Predictive monitoring of production line efficiency

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ABSTRACT
The paper deals with analysis of production line performance efficiency and builds a prediction model that enables a short-term prediction of the expected performance based on the scheduled product mix. The actual schedule can be used as the model input to assist the production operators at the on-line production management. The same model can be used to experimentally evaluate the effect of different scheduling strategies by linking the performance model to discrete event simulator.

Keywords: Production process efficiency, modelling, simulation, optimization

1. INTRODUCTION

Manufacturing companies are facing increasing competitive pressures characterized by requirements on fast responsiveness while maintaining high productivity at high quality. Effective production management is one of the fundamental operational activities that has to be carefully designed and integrated into the overall management structure in order to meet the given requirements.

The integration of production management is a process aiming to upgrade and strengthen the links among the existing management activities. Various information technology products are used to support and improve the efficiency of production management. This way large volume of data is collected that contain useful information about production process performance. But the quality operational decision making still remains one of the most critical challenges for present manufacturing companies. The sole collection of production data is inadequate and a more tangible decision-making support is needed.

Within the third part of IEC 62264 standard - Enterprise-control system integration - entitled Activity models of manufacturing operations management (IEC 2007) the production management activities are decomposed in details. The production control is included among activities of the third level, and is further decomposed. Among others, the Production performance analysis is listed as a part of Production operations management. It is defined as a collection of activities that analyze information on the effectiveness and report the outcomes to the business level. This includes analysis of information on cycle times, resource utilization, equipment utilization, equipment and procedures' efficiency, and product variability. Relationship between these and other analyses can be the basis for the preparation of Key Performance Indicators (KPI) reports. This information can be used to optimize the production and the use of resources.

One way is to develop useful production performance models and integrate them in appropriate software tools to provide a better insight into performance mechanisms. The term model is referred to herein as a relationship between the relevant influence quantities, and one or more selected output variables. Such a model can be used either to analyze the relations between quantities, either for the analysis of scenarios, but it can also be used for short-term prediction of production performance. The models can be used to simulate production efficiency. In this way the effect of changes in the process can be tested experimentally, either changes in the operational settings, changes of production procedures or changes in the production path. Also the impact of external influences can be tested, such as the structure of the work orders, changes of material inputs etc. This enables an advanced evaluation of control measures and improves the quality of the operations management decisions. The models can be built on the basis of historical production data and may reflect different aspects of the production based on the intended purpose of their use.

This way the models are used in the context of production efficiency management, which is a set of activities that systematically record, manage and present information about the performance in a consistent manner, including corrective actions to affect the operational improvements. One of the main activities of the production efficiency management is the transformation of large amounts of raw data into information that can be used as a decision support on the management of production.

As discussed above, the ability of KPIs' prediction is an important aspect of the production efficiency management. The traditional implementation of this prediction is within the production planning/scheduling. Plans and schedules contain information that indicates the future production activities and can be used to estimate the future KPI values. An advanced implementation of KPI predic-

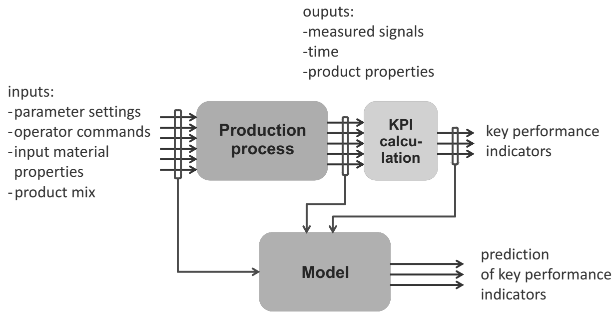

Figure 1: KPI prediction model

tion is based on the use of statistical techniques and experimental modeling methods (identification) on the existing KPI data values, and development of prediction models for the future values (Figure 1).

The paper investigates the applicability of modelling methodology in the context of production performance prediction and optimization. This is one of the fields where information technology has an immediate and considerable impact on the efficiency and quality of production control and related manufacturing processes. A case study is presented, where a production line for making building construction panels is analysed and various uses of derived model are proposed to improve the production management and manufacturing execution.

2. PRODUCTION PERFORMANCE MEASUREMENT

Measurement and evaluation of production performance is a key component of production efficiency management. One of the main challenges it to orchestrate various performance metrics in view of the changing list of production objectives. The purpose of performance indicators is on the one hand to provide information on the achievement of a set of objectives and on the other hand to connect the observed values with the improvement measures that should be taken. In this sense, the Performance Measurement Systems (PMS) are tools for decision support (Kaplan and Norton 1992, Neely et al. 1995, De Toni and Tonchia 2001) in a process of continuous improvement.

The importance of performance measurement drives a rich variety of method proposals and approaches that can be found in research literature. Nudurupati et al. (2011) give a recent survey of PMS developments in relation to management information systems and change management. From a global point of view, PMS can be treated as a multi-criteria instrument, which consists of a set of performance expressions (also called metrics) that are consistently organized according to the objectives of the company (Berrah and Cliville 2008). In doing so, the metrics can be based on actual measurements as well as on the other types of effects evaluations. PMS is always defined in relation to the global objective, and gives as a result one or more efficiency measures with the purpose of quantitative evaluation of the fulfillment of this objective.

In general the considered global objective is decomposed to a more elementary objectives along organizational levels (strategic, tactical, operational), while the elementary performance expressions associated with the decomposed objectives are aggregated to provide information on the achievement of the global objective. Various quantitative decomposition/aggregation performance measuring models have been proposed in order to control and manage the process of improving efficiency, thus supporting decision making in this process (Ghalayini et al. 1997, Suwignjo et al. 2000, Cliville et al. 2007, Berrah and Foulloy 2013).

2.1. Overall Equipment Effectiveness

The top-down oriented PMS are often combined with specific performance measures, such as Overall Equipment Effectiveness indicator (OEE) (Nakajima 1988, Muchiri and Pintelon 2008). Although OEE measure is not a complete PMS, it is an important complement to the traditional PMS when applied by autonomous small groups on the shop-floor together with quality control tools (Jonsson and Lesshammar 1999). As such the OEE measure is one of the standard indicators of technological performance.

In the foreground of the OEE assessment is the treatment of losses due to various interruptions in production process. They have a variety of causes, but commonly result in activities that consume resources without creating new value. To control the efficiency of discrete production in the context of TPM (Total Productive Maintenance), Nakajima (1988) developed a model of quantitative evaluation of the overall effectiveness of equipment that identifies each type of loss. The model includes the following losses:

- in terms of the availability:
  - time loss due to equipment failure,
  - level of use of the equipment or time wasted due to the preparation, set-up and adjustment of equipment;
- in terms of effectiveness:
  - production speed reduction due to minor stoppages, e.g. abnormal operation of machinery, unexpected shutdown, etc.,
  - production speed deterioration due to the operation of equipment at a speed below the nominal;
- in terms of quality:
  - level of production losses, measured by the volume of low-quality production due to scrap and re-work,
  - the level of other losses, representing lower production yields due to machine start-up runs before the establishment of stable operation of the equipment.

The model is partly based on the SEMI E10 standard that defines the operational status of equipment for semiconductors manufacturing and classifies the associated time intervals. Through the comparison of the time intervals the OEE provides a comprehensive insight into the utilization of available resources. Production is most effective according to the OEE indicator when the production system is operating at full capacity, producing the required product quality while production process is working without interruption.

There are several slightly different OEE definitions. E.g., in determining the availability, the planned production time can include the time that is used for preventive maintenance or not. In the first case we get a higher level of availability while planning more frequent maintenance tasks will not decrease it. But this can lead to poor planning and excessive maintenance time. On the other hand, the inclusion of this time in the planned production time lowers the availability indicator, but it reflects the actual availability and at the same time motivates more effective maintenance planning (Jonsson and Lesshammar 1999).

Similarly, slightly different definitions of the performance and quality indicators are used. At this point, the definition of OEE is used, as defined by the ISO 22400-2 standard. OEE is composed as a product of three independent components

$$OEE = A \cdot P \cdot Q \tag{1}$$

In equation (1) the three components have the following meanings:

- A - Availability (in terms of performance availability)
- P - Performance (efficiency in terms of capacity)
- Q - Quality (effectiveness in terms of quality)

Such a structure of the OEE indicator means that a disturbance in the manufacturing process is reflected on one of the components, enabling the identification of the cause of loss in efficiency. At the same time such a structure allows easy detection of weaknesses in the organization or operation of the production process.

3. PRODUCTION PERFORMANCE MODELLING

Production models are often developed to cope with technological efficiency. In particular, the model is used to obtain an insight into the future behaviour of key variables. This information can facilitate the effective ergonomic (re)design and its optimization (del Rio Vilas et al. 2013, Latorre et al. 2013) but can also be used in the context of real-time operational management (Curcio et al. 2007, Mujica et al. 2010).

The primary purpose of the modelling of technological efficiency, therefore, is the prediction of technological efficiency-related indicators. This allows for better corrective actions in the context of production efficiency management in order to increase technological efficiency. Particularly, modelling can be seen as an aid in deciding on production management measures.

In terms of the standard performance indicators it is particularly important to enable the prediction of indicators that are linked to productivity (efficiency, availability, ...) and quality. The impact on these indicators is highly dependent on the actual production process, but some general dependencies can also be extracted.

As a starting point for performance modeling standard dynamic systems modelling approaches can be applied: theoretical modeling based on the known physical and other relationships among the considered quantities, experimental modelling based on the measured signals and archived data, and a combination of the two approaches.

3.1. Theoretical modelling

The theoretical modeling is based on assumed a-priori known relationships. For example in the process industry the duration of the manufacturing operations can be determined if the dynamics of processes within a specific operation is modelled. Such theoretical modelling works well for smaller problems where we have a good insight into the system.

Another aspect of theoretical modeling, which is particularly important in the discrete production, is the structural aspect. Production processes are very diverse, so we use the analysis of the general properties and characteristics of the production processes during the modelling.

With the model of the structure of the manufacturing process, we wish to create a universal presentation for any real production process, and on the basis thereof design a performance model of the specific production process. The structure model should include basic building blocks and the links between them that can describe the nature of most manufacturing processes, with an emphasis on the presentation of the flow of material among operations. In literature, the basic building blocks of the production process model are production equipment devices (machines), and these can be then connected together in different ways. In general, in any manufacturing process we can distinguish:

- equipment,
- connections among pieces of equipment.

3.2. Manufacturing process effectiveness

The OEE indicator is calculated for each peace of equipment, e.g. each machine, but for a comprehensive evaluation of the production efficiency the metrics for individual machines must be combined into a single performance metric of the manufacturing process. The problem here is that not only the integration of various indicators has to be considered, as is the case with PMS systems, but it is necessary to take into account the structure model of the process.

Only the evaluation of the effectiveness of the production process as a whole provides a link with cost efficiency. For performance measures of the entire production process the abbreviation OFE - Overall Effectiveness Factory is used in the literature.

Metrics at the level of the production process should summarize the situation in individual machines and at the same time add a holistic perspective - the aspect of machines coordination. Therefore, the way of machine level metrics integration to the level of the production process is significantly affected by the interconnection of equipment.

3.3. Overall throughput effectiveness

In the literature several attempts can be found to design procedures for determining metrics based on the model of the structure of the production process. Huang and coauthors designed an OEE type metric to measure the efficiency level of the plant or factory. The measure is called Overall Throughput Effectiveness (OTE) (Muthiah and Huang 2007).

This measure was derived similarly to the overall effectiveness of equipment (OEE), on the basis of the finding that the efficiency of the entire production process, is the ratio between the actual quality product and the normalized product (quantities produced) in a selected time interval. This relationship is given by:

$$OTE = \left.\frac{P_{act}}{P_{norm}}\right|_{t_{observation}} \tag{2}$$

where P_{act} is the actual amount of quality (appropriate) product after completion of the production procedure, P_{norm} is the normalized (expected) quantity of product at the end of the production process.

In determining the two variables that appear in this equation the machine level quantities should be acquired and mapped to the production level, whereby it is necessary to take into account the connection between the machines. For the assumed model structure the OTE calculation formula can be written.

Serial connection of machines

In the calculation of this type of structure we assume that the machines are rigidly connected, so the slowest machine dictates the operation of the entire line. The basic equation is adapted and taking into account the structure of the OEE metric we obtain

$$\begin{aligned} &OTE_{ser} \\ &= \frac{1}{\min\limits_{i=1,2,\ldots,n}\{R_{th(i)}\}} \min\left\{\min_{i=1,2,\ldots,n-1}\left\{OEE_{(i)}\right.\right. \\ &\qquad \left.\left.\times R_{th(i)} \times \prod_{j=i+1}^{n} Q_{eff(j)}\right\}, OEE_{(n)} \times R_{th(n)}\right\} \end{aligned} \tag{3}$$

where $Q_{eff(i)}$ is quality component for machine i (quality efficiency); $R_{th(i)}$ is a capacity component for the machine i (theoretical processing rate), $OEE_{(i)}$ is the OEE for machine i, and n is the number of machines in the chain.

The equation can be illustrated with the following example (Muthiah and Huang 2007): suppose that the line consists of machine A and machine B, processing begins on machine A, and is continued on machine B. So the amount of good product of the machine B is limited to that of machine A. If the performance of machine B is not limited by the quantity of product from the machine A, then the quantity of product from the machine B, and thus of the entire line is dependent on the efficiency of the machine B. Otherwise, the amount of good product is limited by the efficiency of machine A and machine B quality factor.

Similarly the formulas for parallel connection of machines and assembly/distribution connection of machines can be derived.

OTE metric restrictions

Weaknesses of the metric for serial connection of machines originates from the assumption that the connection is rigid, so a fixed line structure is assumed. Not every serial link between the machines is rigid, and in such cases the stoppage of certain machines does not block the entire production. Other machines can continue working and generating in-process inventory.

Another type of the disadvantages of the OTE is that it does not have explicit components and only the overall efficiency of the production process is evaluated. It does not give information on whether the source of the problem is the machine operation or there is a problem at the level of machines coordination. As a result of this it is not possible to determine the reasons for the loss at the level of the entire production process.

The latter disadvantage is partially eliminated by some of the other metrics, which can be found in the literature, such as OLE - Overall Line Effectiveness and OEEML - Overall Equipment Effectiveness of a Manufacturing Line (Mathur et al. 2011).

4. Efficiency monitoring case study

Presented methods of determining the efficiency of production represent a static model of technological efficiency. Such a model is useful for the evaluation and analysis of specific situations in the manufacturing process, but it is not useful for control in terms of an integrated production management. The prediction of the indicators is needed, which can be used for making decision on the management measures.

In the discrete production there is often a strong dependence of the reachable production speed on the type of product. Knowing the structure of already dispatched work orders, the planned schedule can be considered as a model of future conditions in production. Inputs to this model are: production plan, production procedures, production resources, production times and other parameters, the model outputs are sequences and durations of tasks. Prediction of certain performance indicators can be obtained through the proper evaluation of a given schedule.

4.1. Production line performance modelling

As a practical example the presented approach was tested within a demonstration project in a Slovene company. A building construction panels production line is considered. The panels are produced by gluing the appropriately processed thin plates with a layer of the mineral wool. This way a stripe shape sandwich structure of a fixed width is produced, which is then cut into panels of desired lengths. The basic layout of the line is shown in Figure 2.

In modelling of the production line we start from the assumption of the serial connection among machines that has already been discussed in the presentation of the OTE metric (equation (3)).

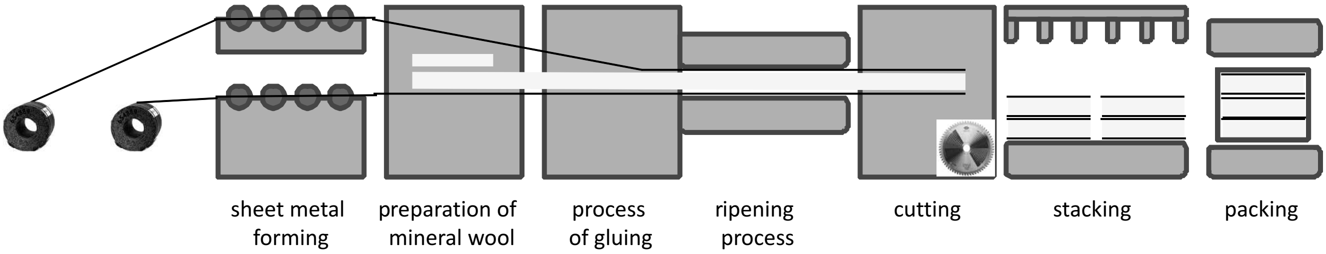

Figure 2: Production line

To better understand equation (3) the equation to calculate OEE for machine i is rewritten by expressing P factor slightly differently, namely as the ratio of the actual (R_{act}) and the theoretical processing rate (R_{th}).

$$OEE_{(i)} = A_{(i)} P_{(i)} Q_{eff(i)} = A_{(i)} \frac{R_{act(i)}}{R_{th(i)}} Q_{eff(i)} \quad (4)$$

It can be seen that the product $OEE_{(i)} R_{th(i)}$ in (3) actually reflects the product of availability factor, the actual performance and quality factor of the machine i. Equation (3) to calculate OTE in the case of serial machine setup can therefore also be written as

$$\begin{aligned} OTE_{ser} = & \left(\min_{i=1,2,\ldots,n} \left\{ R_{th(i)} \right\} \right)^{-1} \cdot \\ & \min \left\{ \min_{i=1,2,\ldots,n-1} \left\{ A_{(i)} \times R_{act(i)} \times Q_{eff(i)} \right.\right. \\ & \left.\left. \times \prod_{j=i+1}^{n} Q_{eff(j)} \right\}, A_{(n)} \times R_{act(n)} \times Q_{eff(n)} \right\} \end{aligned} \quad (5)$$

Next, a new label $Q_{(i..n)}$ is introduced to denote a factor of quality of the rest of the line from the i-th machine (included) to the end of the line:

$$Q_{(i..n)} = \begin{cases} Q_{eff(i)} \times \prod_{j=i+1}^{n} Q_{eff(j)}, & i < n \\ Q_{eff(n)}, & i = n \end{cases} \quad (6)$$

which simplifies Equation (5) into

$$OTE_{ser} = \frac{\min\limits_{i=1,2,\ldots,n} \left\{ A_{(i)} \times R_{act(i)} \times Q_{eff(i..n)} \right\}}{\min\limits_{i=1,2,\ldots,n} \left\{ R_{th(i)} \right\}} \quad (7)$$

In the following we focus on the type of production lines, such as discussed in the context of the decribed project. It is closely related to (rigid) production line with two specific features:

1. Failure of any machine will result in failure of the entire line.
2. Quality is not measured in individual machines, but only at the end of the line.

In calculating OTE, this means that the availability factor $A_{(i)} = A$ is the the same for all of the machines, and the quality factor of the remainder of the line can be replaced by the total quality factor: $Q_{eff(i..n)} = Q_{eff}$. The equation for calculating OTE thus simplifies to

$$OTE_{ser} = A \times \frac{\min\limits_{i=1,2,\ldots,n} \left\{ R_{act(i)} \right\}}{\min\limits_{i=1,2,\ldots,n} \left\{ R_{th(i)} \right\}} \times Q_{eff} \quad (8)$$

We can see that the availability of machines on the line affects the efficiency of the line, but since the loss of any equipment will result in failure of the entire line, we can only discuss the availability of the line as a whole. Availability is therefore important especially in terms of monitoring and analysis, but it is less useful in the on-line production management. The same goes for quality. Although it is an important aspect we can only discuss the quality of the entire line. From the perspective of the individual machines we therefore focus only on performance.

A simplified model describes the performance of the line depending on the performance of machines on the line. If we compare equations (4) and (8), we see that the result is expected. The described derivation actually only shows that OTE of a rigid production line can be seen as OEE of a single machine. But the calculation in accordance to the equation (8) has a significant advantage in terms of operational management of production - because we deal with the capacity of individual machines a detailed analysis of bottlenecks is possible, and in particular we can predict the performance depending on the flow of products through the line.

The key variable that determines performance is the speed of the line. Since we deal with a closely linked production line with no intermediate storage buffers, the capacity is proportional to the line speed.

If the processing rate is observed by the number of produced panels, $R_{(i)} = V_{(i)}/L$, where $V_{(i)}$ is the speed of the line at the point of the i-th machine and L is the length of the panel. Assuming a strip shape of the intermediate product, which is cut to panels of variable lengths, a more appropriate expression of the capacity is based on the produced panel surface. In this case, the performance is expressed as $R_{(i)} = V_{(i)} \cdot D$, where D is the lateral dimension (width) of the strip. In both cases, the ratio of actual and theoretical performance is expressed by the ratio of actual and theoretical speeds, which is in the case of closely linked machines determined by the minimum of the maximum attainable speed for each machine:

$$OTE_{ser} = A \times \frac{\min\limits_{i=1,2,\dots,n} \{V_{act(i)}\}}{\min\limits_{i=1,2,\dots,n} \{V_{max(i)}\}} \times Q_{eff} = A \times \frac{V_{act}(t)}{V_{max}} \times Q_{eff} \tag{9}$$

The theoretical maximum line speed V_{max} is a technological parameter and is constant at the given operating conditions. For short-term forecasting of overall production efficiency changes it is necessary to build a prediction model of the actual line speed $V_{act}(t)$.

Model of the actual line speed is built from submodels of attainable speed for each machine, by considering the dependence of the speed of the product on the machine:

$$V_{act}(t) = \min_{i=1,\dots,n} \{V_{act(i)}(I_{(i)}(t))\} \tag{10}$$

Here V_{act} is the actual achievable line speed, $V_{act(i)}$ is attainable speed for the machine i, $I_{(i)}(t)$ is a set of parameters linked to the product, which is produced at machine i at time t, and n is the number of machines in the line.

Due to flow of products, which have different parameters, the actual speed varies. Its prediction may be based on products that are already on the line and the known schedule of products that will be produced within the prediction horizon.

For easier computation both the products that are already under processing on the line, as well as the planned items for a chosen horizon, are put in a common queue, called stack S. Product is in line until the last technological operation on the line is carried out, then it is removed from the stack. Products in the stack are indexed backwards from the end of the line. The product is presented in accordance with a set of parameters which affect the speed. The first record in the stack $S(1)$ thus represents the parameters of the product at the last machine of the line, $I_{(n)} = S(1)$.

Also for other products in the stack the mapping

$$F : i \mapsto s; \quad i = 1, \dots, n, \quad s = 1, \dots, k \tag{11}$$

can be defined connecting the machine i and the index s of the product in the stack, k is the number of products in the stack. The searched parameters of the product at the machine are obtained as $I_{(i)} = S(F(i))$. Here $F(n) = 1$.

Since the dimensions of the product, as well as other parameters may have an impact on the number of products between the machines, the mapping depends on all the products, which are in the processing between the machine and the end of the line at time t. In addition, the mapping F is time-dependent, because the composition of the product mix between the machines changes.

Specifically, the mapping has to be determined for each specific type of production line. If for example the final products are obtained by cutting the intermediate product stripe into panels, then the relative positions of machines $X_{(i)}$ to the end of the line can be determined. Mapping F is then determined by the sum of lengths of the products in in the stack:

$$L(m) = \sum_{j=1}^{m} L_j \tag{12}$$

$$F(i) = \underset{m}{\arg\min}\ L(m) \quad s.t. L(m) > X_{(i)} \tag{13}$$

At the known product mix in the stack for the selected time t the actually achievable speed of the line at the moment can be calculated as:

$$V_{act}(t) = \min_{i=1,\dots,n} \{V_{act(i)}(S(m))\} \tag{14}$$

Consequently, for a period of planned production, which corresponds to the length of the stack, the prediction of overall production efficiency indicator OTE can be calculated by inserting (14) into (9).

$$OTE_{ser} = A \times \frac{\min\limits_{i=1,\dots,n} \{V_{act(i)}(S(m))\}}{V_{max}} \times Q_{eff} \tag{15}$$

Dependencies of the attainable speed $V_{act}(i)$ on the currently processed item parameters have to be empirically determined for every machine i.

5. IMPLEMENTATION AND RESULTS

To asses the usability of the proposed model the speed dependencies were first identified through the interviews with production operators and critical evaluation of results. An example of the determined dependency for the wool preparation machine is shown in Figure 3. The speed depends on the product type, the thickness and the lateral dimension of the product.

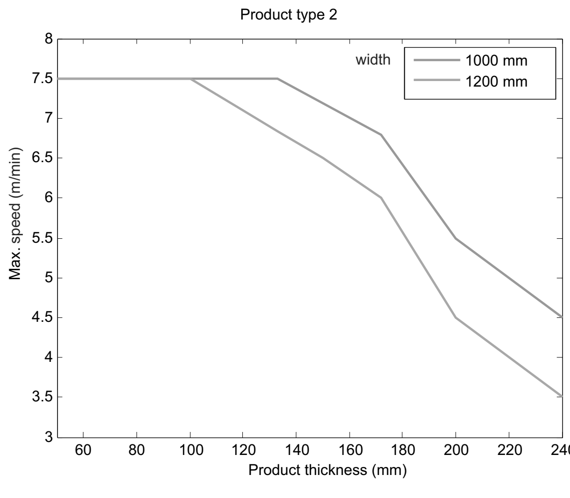

Figure 3: Speed of mineral wool preparation

Next the dependencies were coded into SQL procedures, which collect the data and perform all the necessary calculations. The overall structure of the solution is shown in Figure 4.

The relation of the actual speed to the maximum attainable speed, which is a direct measure of the line performance, is shown through a Web interface. An example

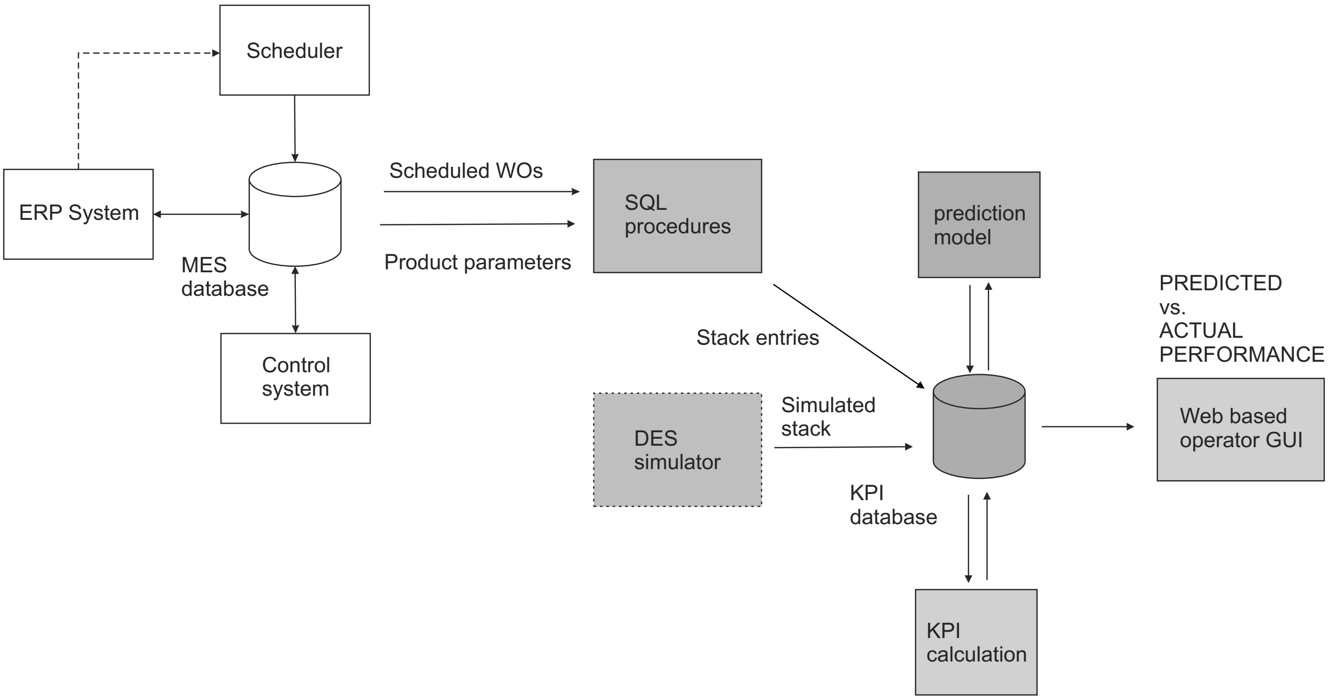

Figure 4: Solution structure

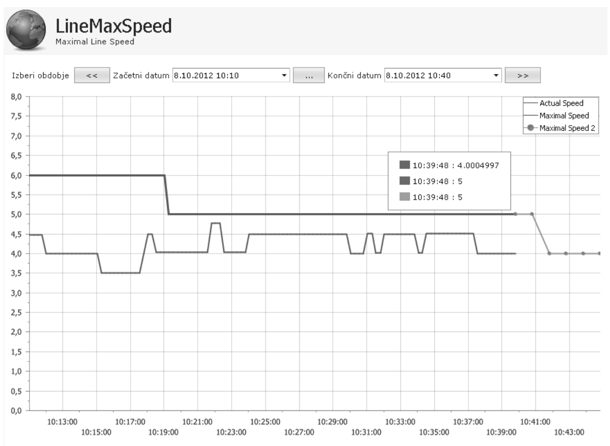

Figure 5: Actual vs. predicted line speed in the operator interface

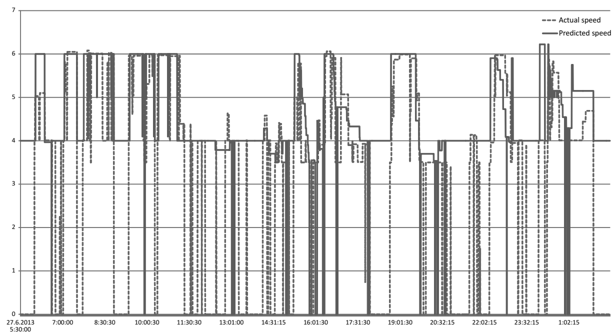

Figure 6: Actual vs. predicted speed for a day of production

is shown in Figure 5, where also a few minute prediction of the expected speed is shown.

The actual and predicted line speeds are archived for analysis purposes. Historical values for a day of production are shown in Figure 6. Note that production started at 6 a.m. while the line was stopped next day at 2 a.m. It can be observed that we have a relatively good matching of the actual and predicted line performance except at downtime. The model can not predict unplanned interruptions, it only predicts temporarily stops when the number of panels at stacking machine exceeds certain threshold. The matching of the two speeds is better shown in Figure 7 where only non-zero speeds are shown.

Its is also interesting to analyze the performance of individual machines on the line, in particular to determine the machine that limits the performance of the line at the given moment, i.e., the bottleneck. This can be analyzed employing the influential variable selection methods that are used in data driven model building. Application of the software tool build to support the Holistic Production Control (HPC) concept (Glavan et al. 2013) results in Figures 8 and 9. Various variable selection methods were used: Linear Correlation, Partial correlation (with forward selection approach), PLS (variable importance in projection – PLS VIP), Non-Negative Garrote, LASSO, DMS search (pareto search of minimum error of linear model as objective function) (Glavan et al. 2013).

It is clear that gluing process represents the bottleneck that dominantly restricts the production speed. Since the gluing process directly affects the quality of the product, operators are prone to further decrease the speed to avoid the quality drop. At the same time the attainable speed model of the gluing process is rather coarse, because no measurements of the glue distribution are available. The

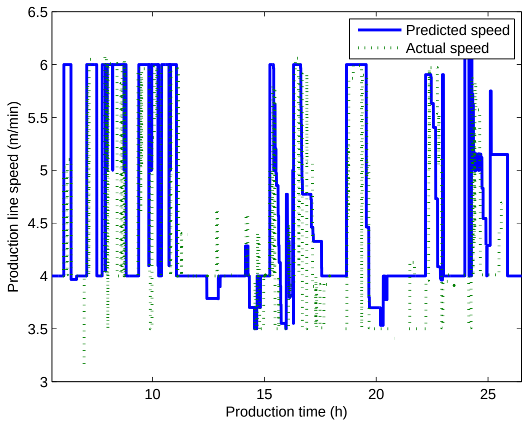

Figure 7: Actual vs. predicted speed without downtime

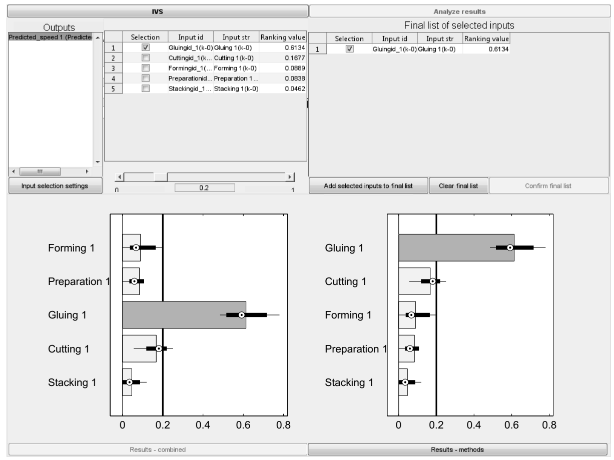

Figure 9: Results of the bottleneck analysis

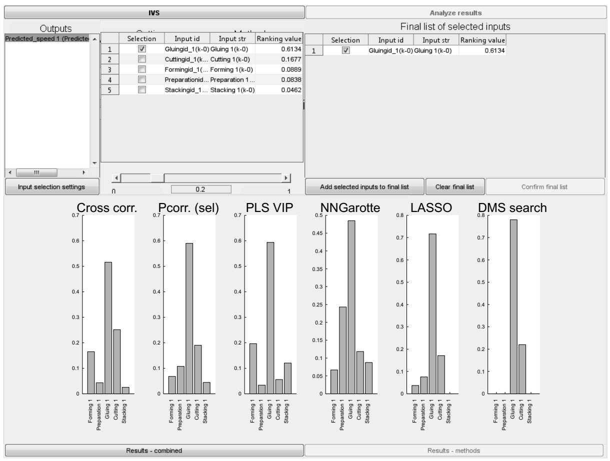

Figure 8: Analysis of the bottleneck by input variable selection methods

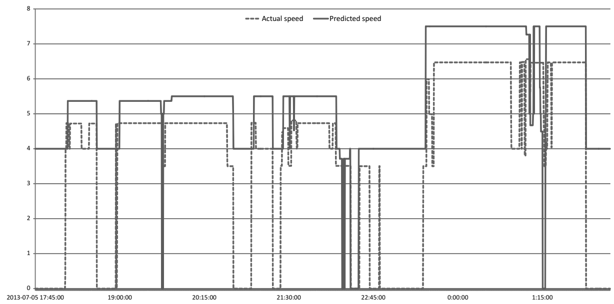

Figure 10: Actual vs. predicted speed with a conservative operator

improvement of the gluing model therefore remains one of the main open challenges.

Another open issue is rising the operator confidence into the model. E.g., Figure 10 shows another part of the speed archive, where the operator obviously followed the model recommendation with a large safety margin. This should be overcome by the gradual improvements of the model and positive operator experience.

6. CONCLUSIONS

The presented results indicate that the derived model can be used to predict the production line performance. The operators can use the prediction to adjust the actual conditions on the line as close as possible to the optimal ones. This is particularly important for new operators, which can faster gain the necessary experience. Nevertheless, the analysis of history logs show that also experienced operators often drive the line at a lower speed, which decreases the line performance. The main reason is the potential drop of quality if the product moves through gluing machine too fast. This way the obtained information from the prediction model can be used to improve the production operation and manufacturing execution performance while maintaining product quality. The decision-supporting functionality can be even increased by implementing a link to discrete-event simulator, which is one of the issues for the future work.

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