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TRENDS IN DATA PROCESSING CONTROL IN CONTINUOUS PRODUCTION SYSTEMS

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Purpose: This paper presents application solutions related to the use of Fourth Industrial Revolution technologies in industry. The aim of the paper is including in a discussion about new trends in the development of information systems supporting monitoring, control and diagnostics of production processes. The objective was realised using the example of continuous production in steelworks.
Design/methodology/approach: The aim of the paper was realized in theoretical and practical part of the paper. The empirical part of the was the form of a case study – approach to mathematical model for predicting the enthalpy of foundry ladles.
Findings: The conclusion is simply: each industrial branch has to use own transformation path towards Industry 4.0.
Practical implications: Prepared approaches - based on analysis of trends in data processing control system in the continues production - can be used to build algorithm of predictive model in its system.
Research limitations/implications: The authors are aware of the limitations resulting from the excessive generality of the model, but they ensure that they will continue research on the implementation of Industry 4.0 technology in the metallurgical (metal) industry, with particular emphasis on the continuous course of manufacturing processes.
Originality/value: The value of the paper are prepared approaches to mathematical model for predicting the enthalpy of foundry ladles.

Keywords: data, process, control system, continuous production, steelworks, foundry.

Category of the paper: conceptual paper.

1. Introduction

The Fourth Industrial Revolution has led to improvements in computer systems for process control. The concept of 'Industry 4.0' signifies a new approach to manufacturing, henceforth supported by intelligent information systems in the area of planning, monitoring and control of technological and manufacturing processes and decision-making at strategic, tactical and operational levels. The beginning of the ongoing changes is digitization, on the basis of which new smart technologies are built (Kagermann, 2015). Modern industry is based on the integration, coordination and cooperation of autonomous machines, robots and different classes and generations of transactional and analytical systems (Kamiński, 2018). According to Skobelev and Borovik (2017) there are four key components in Industry 4.0: Cyber-physical Systems (CPS), Internet of Things (IoT), Internet of Services (IoS), and Smart Factory and six major technologies: the Industrial Internet of Things (IIoT) and Cyber-Physical Production System (CPPS), additive production (3D - the printing), Big Data, an artificial intelligence (AI), Collaborative Robots (Co-Bots) and the virtual reality. Smart factories are the integration of technical means of production (machinery, production lines, industrial infrastructure, means of transport) and cyber-physical systems to support operational and management processes, which will achieve full autonomy of control operations, monitoring and control of production through the direct exchange of data and messages between different machines and industrial robots and the application of a new generation of information systems using artificial intelligence solutions. At the heart of factories are cyber-physical systems (CPSs) with process control systems via industrial sensor networks and remote monitoring of these processes via a global digital network. Lee (2015) and Lee et al. (2015) wrote about the architecture of CPSs. Smart factories are the combination of key technologies of Industry 4.0 with information and computer systems, using in control processes with their visualisation and predictive analysis. In cyber-physical system is the continuous detection and localisation of signals from industrial sensor networks. Computer systems not only control processes, but will also support decision-making based on expert knowledge bases, as well as predictive functions (machine learning techniques) (Kamiński, 2018). Nowadays companies use integrated IT systems of the MES (Manufacturing Execution System) class. MES systems have been developed for the purpose of computer support of company processes. Production management systems have been around for almost two decades, so they are no longer something new. They emerged as a natural recognition of the fact that computer technology could be integrated with mechanical engineering to produce more, faster, more efficiently and with higher quality than ever before. MES bridges the gap in-between planning system (such as ERP) and controlling systems (such as sensors, PLCs, SCADA systems) and uses the manufacturing information (such as equipment, resources and orders) to support manufacturing processes (Mantravadi, Møllera, 2019; Mcclellan, 2001). In addition to the MES, companies use: Enterprise Resource Planning

(ERP), Supply Chain Management (SCM), Customer Relationship Management (CRM), Product Lifecycle Management (PLM), Enterprise Asset Management (EAM) or Business Intelligence (BI). All the systems create the Enterprise Information Systems (EIS) (Romero, Vernadat, 2016).

No process, whether manufacturing or service, is perfect. Neither the product nor the service is completely repeatable. This is caused by disturbances, which determine the variability of process parameters and indicators. Process improvement should therefore focus on identifying the causes that cause special disturbances and try to eliminate them or at least reduce their impact. The most common method used to identify disturbances is statistical process control (SPC) based on Shewhart control cards (Szymszal et al., 2016). In addition to statistical control, predictive analytics and learning algorithms are used in Industry 4.0 technologies. Process control takes place in real time. With the development of ICTs, control systems have access to Big Data and cloud computing. Modern control systems cannot operate effectively without IoT. IoT connects things to their virtuality on the Internet. Automatic identification of physical objects on the network is done using RFID technology. With the help of sensors, it is possible to automatically detect the status of a device, read out process parameters in real time, transmit control signals, and exchange messages and cooperate with other devices connected via wireless networks (Vermesan, Friess, 2014; Wortmann, Fluchter, 2015).

In Industry 4.0, process control is transforming from static to dynamic and anticipatory control. Process Control (PC) is a process-oriented method and has the character of active control, as its results are used to identify process disturbances that need to be eliminated. Process control is carried out in real time and its objective is to continuously improve the course of processes and achieve the best results. Modern technologies - process control systems - are highly autonomous, i.e. they are able to control the process without human intervention and make decisions for them (Benotsmane et al., 2018; Ahuett-Garza, Kurfess, 2018).

This paper focuses on trends in the control of production processes in the ongoing industrial transformation towards Industry 4.0 (I 4.0). The paper presents considerations for the development of control systems using the example of continuous production. In many publications, the authors describe control systems for discrete production. A popular benchmark is the automotive industry. In this work, the authors provide a conceptual consideration of continuous process control systems in metallurgical industry (metal industry).

2. Trends in data processing control system in Industry 4.0

In 1909 Henri Fayol, in a book entitled L'exposee des principles generaux d'administration, distinguished 5 basic functions of management by listing: planning, organising, coordinating, leading, controlling. Up to the present day, successive studies and elaborations do not indicate that other functions of organisational management are possible. However, over the course of more than a century, the way in which these functions are carried out in companies has changed significantly, which is primarily linked to the development of civilisation and globalisation. With the progress of mechanisation and later computerisation of manufacturing processes, the ways in which management functions were performed changed. Human beings have been supported by information and computer systems and AI. Computers and AI can make decisions to increase process efficiency and reduce costs. In Industry 4.0, new opportunities for effective management control emerged.

An enterprise's control system is the range of standards, principles, methods and forms of control available at its different organisational levels. When constructing an enterprise's management control model, it is necessary to understand its essence and context based on the models and tools developed by practitioners. By applying these standards, a tailor-made model of control processes can be created for each enterprise. Control systems support the achievement of the enterprise's strategic and operational objectives. The right choice of computer-based control systems will enable efficient collection of process data. Control helps to optimise processes and continuously improve them. Systems use KPIs, or simply comparing set targets with the current result. In industrial transformation we can monitor the processes that are change towards smart manufacturing, observe the production lines, departments, or machines that are benefiting from Industry 4.0 technologies, and guide decision-makers towards Industry 4.0 technologies (Braglia et al., 2022).

Automation and collaborative robots have given manufacturing companies the ability to deliver quality products and services more efficiently while reducing overall operating costs. However, employees still need to interact with automated systems and make the right decisions based on the data generated. Without the right industrial process visualisation system or production process monitoring software, a company may struggle to fully utilise resources. There are a growing number of systems and software platforms on the market, developed by IT companies, with the aim of overcoming standard visualisation and control challenges, so that production processes can be better understood and more easily controlled (Tezel, Koskela, 2009).

In recent years, with the rapid development of smart ('smart') measuring devices that are easily integrated into the network, the amount of data (Big Data) has been growing exponentially. Collecting large amounts of data is relatively easy technically (devices equipped with the ability to make various measurements and with extensive communication functions with other devices and with the user form the Internet of Things). What becomes problematic, however, is the effective use of the collected information and quick and intuitive access to the information that is needed at any given time (Werner, Woltsch, 2018).

In Industry 4.0, efficiently maintaining or scaling operations requires solutions that enable better and more reliable remote monitoring and control of critical process parameters in a secure manner. Manufacturing environments and supply chains can respond more dynamically to changes in demand with the help of edge processing. IIoT-enabled devices, such as sensors and programmable logic controllers (PLCs), improve manufacturing processes when combined with modern monitoring and control software powered by edge devices. This combination enables real-time data to be transformed into actionable insights that result in specific actions with little human interaction. It also opens up the possibility of connecting edge devices to the enterprise and, if necessary, to the cloud. The increased use of IIoT devices in edge computing architectures can introduce security vulnerabilities if not properly secured. The risks associated with software vulnerabilities and system tampering reinforce the need to invest in systems that provide self-monitoring and diagnostics, as well as built-in physical and cyber security. Edge processing platforms are by design and proven to be secure. They can protect data collection and analysis points and enhance the effectiveness of process control programmes (https://www.plantautomation-technology.com/…). Edge computing platforms collect, organise and analyse sensor data and process data on-site in real time, without worrying about latency, connecting critical applications to critical hardware or enabling advanced and remote monitoring and control. Distributed computing automates core processes and helps ensure availability. This enables manufacturers at the local plant or factory level to remotely increase operational efficiency and productivity.

Reis and Gins in their paper (2017) present such trends in data processing: (i) from Univariate, to Multivariate, to High-Dimensional ("Mega-Variate") (ii) from Homogeneous Data Tables to Heterogeneous Datasets, (iii) From Static, to Dynamic, to Non-Stationary, (iv) from Monitoring the Mean, to Dispersion, to Correlation (v) From Unstructured to Structured Process Monitoring.

The exploitation of emerging Industry 4.0 technologies in the pharmaceutical industry de-scribe Ntamo et al (2022) from University of Sheffield. Paper presents integrated digital architecture consisting of an Advanced Process Control system (APC), mechanistic model platform, industrial IoT platform for data analytics and visualisation. using Siemens cloud service called MindSphere. MindSphere is an open operating system and cloud solution for the Industrial Internet of Things, which is used to connect various devices to the cloud and collect data in real time. The combined solution aligns with the concepts of Industry 4.0 by providing a digital twin, cloud integration, sophisticated statistical, as well as hybrid and mechanistic models. The models are in turn, used for soft-sensors, model predictive control and optimisation algorithms to predict and control product Quality Attributes.

The application of the Industry 4.0 concept to the management of production processes requires overcoming several barriers also. A detailed analysis based on the study of secondary data is presented by Ślusarczyk (2018). According to Ślusarczyk survey, the most important challenge to implementing Industry 4.0 is a lack of digital culture and training, lack of support from managers, ambiguous economic advantages from investments in digital technology, cyber-physical security and significant financial investment needs are all major considerations, and the fear of losing control over the company's intellectual property.

Data processing control is a part of company control system. Steel plants are constantly improving computer support and process control systems. Digitalization of the steel industry (Gajdzik, Wolniak, 2021). Digitization has entered the metallurgy gradually, covering subsequent processes. Digital technologies are used, among others, to monitor the operation of devices in selected sections of production, technological maintenance services (MS), control of parameters of the production environment, control of equipment operation, tracking of processes. In the industrial transformation, steel mills invest in smart sensors, compiling IT and communication solutions and CAx systems, combining process technologies into compact structures as part of common OT and IT applications. The actions being taken now will create a cyber-physical steelmaking system in the future. Data from the installation of production lines enable the coordination of the parameters of the entire process of manufacturing steel and steel products. Steel smelting technology (e.g. blast furnace) is automatically controlled by computer and IT systems. Devices in steel mills and rolling mills are equipped with intelligent sensors that provide data on the course of processes in real time and support operators of technological installations in controlling operations. The data concern not only the operating parameters of the equipment and the conditions in which steel production takes place, but also the consumption of raw materials and energy media. Data from devices are transferred to the decision center system, which is the central center for ongoing process monitoring. Each production process has its own decision-making center, and information from individual decision-making centers reaches the central center (Gajdzik, 2021, 2022).

According to Peters (2016, 2017), metallurgical processes are entwined with many IT (computer) systems. Examples include: material planning system (MRP) or its extended version, i.e. ERP, support system (CAx), project management system (Project Management), production planning and scheduling system (APS), document management system (DMS), document exchange (EDI), product documentation management (PDM) and other systems. The IT systems available in the steelworks are constantly being developed and improved. All cooperating systems create an integrated IT and computer environment of the enterprise or capital group to which the steelworks belong.

The latest versions of MRP and ERP systems have an application for predicting problems that may arise at different levels of resource use (Śliwczyński, 2015). Monitoring of stocks using the latest generation of IT and computer systems makes it easier for mills to ensure continuity of deliveries and timeliness of production. SAP class solutions are the multi-process system used in steelworks. The following services are also useful solutions: Google Cloud, Microsoft Azure. Data from machines, installations, facilities and products are collected in the MES (Manufacturing Executing Systems) system. Both MES and ERP build a vertical system of process links. The result of the cooperation of ERP and MES systems is the sharing of information between objects in the implementation of common processes. Data from devices are used to analyze the rationality of resource management and process optimization (Gajdzik, 2022; Torn, Vaneke, 2019).

Current trends in data management in production processes are addressed in the article Raptis, Passarella and Conti (2019), which surveys the recent literature on data management. The paper can help the readers to deeply understand how data management is currently applied in networked industrial environments. For data management in Industry 4.0, the following key areas have been identified for further analysis: industrial data management for dedicated applications, cloud manufacturing, industrial wireless standards, data-driven manufacturing (including machine learning and deep learning), data from IIoT technologies, scheduling and synchronization of multiple factories. With Industry 4.0, the paper focuses on four data properties: data volume, data variety, data traffic and data criticality. The future of the steel industry in the digital transformation can change in next ways (Peters, 2016; Berger, 2015; Neff et al., 2018; Cheng, Westman, 2020; Vernersson et al., 2015):

- machine learning could simplify manufacturing processes while streamlining steelmaking operations,
- virtual reality (VR) could enable virtual operations in plants, allowing for the creation of new business models,
- blockchain could enable tracking of verified materials in purchases, such as recycled steel, steel production in net zero technologies – deep decarbonisation in steel industry,
- smart technologies with machine communication (M2M) in steel supply chains could strengthen the structures of business networks and at the same time increase their flexibility (quick response to market needs, shorter delivery time, customization of steel (metal) products etc.),
- technologies replace the work of people in hard work conditions, workers are operators of metallurgical technologies.

3. Industry 4.0 specifics in data processing control system for continuous production

There is a basic categorization of production control systems according three fundamentally different types of production: discrete, batch and continuous. These control systems differ fundamentally according to the type of production - the key tasks are different for each type. Discrete production is primarily based on work with the identification of a specific product and monitoring its life cycle. A key role in Batch processing is working with batches, from the supply chain to the trade channels to the end consumer. In continuous production, the output is not a specific identifiable product, but a certain volume of produced material. Key to management is maintaining the quality required by customers and ensuring the stability of the production process. This leads to the requirement to store large amounts of production data and then implement advanced tasks from trend analysis, quality analysis to forecasting.

A production organisation in which the technological process is carried out continuously (24/7) requires the development of dedicated control systems. The production area in this case requires multidimensional support and management must be based on reasonable assumptions. A number of quality requirements for manufacturers must be taken into account when designing a management support system. In this process, the product may be the final product, but may also be an input to another process. It is also characterised by irreversibility, which distinguishes this type of manufacturing from the discrete processs. The nature of continuous production requires the system to be flexible. This includes, for example, the scalability of production. Another example is the multiplicity of units of measurement. Raw material may be received in stock in square metres and issued for production in kilos and sold in running metres. The system must support the handling of this aspect (Durlik, 2019).

4. Case study: Steelworks – approach to mathematical model for predicting the enthalpy of foundry ladles

An example of the control system for continuous processes control is a production control system at Liberty Steel Group steelworks located at Ostrava, Czechia (formerly ArcelorMittal). The MES system for the steelworks was designed and put into operation by company R.T.S. cs Ltd (1993-present). It is a comprehensive system consisting of a wide range of modules and components, such as process data collection, dispatch control, technology monitoring, balance calculations, and data transfer to the corporate ERP system. One of the modules is responsible for controlling the operation cycle of foundry ladles. Prior to tapping the foundry ladles are heated to the desired temperature by high-temperature heating. During an operation cycle the foundry ladle goes through the following operating steps: high-temperature heating, tapping, transporting the molten steel, processing in ladle furnace, casting, open air cooling (before tapping or after casting the steel) and cooling below the lid. Ladle state diagram is at Fig. 1. Ideally, after casting the steel, the ladle does not need to be repaired in any way and can be used immediately in the next cycle. When operating foundry ladles the temperature control is crucial in order to avoid undesired cooling-down. If the ladle contains molten metal and the temperature falls below a certain threshold, solidify may occur which can cause damage to the ladle.

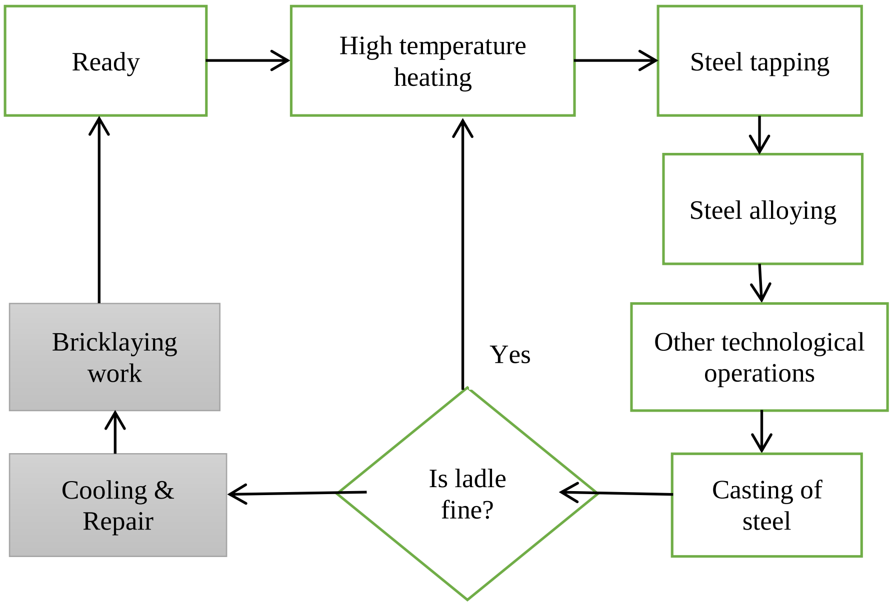

Figure 1. Foundry ladles state diagram.

Source: own elaboration.

Within Industry 4.0, for all of these states of the ladle a mathematical model was constructed to calculate the enthalpy. An enthalpy is a quantity expressing the thermal energy stored in a given material/substance. The automated control system of the steelworks contains partial technological models monitoring the entire operating cycle of foundry ladles, namely the thermal state of the ladle lining. From the analysis of experimental measurements of surface and internal temperatures of the ladle and concurrent measurements of steel temperature during all operation steps with a filled ladle, model constants were created for ladle thermal state assessment. The basis of the enthalpy calculation is the autoregressive analysis of time series. Enthalpy information available to the dispatchers describes temperature conditions in the ladle, allowing optimizing the production sequence. The heating time thus can be set to give the ladle sufficient enthalpy for tapping, and the ladle operation cycle can be optimized so that the ladle heat loss is minimized and at the same time the conditions for operation of alkaline ladle linings are met. The calculation of the ladle enthalpy showed that it is unnecessary to heat the ladle for the whole time while it resides at the high-temperature heating station before the next tapping. To preserve the heat accumulated in the ladle lining it suffices to cover the ladle with a lid as soon as the casting is finished. Using the model calculating and forecasting the foundry ladle thermal state in controlling the high-temperature ladle heating led to the considerable savings of fuel gas.

In order for this calculation to work reliably, the entire control system must be solved as a fault-tolerant. This means it is resilient to any outages and failures. The key part of a fault-tolerant solution of a system that works with data in the form of time series is the continuity of operation of the database system. A database mirroring technology was used in the described steelworks control system (Danel et al., 2016).

The predictive part of the model is designed to calculate the estimate enthalpy in the following technological operations, based on the duration of the previous operations. This makes it possible to control the state of the technological process so that there is no danger of unwanted cooling of the ladle. Prevention against the cooling of the foundry ladle at the moment when it contains molten steel to a state where it can solidify and subsequently damage is absolutely essential. In that case, the minimum temperature of the ladle must be maintained by electric heating to avoid solidification, which means huge energy losses.

The enthalpy calculation is started periodically after a certain time and also when the state of the ladle changes, which is indicated by the steelworks information system. The calculated enthalpy is displayed to dispatchers, who can adjust the current cycle accordingly.

In the future, it is expected to expand the model by an optimization function based on a larger number of parameters with the aim not only to prevent damage to the ladle but also to optimize (to a minimum) the consumption of electricity.

5. Conclusion

Technological changes in steelworks are necessary for the European steel industry to compete with the cheap steel industry from Asia (Industry-Report, European Commission, 2018). The modern digitization of industry is a set of opportunities to improve business processes by creating efficient interfaces and data exchange, as well as by IT systems for process management and support (Branca et al., 2020; Bogner et al., 2016, Vernersson et al., 2015). Modern production equipment with a wide range of wireless controllers participate in streamlining processes. Computer systems enhance the efficiency of technology (Pichlak, 2020; Kiel et al., 2017). In the conditions of the Fourth Industrial Revolution, steelworks in industrial processes are increasingly using the Industrial Internet of Things (IIoT) and the latest generation of IC technologies. The digital technologies used enable the integration of processes in steel mills and value chains, from procurement through production and sales to reverse logistics. The introduced changes are aimed at creating the architecture of Cyber-Physical Steel Production Systems (CPSPSs).

In the steel industry, digitization combines technologies in production processes, focusing on advanced prediction models. Steel is produced in a continuous process, the specificity of which must be reflected in the designed models. The metallurgy is gradually implementing mathematical models to control processes.

The prepared discussion about the areas can support steelworks in the design of process control systems, which are continuous processes. The market still lacks publications on modeling continuous production as opposed to discrete production.

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