特集記事・13
鉄鋼業におけるAI・IoT技術の最前線

Optimizing Steel Production by Digital Means with Examples for Process and Quality Optimization

デジタル手法を用いた鉄鋼生産のプロセス及び品質の最適化事例について

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Abstract:

Intelligent combination of process automation, information technology, and connectivity enables the digitalization of steel production that goes far beyond conventional automation of industrial production. Several initiatives enabling the fourth industrial revolution have been implemented all around the world. Smart sensor technology combined with advanced digital models as well as quality and production planning and control systems provide huge potentials along the entire production chain. The result is quality improvement and production cost reduction together with process flexibility.

This paper is drafting a vision of the intelligent steel production of the future as well as showing a stepwise approach to reach this ambitious target inspired by the experience of more than 2,000 successful automation projects executed in the metals industry.

要旨

鉄鋼生産において、生産工程の自動化、情報技術、コネクティビティを高度に組わせることで、従来の工業生産の自動化を遥かに超えるデジタル化が可能である。世界中で第4次産業革命ともいえるデジタリゼーションの取り組みが行われているなか、高度デジタルモデル、品質、生産計画および制御と組み合わせたスマートセンサー技術は、製造の柔軟性を維持しつつ、品質向上と生産コスト低減を実現できる可能性を秘めている。

本稿では、金属産業で実施された2,000を超える自動化の成功経験を踏まえて、将来のインテリジェント鉄鋼生産のビジョンを描くとともに、それに向けての段階的アプローチを示す。

1 Introduction

The technological developments of the recent years in the areas of communication technologies and IT, both hardware and software, allow handling a complexity at formerly impossible extent. The production process of steel is a very complex process, and therefore, the application of new technologies in the field of steel production is already supporting and can further support to optimize the entire production chain including the integration of business processes along the life-cycle of production facilities. Initiatives supporting the digitalization of industries have been started around the globe. Industrial IoT[1] in the US, Industrie 4.0[2] in Germany or Chinese “Made in China 2025”[3] are some well-known initiatives reflecting the digital transformation in industry. Although these concepts are slightly different, they have one thing in common: The concepts are generic and need to be specified and applied in a more specific way in the different industries.

In the following, a way how these concepts can be applied in the steel industry is drafted and examples for the optimization of a production process of a single production unit as well as the optimization of the product quality along the entire production chain are given[4).

The central question is, what is the steel industry expecting from the digitalization?

One example may go into the direction of just-in-time production. Selling of the final product will take place via Internet, may be even via Trading-Platforms not operated by the steel producer. To be competitive in such an environment, it is necessary that a wide range of products can be produced in small batch sizes with minimal lead time. To achieve this goal, flexibility of the production chain is crucial.

The pressure on product prices and production cost will stay as high as it is or will even increase. This requires, that all possibilities to reduce production costs, productivity and product quality have to be exploited.

As shown in Fig.1, the digitalization of steel production can be seen as the consequent application of new digital technologies to fulfil steel producers' requirements. The focus topics in all cases are quality, flexibility and productivity[5).

Quality is conformance with requirement, allowing steel producers to achieve product quality with narrow tolerance bands, a high degree of reproducibility and seamless documentation of the produced quality in each production step.

Flexibility means flexibility of production facilities and routes to produce a wide range of different steel grades and products in very small batch sizes. Flexibility can also mean flexibility in used raw materials.

Productivity is reflected through its KPI's like throughput, yield, plant availability, operation and maintenance costs as some examples. Although all three aspects, quality, flexibility and productivity, are of importance for every steel producer, the focus needs to be balanced depending on the business strategy of the individual steel producer.

Today steel production is already automated to a certain extent, however, often the systems in place work in an isolated way or with limited interfaces to other systems. One of the major challenges in digitalization is the integration of all systems and productions units. This integration of systems takes place in three different dimensions and will be further described in the following paragraphs:

- Vertical Integration - Integration of systems across the classic automation levels from the sensor to the ERP system towards a fully-automated plant
- Horizontal Integration - Integration of systems along the entire production chain and beyond
- Life-cycle integration – Data integration along the entire life-cycle of a plant from basic engineering to decommissioning

2 Vertical integration – The fully-automated plant

For each production facility it needs a comprehensive automation considering all aspects as shown in Fig.2. The consequent integration of these systems enables a

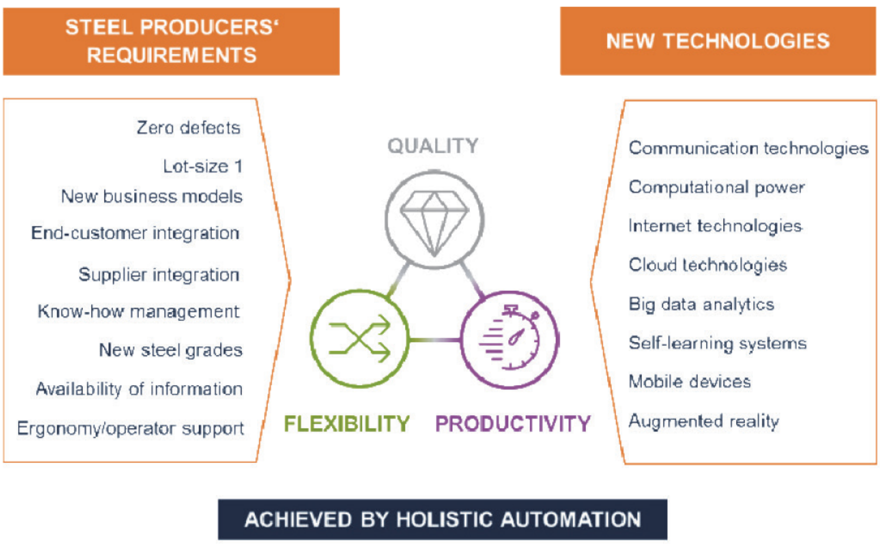

Fig.1 Application of new technologies to fulfill steel producers requirements

maximum degree of automation to achive the target of a fully-automated plant.

The goals of vertical integration are:

- Perfect mastery of the local production process
- Networking of data from the sensor to the planning level as the basis for data analysis, model optimization and, in future, use of artificial intelligence
- Adaptive systems that optimize themselves to the current plant status
- Flexible response to disturbances or changes
- Robot and assistance systems to relieve control personnel by increasing the degree of automation
- Automated diagnostics
- Modern intuitive HMI for efficient operation and decision-making support

The core elements of the digitalized plant as shown in Fig.2 are:

(Smart) Sensors: Sensors provide essential information about the process or the entire plant. They either directly measure physical values or use existing measurements to indirectly calculate additional information. This information is the enabler for the implementation of advanced automatic functions, process models as well as condition monitoring.

Automatic functions: Repetitive, labour - intensive and dangerous work is supported by fully-automated mechatronics solutions, robots and assistant systems.

Cyber-physical systems: Cyber-Physical Systems are the tight integration of the real world with a digital model – the digital twin. A digital twin can cover several aspects like modelling the physical plant, the production process or the produced material. The models can not only be used online for the process optimization, but can be used for offline-simulation to develop new production strategies and can also be used for the design of the equipment.

Condition Monitoring: Comprehensive information about the condition of the equipment and the respective processes enables predictive maintenance, which will help to avoid unplanned outages.

Smart work: To ensure best possible operation and maintenance of a plant, a vast variety of information sources is required. The concept of "smart work" is, that all personnel will automatically receive exactly the information needed at the time to get their job done.

Connectivity: Advanced communication technologies allow for information to be transported beyond conventional limitations. From the collection of sensor data in harsh environments to displaying the information on mobile devices. From the shop floor to the "manager's pocket".

2.1 The Continuous Casting Model Suite – The caster as a cyber-physical system

Model-based process automation control is to link the real plant with the virtual plant (digital twin) in a so called "Cyber-Physical System" [6,7]. This is done by modelling and simulation of the casting process, the material properties and the spray nozzles in the cooling zone. The models are

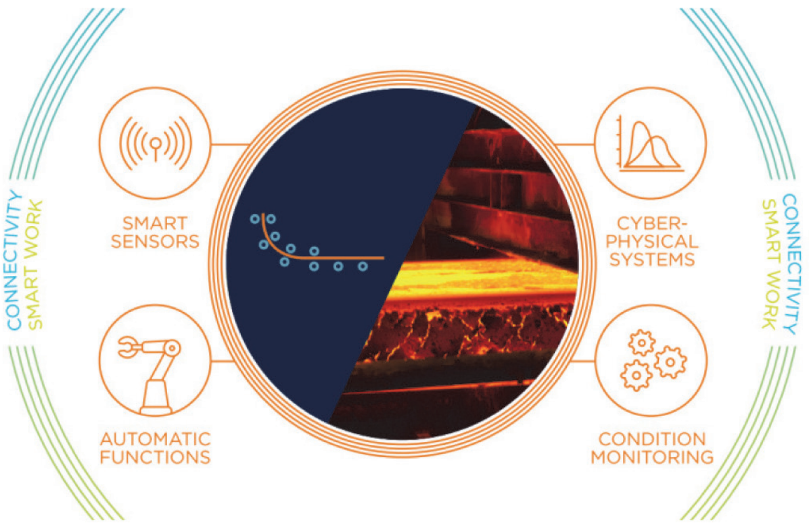

Fig.2 Core elements of a digitalized, automated plant

not only used online for the optimization of the casting process, but can be used for offline-simulation to develop new cooling strategies and the models are also used for the design of the casting machine and for condition monitoring.

Primetals Technologies has developed a set of models considering all aspects of the solidification process and put them together in the *Continuous Casting Model Suite* (Fig.3).

Model suite setup

The Model Suite considers all relevant machine data as well as the spray distribution of the used nozzles which are measured at the nozzle test stand. Considering the spray distribution of a single nozzle and the geometry of the entire spray bar the spray distribution of an entire nozzle row is derived and used to set up the Dynacs 3D model.

DynaPhase – calculation of material properties

In order to calculate a 3-dimensional temperature profile of the strand material properties like enthalpy, solid fraction, density and conductivity as a function of the temperature have to be known.

Traditionally the steel grades are grouped and a typical chemical analysis for this group is used to determine the material properties. With DynaPhase the material properties are calculated online, derived from the actual steel analysis.

Calculations show that there can be a difference in the point of final solidification of half a meter or even more by comparing the results of the actual steel analysis versus the grade group analysis.

Moreover, DynaPhase indicates whether the current analysis of the steel is peritectic or not and alerts the operator in the event of an unexpected peritectic grade. This can reduce the risk of breakouts and improves quality.

Using offline simulations of DynaPhase together with Dynacs 3D allows metallurgical development of new steel grades.

Dynacs 3D – secondary cooling system

Former two-dimensional temperature model calculations of the strand center were largely neglecting strand corners. Continuous improvements in computer performance have made it possible to calculate the temperature at any point within the entire strand in real time, in a full three-dimensional mode and in a sufficiently fine discretization yielding very detailed temperature profiles as can be seen for strand surface and strand center in Fig.4 and Fig.5.

Dynacs 3D accurately assesses the heat transfer from the slab surface resulting from radiation, heat transfer to the rolls, natural convection and spray water (both both spray cooling and air-mist cooling).It takes into account the spray-distribution pattern of the nozzles and the actual spray water temperature. This ensures an accurate spray-cooling heat transfer prediction to temperatures below 700°C when the Leidenfrost phenomena disappears.

Based on the precise temperature calculations the Dynacs 3D model allows specifying the desired surface temperature not only along the strand length, but also across the strand width. Even individual control of the water flow and positioning of each cooling nozzle is possible. The control algorithms of Dynacs 3D calculate the water-flow set-points to achieve the target strand-surface temperature values.

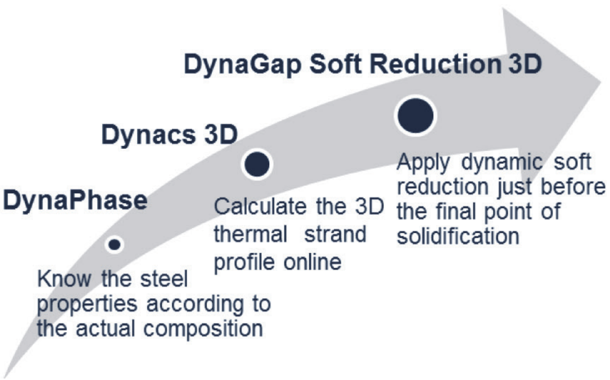

Fig.3　The Continuous Casting Model Suite

Fig.4　Calculated temperature profile of strand surface (top and side view, true colors)

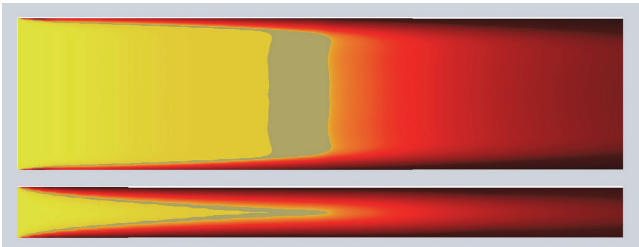

Fig.5　Calculated temperature of strand cross section(center view, enhanced colors indicating the mushy zone)

The results of the Dynacs 3D model are a necessary input for the DynaGap soft reduction system optimizing the inner quality of the casted strand.

DynaGap Soft Reduction

This package is based on the combination of Smart Segments and Dynacs 3D thermal tracking module. It dynamically adjusts the roll-gap profile even in transient casting conditions.

- Dynamic adjustment of the roll-gap profile for the entire strand (depending on mechanical segment setup)
- Flexibility to cast any thickness within the design range
- Optimized roll engagement for machine protection
- Improved internal quality thanks to minimized center segregation, especially for pipe and plate grades

The Continuous Casting Model Suite is one example, where digitalization can support the optimization of the production process of one single production facility. In the next chapter the focus will be on the optimization of the production process across the individual production steps.

3 Horizontal integration – The Digital Unity

Horizontal integration means integration of systems along the production chain to orchestrate the individual production steps. This is carried out by three systems (Production Management System - PMS, Through-Process Optimization - TPO and Maintenance and Asset Technology – MAT). As these systems which are partly available and in operation already, are strongly interacting in future, to further optimize production in a holistic manner, We have introduced the term Digital Unity for the combination of these systems (Fig.6).

The objectives of the horizontal integration are:

- Perfect control and optimization of the entire process chain (“through-process”)
- Expert systems for management of through-process know-how
- Integration throughout the entire value chain, also cross locations and industry wide
- Modern intuitive HMI to support humans in decision-making within the production process

3.1 Production Management System

The production management system (PMS) covers the metals production process from iron and steel making, rolling till shipping of the final product.

Following the process, at first, it has to be evaluated, if and how a product can be produced with the available plant equipment. Therefore the “Product Design” requires extensive through process know-how and is in turn again the basis for Through Process Optimization during the actual production:

- Rules need to be defined that allow a dynamic translation of customer orders to production instructions including their processing route until shipment of the ordered product.
- Technological target data for intermediate products are defined
- Definition of quality targets and quality envelopes
- Testing and sampling instructions to meet standards and customer requirements

Product specific information is combined with machine data and constraints and logistics information to compile all production relevant master data into a central repository. This approach allows to dynamically follow a strategy of increased individualized customer products and allows ad-hoc statements on the feasibility to produce a required product.

The planning system has the ability to produce an order according the current utilization taking into account machine capacities and throughputs, planned maintenance and/or reduced machine capabilities. Both aspects – the general feasibility to produce and the available capacity to fulfil required customer due dates – need to be available in real-time and de-central, to allow the sales department to act immediately.

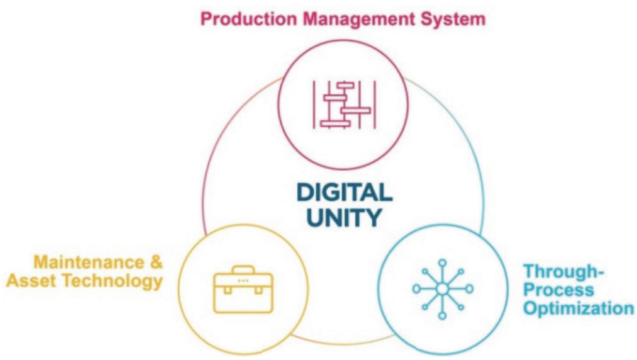

Fig.6 The Digital Unity

3.2 Maintenance and Asset Technology - Computerized Maintenance Management

Maintenance Asset Technology (MAT) is a know-how system supporting management and execution of maintenance in an entirely new way. Based on the defined maintenance strategy for each asset and the condition information it creates actionable items for the maintenance team and guides through the entire maintenance process to increase the efficiency of maintenance efforts.

Advanced analytics can be used to gain further insight into the ongoing maintenance activities. Planned production, driving upcoming machine utilization and type of products planned for production are considered when predicting machine's future condition. MAT is the basis for the optimized, holistic planning of the maintenance actions and maintenance shut-downs. The maintenance plan and the production plan are harmonized between the MAT and the PMS in a holistic way in order to realize the overall benefits described in the section aims above.

3.3 Through-Process Optimization

Through Process Optimization (TPO) is an integrated know-how based concept developed by us to improve efficiency and quality across all plants of a steel producer[7]. The digital platform of TPO is the Through-Process Quality Control (TPQC) system, which stores the expert know-how in terms of quality rules that are applied to all the gathered high resolution process data recorded across the entire production chain.

The main parts of TPO comprise Through-Process Know How (TPKH) and Through-Process Quality Control (TPQC). The main features are shown in Fig.7.

The essential functionality of TPQC is to ensure desired product properties and increase quality levels by monitoring all quality-relevant process parameters along the full production route and the genealogy information interconnecting this data across all involved processing unit. I.e., the genealogy keeps track about elongation factors, head/tail changes, upside/down-changes as well as cutting and welding operations between different processing units of the production chain (Fig.8).

Quality conformance checks are carried out by means of a specific rule system on the production data and the results will be shown to operators and quality engineers, respectively. The rule system of TPQC is also an important pillar for Through-Process Know-How described above.

In case of deviations or non-conformities, TPQC provides a semi-automatic approach to identify the root-cause[8]:

1. In case of a detected deviation, a list of highly probable root-causes is shown to the operators or quality engineers.
2. Each root-cause comes with a specific description for root-cause verification, in order to eventually remove any doubt in cases in which more than just one root-cause might be possible.
3. After identification of the actual root-cause, the responsible person confirms the root-cause for the given

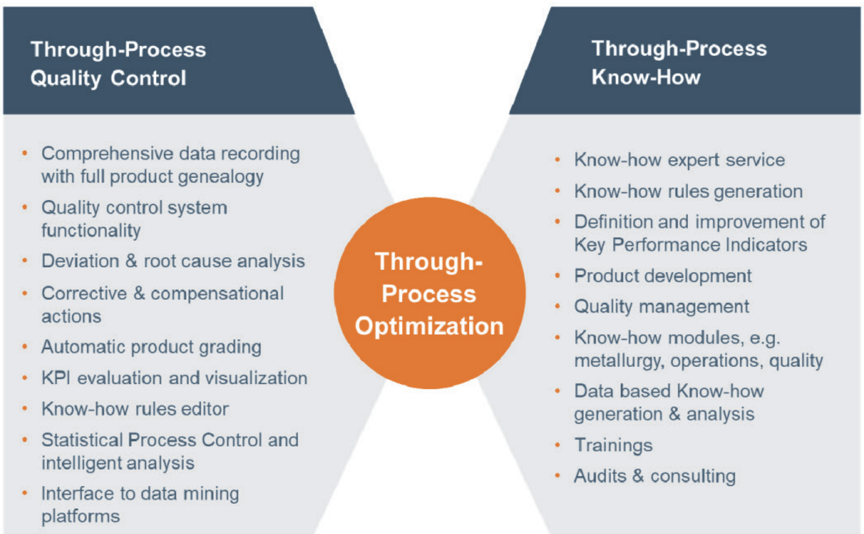

Fig.7 Through-Process Optimization

quality deviation.

4. The system keeps track of the root-causes for any detected quality deviation and calculates a root-cause statistic.

A corrective action can be defined as a set of actions to eliminate the cause of a quality deviation under specific conditions. As it is seldom possible to eliminate the cause of a quality issue permanently the definition of corrective action has to be broadened in so far as a certain corrective action for a given root-cause may eliminate a quality deviation absolutely and permanently only under the specific condition that applied previously, although not all of them can be determined or measured and archived.

A compensational action is defined as an action to repair an already affected semi-finished product as shown in Fig.9.

Thus, TPQC can be used as a pure conformance tool for quality checks and root-cause analysis support, but the real benefit of this system is realized when it is also used as a continual learning tool in order to improve the skill level of operators and quality engineers.

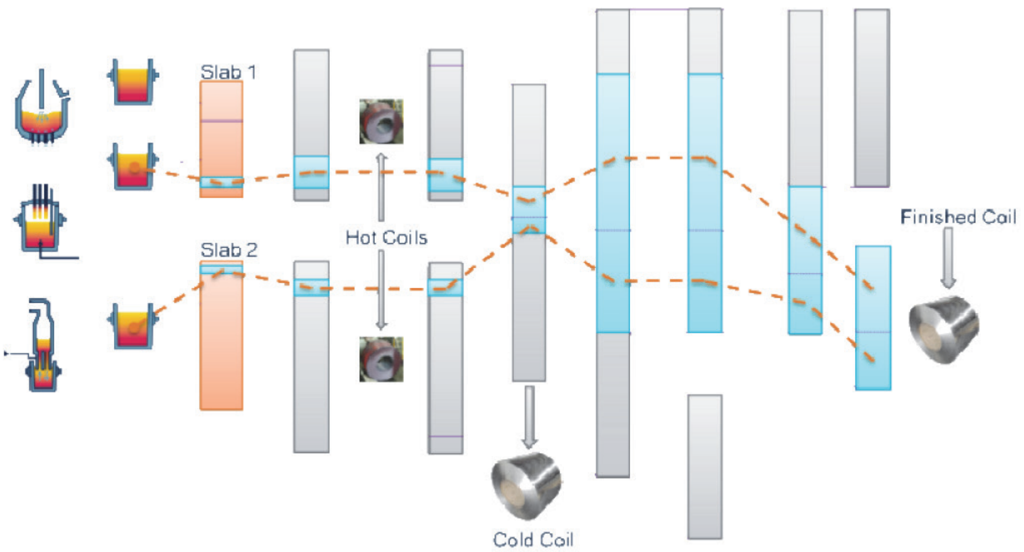

Fig.8 Product genealogy

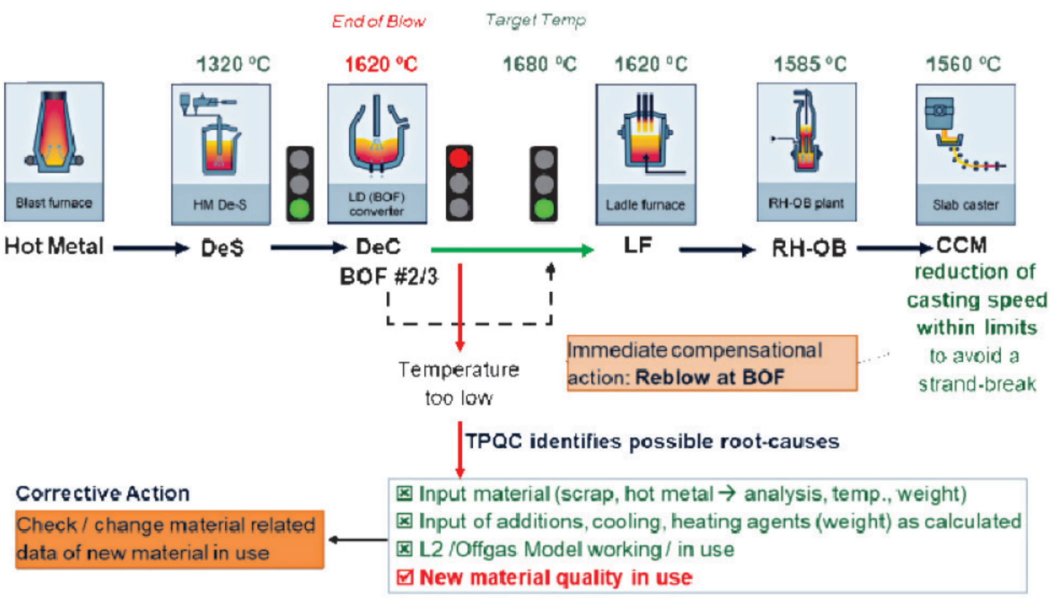

Fig.9 Root-cause analysis and compensational actions

4 Summary

The digitalization of steel production will be achieved by integration of sensors, automation and IT systems in several dimensions. A maximum degree of automation and the local optimization of each production facility can be reached by vertical integration. Smart sensors provide information to implement additional automatic functions and enable cyber-physical systems, which play a major role in vertical integration. Condition monitoring and furthermore condition prediction reduce downtime and support predictive maintenance to reduce maintenance costs.

The optimization along the production chain – the horizontal integration – is carried out by three systems: Production Management, managing and optimizing the production, Through-Process Optimization optimizing the production process and the product quality and finally a Computerized Maintenance Management System supporting all aspects of maintenance. These systems will grow together and interact to further optimize quality, flexibility and productivity.

Along the entire life-cycle of a plant, from engineering to decommissioning, all relevant data about the plant will be made available to operators and maintenance staff in a context-oriented way to support tasks and decisions in the best possible way.

The benefit of digitalization for steel producers is better product quality, more flexibility in production and increased productivity.

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