GUI) is closely related to data, collected in the workshop. One of the ideas of visualization is to present complex data in a simple way. It may help to find patterns in a large amount of data and take quick decisions. Data visualization should be available between company's different departments. Proposed production monitoring system visualization module may be presented as a three-level structure. Table 2 below shows the main tasks of the GUI on different levels. These tasks are not limited, and depend on customer requirements and investment costs.

In manufacturing environment, it is not always ergonomic for operators to use keyboard and mouse, so in some cases touchscreens may be preferred. But when developing GUI for touchscreens, not all "fundamentals" of mouse & keyboard interfaces should be used, e.g., if quick inputs are closer to the corners to reach easily with the mouse pointer. As for big touch

Table 2. Proposed structure of GUI for the production monitoring system

Level	User/Department	Main tasks
View 1	First-level managers and experienced workers (working foreman, operator)	Workplace KPIs, produced items, quality inputs, system condition monitoring
View 2	Mid-level managers (foreman, department leader)	Combined department/ workshop view, extended reports (performance comparison), reporting and statistics module, system administration
View 3	Upper-level managers (management, maintenance manager)	Production statistics, overall workshop performance, forecasts

screens, operators will have to stretch they hands to reach the corner of the screen.

When the operator has to make choices from the data presented (e.g., menus, buttons), the number of choices should be limited to decrease the responding time according to the Hick's Law [21,22]. In some cases it is possible to achieve it by combining or removing some items. Also, frequently accessed items should be of large size and with the possibility to replace its position on the screen to be more suitable for each operator that is in line with Fitts's law [23,24].

Here some of the Shneiderman's design principles [25] may be useful, like (1) an identical terminology used through all the GUI menus, (2) possibility for advanced users to use shortcuts, (3) system designed so that the user cannot make serious errors, (4) the undo possibility. Regarding the reverse functionality, it may encourage operators to try unfamiliar options. But review of main changes should be stored. Despite the number of advantages, the following limitations should be considered:

- It may be faster to type words with conventional keyboard for most of the users, comparing to on-screen keyboard.
- Finger size defines the size of icons, and, e.g., haptic technology should be used as a feedback that the option has been selected.

It is beneficial to take these advices when designing GUI for PMS, but it does not warrant decrease of time for critical responses. As there is no unique approach that will be suitable for all production environments, each interface should be possible to adjust on site. And the need of additional prompting of confirmation requests, when the option is selected, should be definitely discussed with the users.

Preferably, client server model should be replaced by web-based platforms with operating system independence and remote functionality, but here the question about the web-based security arises, as data is more easily to be accessed remotely by 3rd parties and web page loading speed from the web server may be lower comparing to desktop software. Of course, there is a number of hacks existing to improve performance of web page loading (e.g., AJAX, JavaScript/CSS files delayed loading, etc.). But these questions are related more to software engineering and architecture.

3.4. Data storage

A data storage module is responsible for data archiving, distribution, and storage. Collected data could be saved to on-site database server (SQL or NoSQL databases) or to cloud-based platforms. Cloud storage is closely related to cloud computing that is consisting of different services, e.g., (1) platform as a service, (2) infrastructure as a service, (3) software as a service. It may help to cut the investment costs of the designed system, but a drawback is the responsiveness of the system compared to the on-site server.

Data may be stored in different formats like ASCII, XML, Binary, Database Files, etc. Depending on the application, they have their strengths and weaknesses. Such factors as data-streaming speed, human readability, file size, and exchangeability should be taken into consideration. It should also be decided for how long data should be saved in the databases. Possible system expansion in the future should be considered, as it may bring changeover in database structures. Data should be protected (e.g., network security standards). As a preventive tool of user logging management, system privileges may be applied. Policies inside the company should exist to maintain data protection.

If by some reasons there is no connection with the remote database, local data acquisition terminals should keep collected data until the connection is restored and synchronize with the central database. One simple example can be how the Raspberry Pi receives data from the Arduino controller (Python script) and logs it to remote SQL server with the possibility to save it on local SQL server that it runs itself (Fig. 3). Additionally, Arduino could be supplied with a SD card for logging as a fail-safe in case of data connection failure between Arduino and Raspberry Pi.

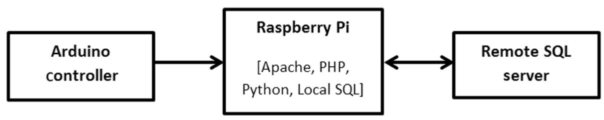

Fig. 3. Example of data logging.

4. A CASE STUDY

Increasing the capacity of a bottleneck production line is usually a long and investment-heavy undertaking and therefore a decision was taken to apply automatic PMS solution on a profile planning line of a mass-production woodworking company with a purpose of collecting data for analysing the need for investing in a new production line. Since the cost of the considered solutions was over the budged, a custom solution was developed for specific needs of the company. And separately a visual module for milling machine DYNA MECH. EM3116 was developed at the Tallinn University of Technology.

The case study focuses on creating custom GUI for application in daily work, instead of time consuming and tedious paper reports.

4.1. GUI development for the production line

The GUI for the PMS was developed by authors as a web-based application. The use of dynamic web pages [26] with the support of AJAX (Asynchronous JavaScript and XML) technology allows updating user interface specific objects and responding to submission events. The idea was also to use tablet devices with Android operation system to lower the cost of the system. Web-based approach allows the use of a wide range of devices with graphical interface support.

To simplify development, open source PHP package – XAMPP version 1.6.6a was installed (that includes MySQL database version 5.0.27; phpMyAdmin MySQL version 2.11.7.1; FileZilla FTP server version 0.9.20b; PHP ver. 5.2.0; and Apache web server version 2.2.3).

Two main GUIs where developed for user interaction with the system for the operator and the quality inspector of the end product.

The GUI for View 1 (Operator screen) – consists of 4 main parts (Fig. 4):

- Screen header – displays the machine id, machine name and the current shift number.
- Stoppage reasons and times – stoppages in chronological order.
- Stoppage overview – stoppage reason summary.
- Shift overview – displaying various machine/production line specific detailed information.

Additionally, there are 3 buttons in the top right corner of the Operator screen for *reporting a breakdown* to the technical department that is a link to an external system; *shift report* which is showing the current shifts more detailed summary and *end shift* button.

Clicking a stoppage in the *"Stoppage reasons and times"* column will open a new screen for specifying a stoppage group and then based on this selection the stoppage reasons in this group will be displayed. There is a possibility for a breakdown registration with a time interval (Fig. 5).

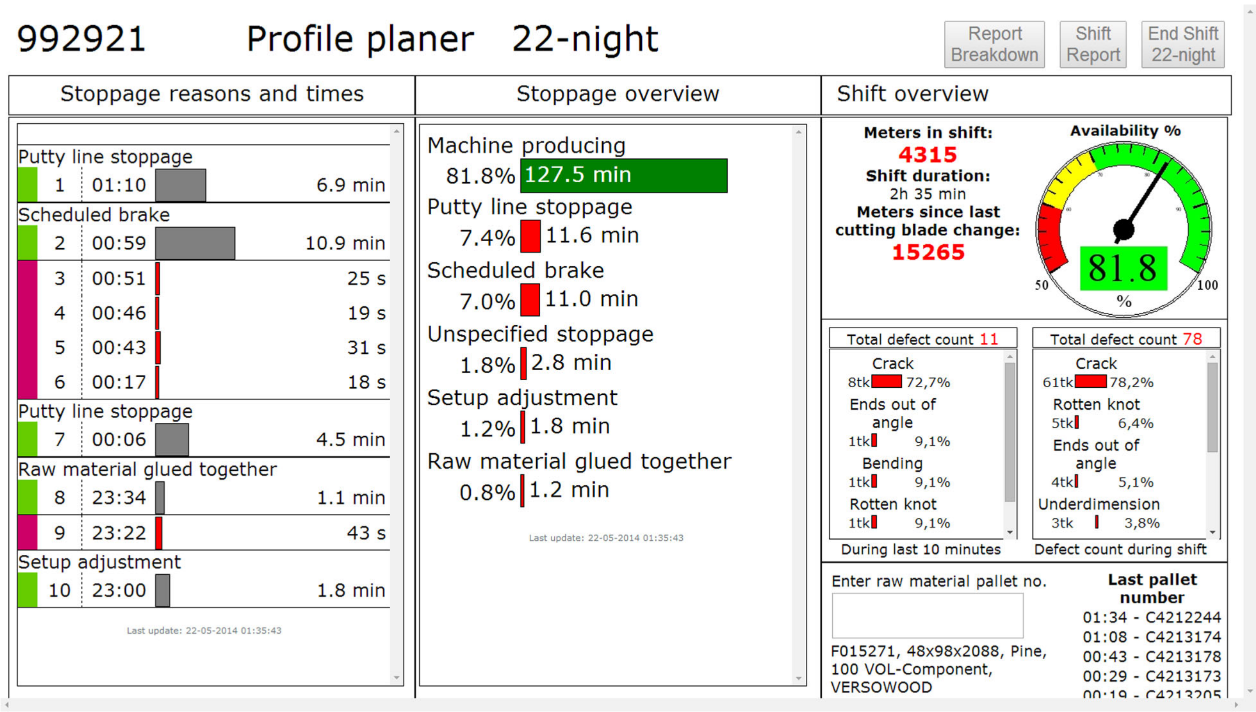

Fig. 4. Machine/Operator screen.

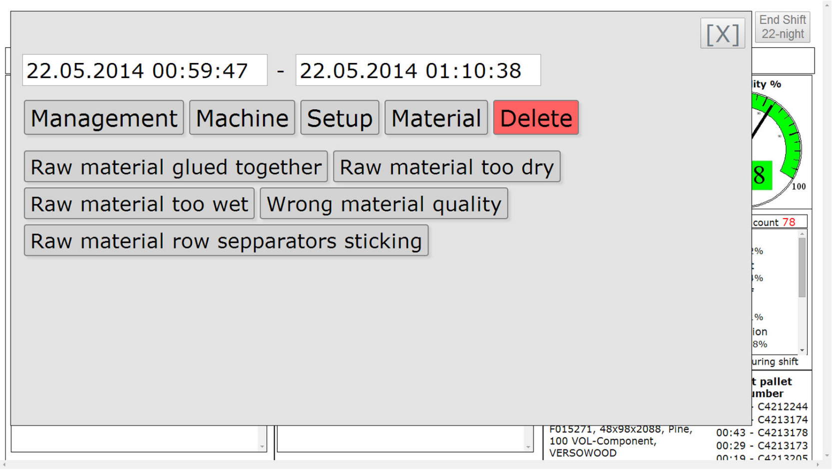

Fig. 5. Machine/Operator screen stoppage reason selection.

Shift overview column in the Operator screen consists of 3 parts: shift overview, quality overview, and raw material consumption registration. In the shift overview section, there are several key performance indicators that are the main measurements of the effective use of the line – meters produced in shift and machine availability. Machine availability is calculated based on the signals from a rotary encoder that measures the length of the material that is molded. Once there is no material under the encoder, the line must be having a stoppage. The sum of stoppages deducted from the total shift length gives the available production time for the machine. In connection with produced meters per shift an important indication for the line can be calculated – the average production speed.

The quality overview shows the data that is entered by the quality inspector, who is inspecting each product that is produced. The information is split in two sections – quality summary for the last 10 minutes and for the whole shift. Reason for such separation is that recent changes in quality of the products may not be visible in the scheme of the whole shift.

Raw material registration is done via a barcode scanner that reads the information from the pallet that is fed into the line. Additionally to the Operator screen, there is a possibility for the workers to look at a report that uses Statistical process control (SPC) approach with the Planner speed (Fig. 6).

The report shows the actual average speed of the line per minute and displays the minimal and maximal speed range based on the product information of the currently produced item.

The Quality screen (Fig. 7) is the main screen for the Quality Inspector of the end-product and is built to give a quick feedback for the quality inspector and the operator. The quality GUI consists of 4 parts:

- The header with machine and current product information and the starting time for the last product (top left of the screen).
- Reporting buttons for each of the predefined defects that should be reported (middle left of the screen).
- There are buttons for viewing the *Last 10 registrations* and *Deleting a registration*; *Current shift report* for displaying a report grouped by products and total for the shift; *Previous shift* report which shows the data of the previous shift; and *Product change* for defining what product the line is producing at the moment.
- Total Defect Count.

The data from the Quality GUI is used for creating a base report for importing to excel for further analysis for the mid-level managers. The Quality GUI allows the workers and mid-level managers to make quick decisions about the raw material they should use for specific product and the weekly Excel report gives a good base for choosing the biggest defect group to work on.

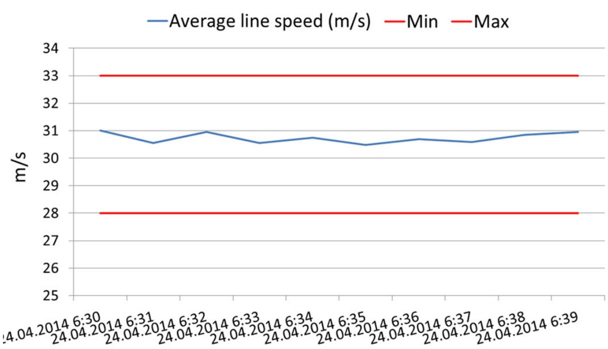

Fig. 6. Average speed during a shift (data grouped by minute).

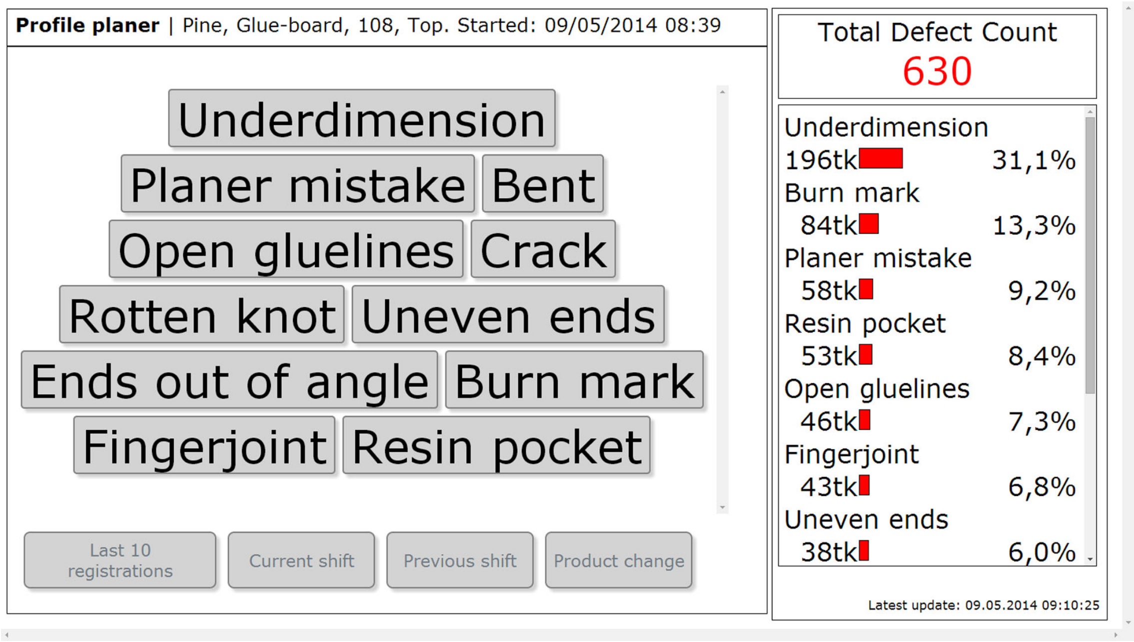

Fig. 7. Quality Screen.

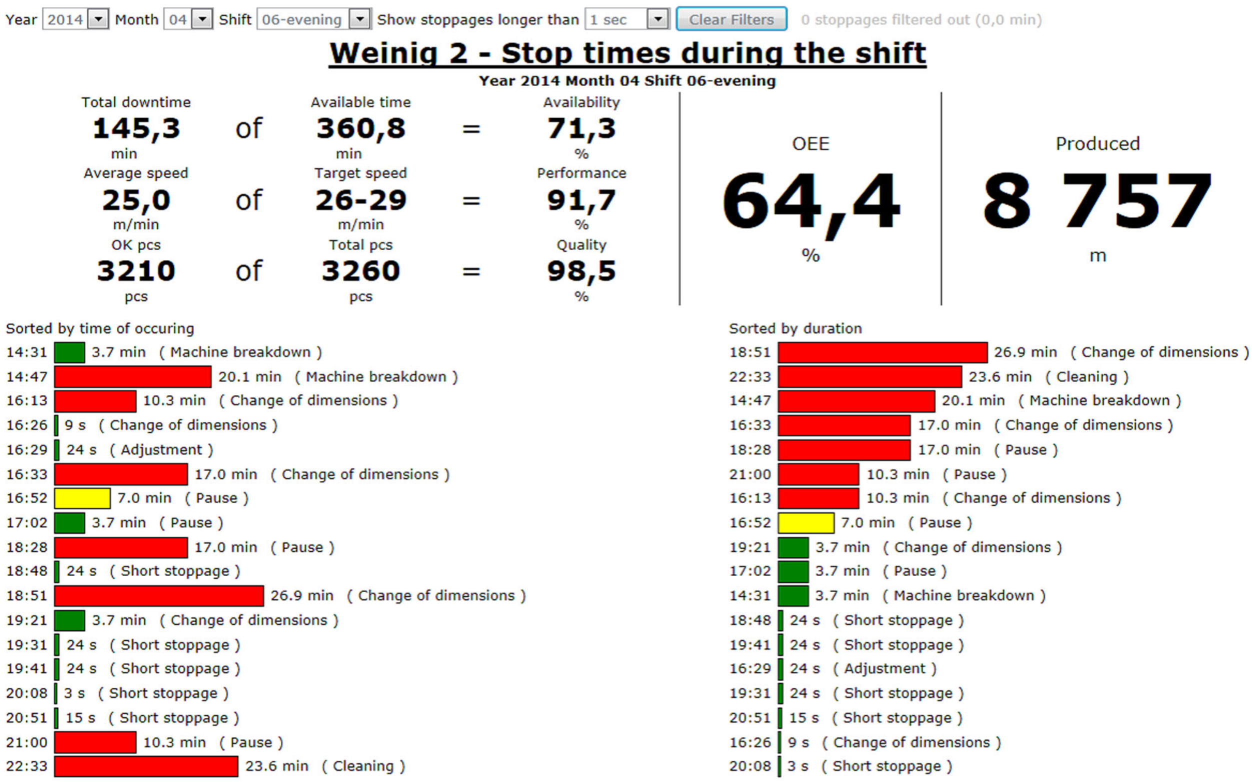

Fig. 8. Reporting module for production line (View 2).

Additionally to the GUIs, a Reporting module for production line was developed and implemented. The Shift report (Fig. 8) provides an overview for the first and middle level management and the operator about the shift results and gives them an idea, what were the biggest stoppage reasons. The user needs to select a year, month and a shift for the report to be displayed. Additionally, the user can filter out stoppages based on duration.

The reports main feature is the OEE breakdown into 3 components and displaying the parameters for the calculation of these components. This gives a very clear indication what component needs to be worked on and gives a clear direction for the root cause analysis. Multiplication of Availability, Performance, and Quality components will result in OEE. As the main indicator of the operators good work is the high quality product that the line produced, the Produced meters are displayed on the report. Additionally the report features the stoppage reasons, sorted chronologically and by their duration. With just a glimpse, the operator can see the longest stoppage and browse through the history of stoppages chronologically. There is a possibility to automatically generate a Pareto chart that will show the summarized version of the stoppages by grouping them together by type, thus enabling to see the biggest stoppage reasons for the whole shift.

Another report that was designed is the summarized report by week, showing the same information as the shift report except for the individual stoppages. Additionally, it displays the products that were produced during the week and the statistics for the individual products. Rows coloured red in product data give the indication where the actual average speed is over theoretical speed, meaning that the ideal cycle time for the product needs to be remeasured and corrected in the system or there are some mistake (Figs 9, 10). This report is ideal for looking at the bigger picture of the production line statistics and making decision for the longer term. That is why it is a good report for the middle and high level managers to get a quick overview.

The system described is in everyday use now and to analyse its effect on the productivity thorough research should be done. According to the data collected from the bottleneck production line during the last two months period compared to the last year average, productivity (units per hour) increased by more than 30%.

4.2. GUI development for the milling machine

Obtaining sample data of the failure progressions to define alarm set points for measured parameters posed is a real challenge, as systems are normally not allowed to run until failure and the vital parts are always tried to be replaced before they fail. Therefore, as an alternative, statistical process control (SPC) was proposed for continuous automatic calculation and update of warning limits (upper/lover limit control). After the survey (interview of operator), the most common breakdown and quality problems were determined for such type of milling machine that helped to make the list of problems for the visual model [11].

Product data

Production start	Production end	Product id	Product Info	Meters	Duration (min)	Running time (min)	Average Speed	Theoretical Max Speed	Performance
12.05.2014 00:00:03	12.05.2014 01:57:43	1979	pine component 93 2077	1 362	118	43	31.4	36.0	87.2%
12.05.2014 01:57:43	12.05.2014 05:58:18	1980	pine glueboard 93 2077	3 838	241	119	32.3	36.0	89.6%
12.05.2014 05:58:18	12.05.2014 07:40:07	1981	pine glueboard 93 2077	3 143	102	91	34.4	36.0	95.5%
12.05.2014 07:40:07	12.05.2014 14:03:46	1985	pine glueboard 93 2077	6 613	384	195	34.0	36.0	94.5%
...									
15.05.2014 14:32:27	15.05.2014 21:31:13	2035	pine glueboard 93 890		3 559	419	142	25.1	24.0

Fig. 9. Summary report group by product data for upper- and mid-level managers.

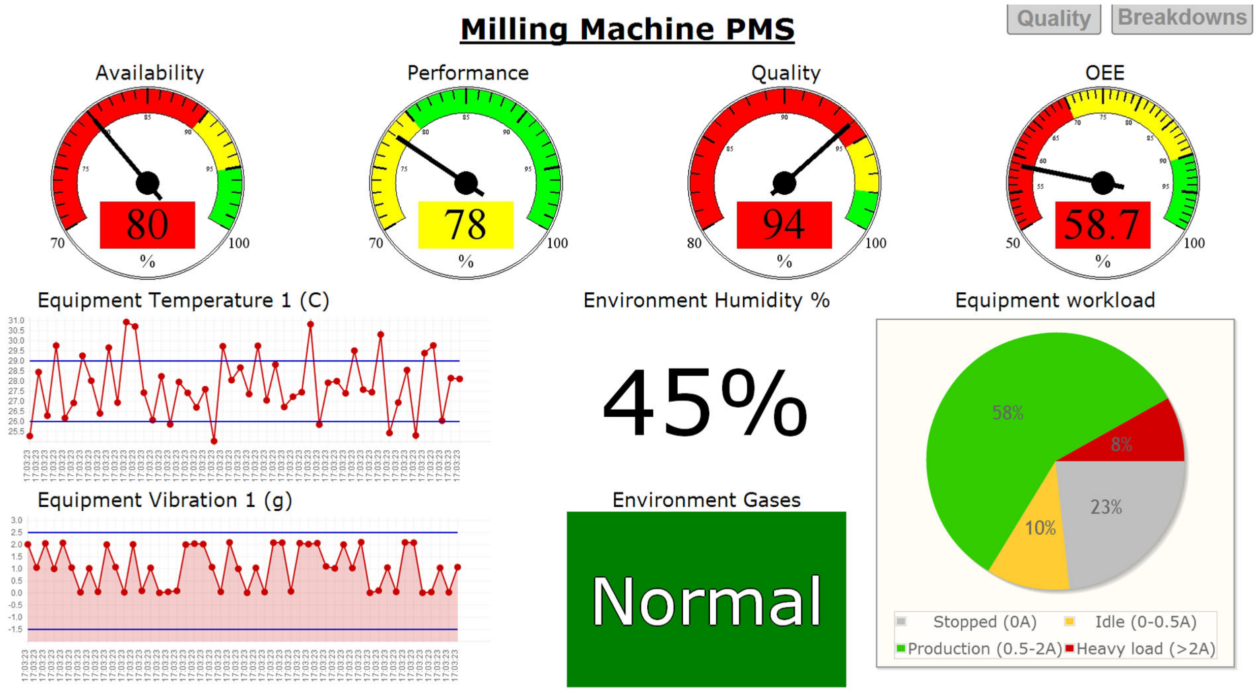

Fig. 10. Developed visual module for milling machine.

5. FURTHER RESEARCH

Advanced data analysis and prognostics methods should be researched, implemented, and tested to enhance proposed PMS for SMEs. Despite the fact that a variety of prognostic models has already been reported in technical literature, an effective prognostic methodology for industrial application has yet to be developed. As prognostics accuracy is a subject to stochastic processes that have not yet occurred, it is difficult to formulate clear systematic methodology for it. Because of that it is still primarily based on human expertise and knowledge through continuous monitoring and analysis of machine conditions.

The model for a group of machines and/or production cells should be tested (combined workshop overview) to help to balance the production and identify bottlenecks. Also different possibilities of integration with existing software (e.g., ERP, MRP) to share information should be analysed. And online training methods for users should be discussed.

6. CONCLUSIONS

Functionality of the core elements of the proposed PMS was described. Visual module for SMEs was designed and implemented in a production company that will help to get manufacturing benefits.

One of the main advantages is that the proposed production monitoring system is based on an open-source software and hardware to make it more affordable for users and support collaborative knowledge creation. Users have the possibility to change the functionality according to their needs. If more production enterprises/developers will implement and share open source production monitoring tools – it may help to simplify the next development to get even more competitive solution comparing to the commercial ones. All this may help to increase the number of companies who can start using advanced monitoring tools to increase shop floor visibility.

Depending on the production company type and organizational needs, PMS functionality may vary greatly. But the main principles described above may be used in different areas like additive manufacturing to even more advanced technology. Detailed information on operating resources and downtime analysis will result in higher utilization ratios. And collected data analysis will also help to find reasons of abnormal conditions. Indeed, development of advanced monitoring tools continues to be an interesting research topic and motivates to find new ways how to improve already existing solutions or develop new ones. This research could provide benefit to those who are going to design and implement production monitoring tools.

ACKNOWLEDGEMENTS

This research was supported by European Social Fund's Doctoral Studies and Internationalisation Programme DoRa, by ETF grants 8485 and 7852, targeted financing project SF0140035s12, and Innovative Manufacturing Engineering Systems Competence Centre IMECC (supported by Enterprise Estonia and co-financed by the European Union Regional Development Fund, project EU30006).

REFERENCES

1. Jardine, A., Lin, D., and Banjevic, D. A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mech. Syst. Signal Process.*, 2006, **20**, 1483–1510.
2. Cowling, P. and Johansson, M. Using real time information for effective dynamic scheduling. *Eur. J. Oper. Res.*, 2002, **139**, 230–244.
3. Gu, Y., Lo, A., and Niemegeers, I. A survey of indoor positioning systems for wireless personal networks. *IEEE Communications Surveys & Tutorials*, 2009, **11**(1), 13–32.
4. Lanza, G., Stoll, J., Stricker, N., Peters, S., and Lorenz, C. Measuring global production effectiveness. *Procedia CIRP*, 2013, **7**, 31–36.
5. Saenz de Ugarte, B., Ariba, A., and Pellerin, R. Manufacturing execution system – a literature review. *Prod. Plan. Control*, 2009, **20**, 525–539.
6. Meyer, H., Fuchs, F., and Thiel, K. *Manufacturing Execution Systems: Optimal Design, Planning, and Deployment*. McGraw-Hill, New York, 2009.
7. Bo, L., Zhenghang, C., and Ying, C. Research on reconfigurable manufacturing execution system. In *Proc. 2004 International Conference on Intelligent Mechatronics and Automation*. Piscataway, N.J., 2004, 157–161.
8. Ben Khedher, A., Henry, S., and Bouras, A. Integration between MES and product lifecycle management. In *Proc. 2011 IEEE 16th Conference on Emerging Technologies & Factory Autom.* (Mammeri, Z., ed.). Toulouse, 2011, 1–8.
9. Snatkin, A., Karjust, K., Majak, J., Aruväli, T., and Eiskop, T. Real time production monitoring system in SME. *Estonian J. Eng.*, 2013, **19**, 62–75.
10. Eiskop, T., Snatkin, A., Kõrgesaar, K., and Søren, J. Development and application of a holistic production monitoring system. In *Proc. 9th International Conference of DAAAM Baltic Industrial Engineering* (Otto, T., ed.). Tallinn University of Technology, Tallinn, Estonia, 2014, 85–91.
11. Snatkin, A., Eiskop, T., and Kõrgesaar, K. Production monitoring system concept development. In *Proc. 9th International Conference of DAAAM Baltic Industrial Engineering* (Otto, T., ed.). Tallinn University of Technology, Tallinn, Estonia, 2014, 198–203.
12. Hashem, I. A. T., Yaqoob, I., Anuar, I. N. B., Mokhtar, S., Gani, A., and Khan, S. U. The rise of "big data" on cloud computing: Review and open research issues. *Inform. Syst.*, 2015, **47**, 98–115.
13. Heron, M., Hanson, V. L., and Ricketts, I. Open source and accessibility: advantages and limitation. *J. Interact. Sci.*, 2013, **1**, 1–10.
14. Wasko, M. M. and Faraj, S. "It is what one does": why people participate and help others in electronic communities of practice. *J. Strategic Informat. Syst.*, 2000, **9**, 155–173.
15. Oakland, S. J. *Statistical Process Control* (6th ed.). Butterworth-Heinemann, Oxford, 2008.
16. Hines, J. W. and Usynin, A. Current computational trends in equipment prognostics. *Int. J. Comput. Intell. Syst.*, 2008, **1**, 94–102.
17. Camci, F., Eker, O. F., and Jennions, I. K. Major challenges in prognostics: study on benchmarking prognostics datasets, In *Proc. First European Conference of the Prognostics and Health Management Society 2012* (Bregon, A. and Saxena, A., eds). PHMS, Dresden, Germany, 2012, 148–155.
18. Zhang, Q., Hua, C., and Xu, G. A mixture Weibull proportional hazard model for mechanical system failure prediction utilising lifetime and monitoring data. *Mech. Syst. Signal Process.*, 2014, **43**, 103–112.
19. Khemapech, I. Feasibility study of direct communication in wireless sensor networks. *Procedia Computer Sci.*, 2013, **21**, 424–429.
20. Kateeb, A. Next-generation wireless sensor networks infrastructure development for monitoring applications. *Procedia Computer Sci.*, 2011, **5**, 749–753.
21. Hick, W. E. On the rate of gain of information. *Quart. J. Exp. Psychol.*, 1952, **4**, 11–36.
22. Hyman, R. Stimulus information as a determinant of reaction time. *J. Exp. Psychol.*, 1953, **45**, 188–196.
23. Fitts, P. M. The information capacity of the human motor system in controlling the amplitude of movement. *J. Exp. Psychol.*, 1954, **49**, 389–391.
24. MacKenzie, I. S. Fitts' law as a research and design tool in human–computer interaction. *Human–Computer Interaction*, 1992, **7**, 91–139.
25. Shneiderman, B. and Plaisant, C. *Designing the User Interface: Strategies for Effective Human–Computer Interaction* (4th ed.). Addison-Wesley, Boston, 2004.
26. Ullman, L. *PHP and MySQL for Dynamic Web Sites: Visual QuickPro Guide* (4th ed.). Peachipt Press, 2011.

Tootmise seiresüsteemi arendamine

Aleksei Snatkin, Tanel Eiskop, Kristo Karjust ja Jüri Majak

Artikli põhieesmärk on lihtsa, kuid tõhusa tootmise seiresüsteemi kontseptsiooni loomine ja visuaalse mooduli arendamine. Kirjeldatud põhiprintsiibid leiavad rakendust eri tootmisvaldkondades. Antud seiresüsteem annab täpse ülevaate tootmises toimuvast, lähtudes masina kasutamisest ja tootmisprotsessi stabiilsusest, võimaldades tekkivaid seisakuid ning kriitilisi olukordi õigeaegselt lahendada. Artiklis on kirjeldatud tootmisettevõtte jaoks arendatud seiresüsteemi visualiseerimise moodulit. Arendatud süsteem põhineb avatud lähtekoodiga tarkvaral. Tehtud uuring toob kasu neile, kes kavatsevad arendada tootmise seiresüsteeme ja vahendeid tootmisettevõtetele.