Optimizing Production Efficiency and Quality With Digitalization

Digital technologies are transforming industry at all levels. Steel has the opportunity to lead all heavy industries as an early adopter of specific digital technologies to improve our sustainability and competitiveness. This column is part of AIST's strategy to become the epicenter for steel's digital transformation, by providing a variety of platforms to showcase and disseminate Industry 4.0 knowledge specific for steel manufacturing, from big-picture concepts to specific processes.

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A key cornerstone for being successful in the steel and metals business is to achieve a highly efficient overall production process, enabling the economical, successful production of high-quality products with high yield at competitive, low costs. This can be pushed to higher levels by digitalization and sufficient know-how. Primetals Technologies has developed a solution for this: through-process optimization (TPO). TPO combines the modern, highly functional digitalization IT system, through-process quality control (TPQC), with the digitalized know-how and experience of domain experts and artificial intelligence (AI) algorithms.

TPO enables metals producers to control and optimize the production and product quality across the entire process chain, enabling real and seamless through-process optimization. By collecting the right data with TPQC out of all automation systems, measurement systems, smart sensors and even from operators, data are transformed into valuable information, key performance indicators (KPIs), decisions, advice and actions, enabling a higher level of production and product quality. So TPO is a digitalization solution for making the next big steps toward a fully automated intelligent digital steel production. This paper explains the cornerstones and main elements of TPO, the background of the development, a view and outlook on the further potential, and gives some examples of successful customer implementation. Additionally, the paper discusses experiences and key success factors for a successful execution of a digitalization project, including cultural aspects.

Digitalization of Operational Know-How

Point of Departure — Steel producers globally face increasing technical and economic challenges. While commodity products are coming under pressure, requirements from customers, for example, on the quality of the surface and on the constancy of mechanical-technological properties of complex steel grades, increase simultaneously in all markets. This leads to narrower process windows and requires a more rapid reaction to process imperfections. At the same time, the number of product variants increases. But even for so-called commodity products, the increasing cost pressure requires a fully optimized through-process production in order to stay competitive with these mass products.

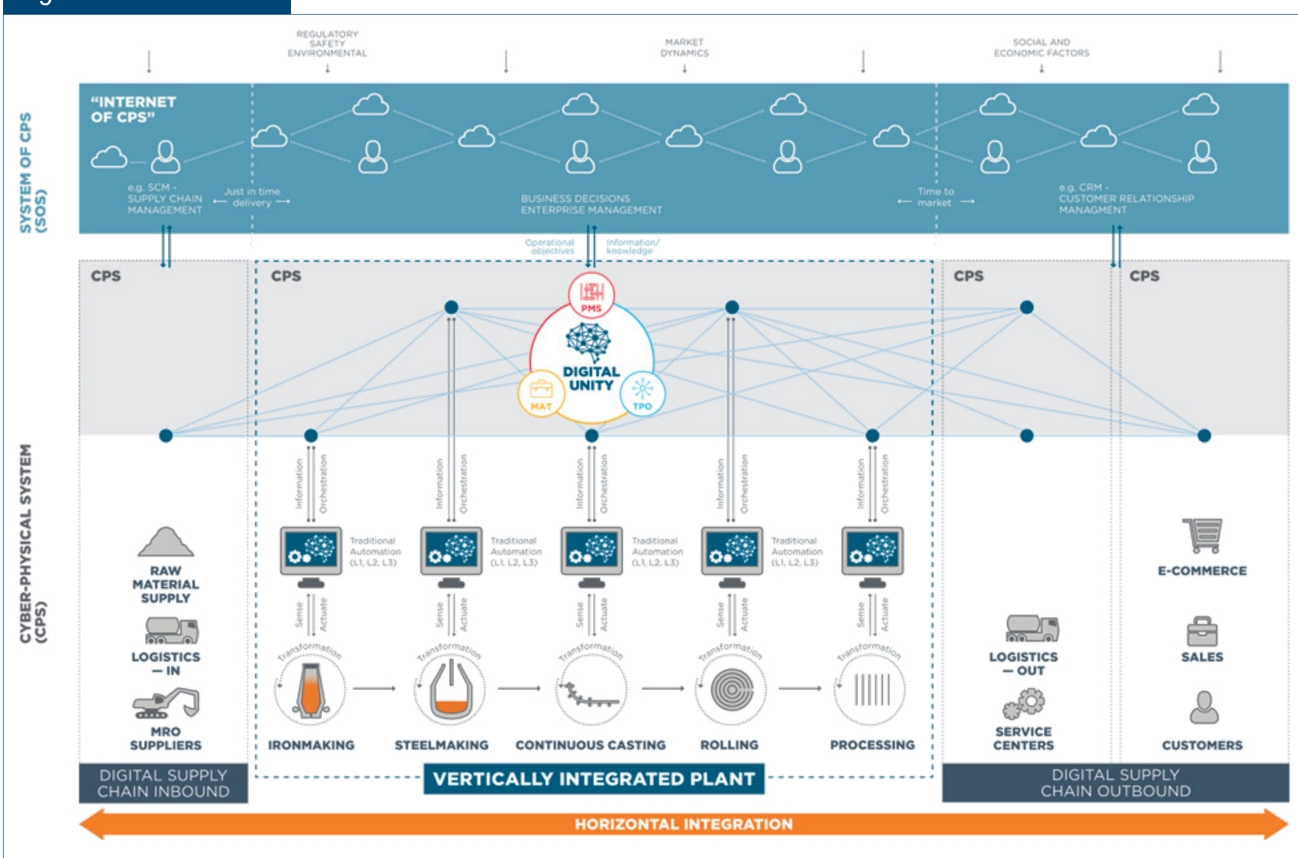
To succeed in such a challenging context, productivity and efficiency must be increased steadily to meet the requirements of customers. Clearly structured management processes form the backbone of successful steel companies and are already widespread, not just in the steel industry. The increased necessity of intelligent digital tools is encouraged by not only productivity and efficiency, but also by the latest releases of quality management standards such as IATF 16949, ISO 9001, etc. These standards demand that the actual process be regarded and additionally require employment with parties interested in the respective companies and emphasize a risk-based approach. This makes the agreement with social and environmental factors even more important and indispensable. Also here, algorithm-based analyzing and evaluating methods[7] begin to play an important role. This increases the complexity of the field of action for companies (Fig. 1). Risks and opportunities are close to each other, and digitalization can be used effectively as a tool to lower uncertainty and to unlock additional value.[10]

IT Systems Start to Map Complete Plants — Over many years, single production units in metals companies were intensively improved and their reliability has been increased. They were upgraded and modernized. Also new production plants and production technologies have been developed, e.g., for the production of new steel grades. Such state-of-the-art plants contain modern mechanical equipment and advanced automation systems, which nowadays integrate the intuitive use of human-machine interfaces (HMIs), new and more powerful control techniques, and modern metallurgical and technological (sub-)process models. Currently, the so-called digital twin, which is an integrated cyber physical model of real-world processes, moves into the focus of attention.[8]

This became possible because, in recent years, the performance of computer power and data storage technology has continued to increase exponentially in accordance with Moor's rule.[1] A weakening of Moor's rule of thumb, although predicted, will be more than offset by recent developments in the area of algorithms, which will make future calculations even more successful.[6] So, for example, physical-based metallurgical models, which had to be executed off-line in the past, can be executed in real time due to the increased processing power of the central processing units (CPUs). The basis for all the capability of models is made not only by the mathematical approach that necessarily represents a simplified image of reality, but by data availability and data quality. Sensors and data acquisition are more or less the digital senses of a cyber physical model and, therefore, determine the level of processing and learning a computer model can achieve. This process is running fast but is still incomplete, as Uhlemann et al.[5] noted: "[…] the application of fully automated techniques […] is not yet common practice. Deficits are to be observed in the course of the use of a fully automated data acquisition of the underlying process data, a key element of Industry 4.0, as well as the evaluation and quantification and analysis of the gathered data."

Therefore and starting from "veracity," one of the "four V's of big data," the authors attach great importance to not only the quality of the data itself, but also on

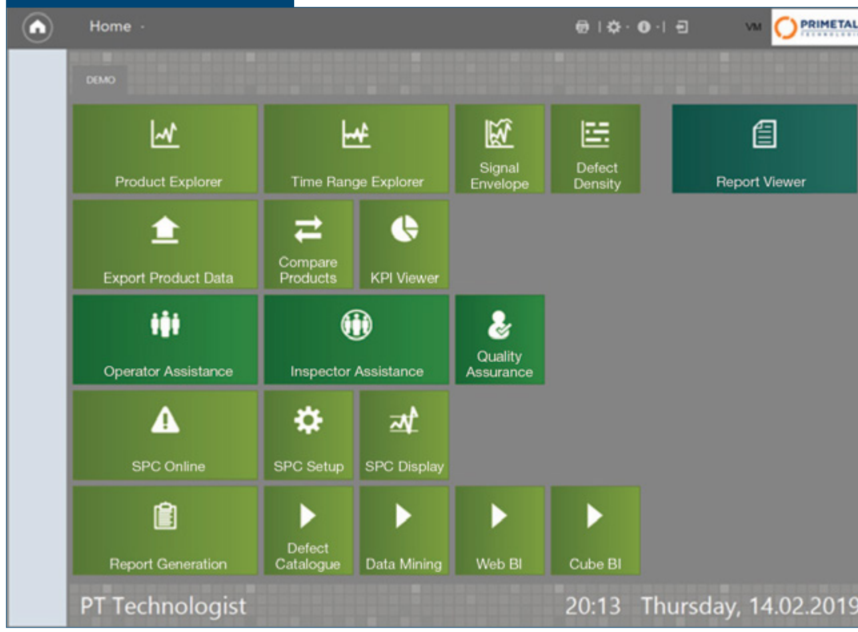
Figure 1



IT systems digitally represent the overall metals business.

increasing the "volume" by means of advanced sensor systems to make data available, which are hardly available today. In a highly digitalized plant, it is crucial to be able to predict end-of-process parameters and to detect and explain process anomalies with an intelligent root-cause analyzing tool. Based on automatic root-cause analysis, compensational actions can be made directly by the IT system to keep productivity at a high level. These IT systems have to combine expert-driven calculation models and data interpretation, which satisfy the necessity of logical correction algorithms of industrial data to avoid misleading predictions.[9] Undoubtedly, optimization of the parts can result in increased efficiency and better quality, but there is no guarantee that it optimizes the whole automatically. Thanks to increased computational power, the combination of formerly standalone simulation models and measured process and product data under the umbrella term "digital twin" has become possible. The combination of models allows a much better prediction of process behavior and product properties resulting thereof.

Figure 2



Screenshot of Primetals Technologies' through-process quality control (TPQC) IT system.

Digitalized Knowledge and Know-How Rules — W.E. Deming said, "There is no substitute for knowledge." In general, one can confirm that knowledge (science) always depends on theory, and information (data) alone is not knowledge. It is necessary to combine a profound physical background with modeling and simulation as well as with data science and, finally, with quality-oriented, practical procedures and recommendations. The result will be digitalized operational know-how and digitalized practical experience, which can be made available in an intelligent way for 24/7 use.

Therefore IT systems (Fig. 2), in which quality- and process-relevant production data from all production units are not only stored but can be combined, processed and evaluated automatically, and where decisions are proposed and actions are triggered, offer great opportunities for improvement. The knowledge-based algorithm that is behind each proposal or action is called a "rule." Rules represent well-proven digital procedures and instructions and represent a central place for operating know-how. A central rule system is, therefore, a core element of a through-process know-how system.

Through-Process Optimization and Digitalization

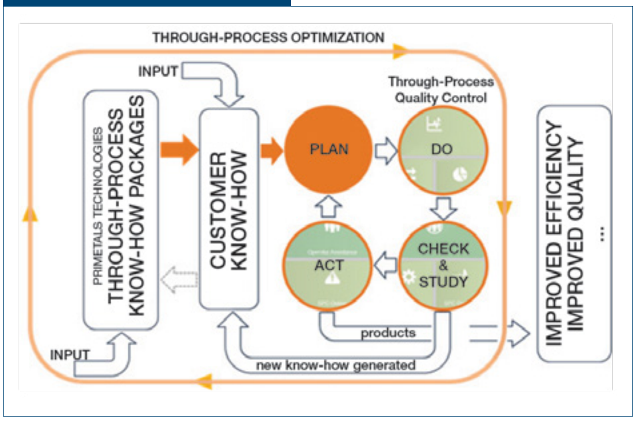
One main lever of efficiency and quality is an optimization process, which covers a total plant comprehensively. One pre-condition for a deep and successful understanding of the interdependence of the different process steps following each other is data acquisition and data interpretation. Well aware of the conclusion "Stored data does not generate business value,"[3] the authors propose a knowledge-based toolbox called through-process optimization, which consists of two main parts:

- A new, intelligent TPQC IT system.
- The through-process know-how (TPKH) packages.

The reason why these two parts were combined is the fact that "the transformation of data into knowledge is by no means an easy task for high-performance large-scale data processing, including exploiting parallelism of current and upcoming computer architectures for data mining. Moreover, these data may involve uncertainty in many different forms."[2]

Digital Genes — Human Brains: The Expert's Role in TPO — Experienced experts in the metals industry are a key factor for successful metals producers. Already today, these specialists are able to highlight, discuss and interpret even the most complex interconnections that are decisive to competitiveness and success. In the future, additional qualifications will be needed to transform human

Figure 3



Through-process optimization and the Plan-Do-Check-Act (PDCA) cycle.

knowledge into computable algorithms and formulas. Human expertise that turns knowledge into useful, permanently available and digitalized know-how is the basis for enabling next-generation intelligent digitalization systems. For the implementation of such IT systems and in order to resolve specific problems, additional support by domain experts can contribute to fast acceptance and payoff.

In exactly this well-balanced combination of modern machinery, high-end computerized data processing, artificial intelligence, and internal and external experts (operators, quality engineers, product development scientists), there the authors look for the reason why a handful of leading steel producers are able to sail nearer the wind.

Expert services and IT solutions have to work closely to the Plan-Do-Check-Act (PDCA) cycle (Fig. 3). While TPO creates something to the effect of a larger outer cycle or of a superordinate optimization process, it is the ease of data access within the IT solution, in combination with human expertise, which enables target-oriented and efficient working. Of course, there can be several optimization cycles running simultaneously or sequentially.

In accordance with QM standards, unusual process or quality deviations or alarms will trigger a so-called root-cause analysis. Following the classical approach, a team of experts will gather information and combine their knowledge in a structured way using methods like 5W or Ishikawa diagrams. These very useful, but more or less still paper-based methods, can be very time-consuming and every team of experts occupied with these tasks will highly appreciate support.

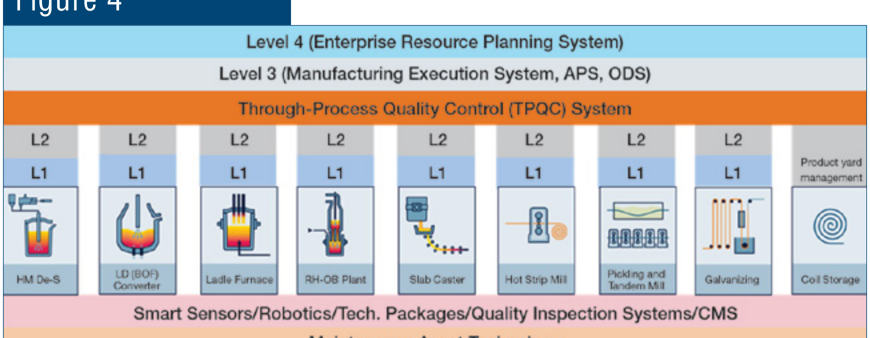
Thanks to comprehensive data and digitalized procedures mapped within TPQC's rule editor, the modern approach allows the system to analyze a situation automatically and to deliver relevant information. The result is a fast, high-quality and highly computerized root-cause analysis, which additionally proposes or even activates model-based corrective or compensational actions to counteract the deviation.

Key Aspects of Implementing Know-How–Based Digitalization Systems — In the case of implementing know-how–based digitalization systems, one has to consider not only technical issues but also cultural and human factors. Digitalization can cause disturbance and unsettledness, especially among the mill experts, quality engineers and technicians, whose roles might change in the sociocultural environment of a production team.

First of all, digitalized systems will increase transparency tremendously and the competition among persons, teams, shifts, etc., becomes obvious. Automatically and permanently updated, real-time KPIs, statistical process controls (SPCs) and other forms of compressed information can raise a human's stress level if this information is used as a human's performance indicator solely. This might lead to a situation of non-usage or of not accepting where people magnify even the smallest shortcomings of a new system. If such a situation occurs, or to which degree it will occur, depends mainly on the quality of working culture and on the personal attitude toward innovation. The supportive mill management's paradigm for digitalization plays a vital role in how well digitalized systems contribute to the success of a company.

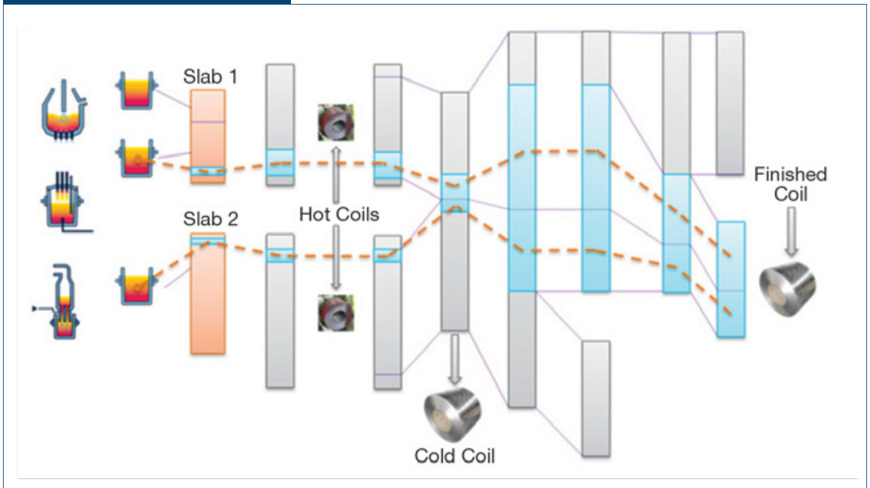
Secondly, the implementation of an intelligent system might, in some cases, create a kind of aloofness or unwillingness among mill experts who fear to render their knowledge to a computerized system because it is regarded as a decrease of the expert's standing within the team. In contradiction, these systems are a personal enrichment because digitalized systems can help experts to be more informed and offer a good

Figure 4



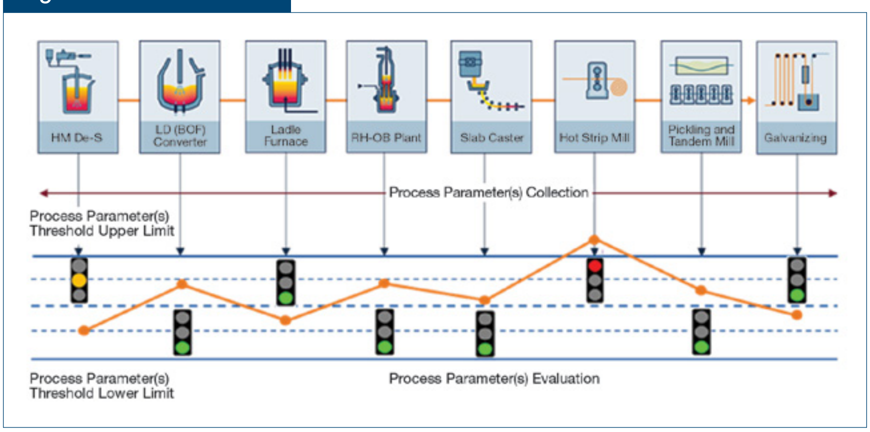
Integration of TPQC with automation and IT systems.

Figure 5



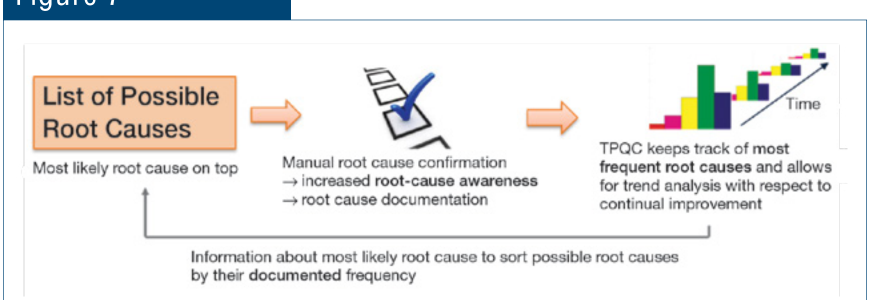
Genealogy-based data tracking across multiple processing units.

Figure 6



Quality control functions along the production route. Red lights will trigger corrective or compensational actions.

Figure 7



Dynamic root-cause analysis support.

chance to increase the probability of making correct decisions. Thus, the role of an expert who transparently leans on reliable data, methods and mathematical algorithms and whose analyses and decisions are highly correct is strengthened.

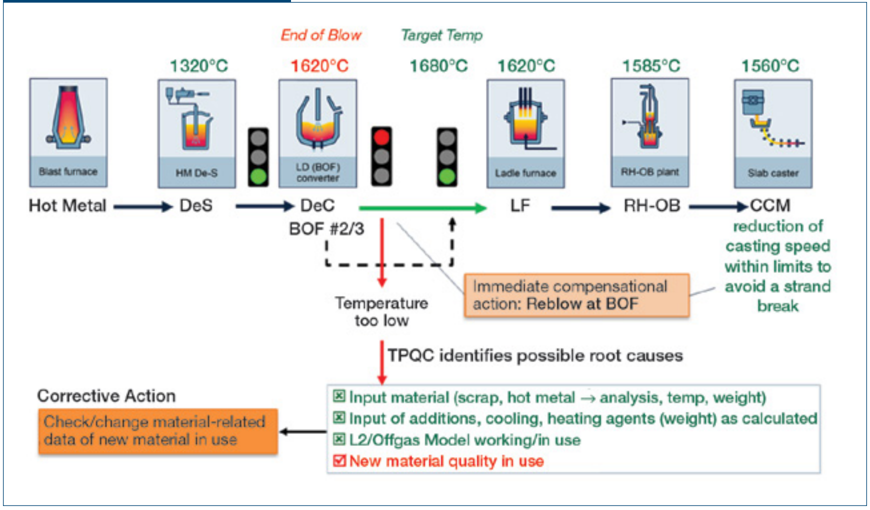
Through-Process Quality Control — Within the system, an information-rich genealogy of each individual processed product[11] makes it possible to retrieve process data of all production steps for every part of the product. This allows users to track quality issues in very little time and analyze them by reviewing process data for all relevant production steps, which is the key for fast troubleshooting and claim management. Fig. 4 shows the TPQC system embedded into the automation and IT environment and can cover the whole process chain (Fig. 5).

The essential functionality is to ensure desired product properties and increase quality levels by monitoring all quality-relevant process parameters along the full production route at defined quality gates. In addition to pure process data, which is collected from various processing units, the genealogy information interconnects this data across all involved processing units, i.e., the genealogy (Fig. 5) keeps track about elongation factors, head/tail changes, upside-down changes as well as cutting and welding operations that are possible between different processing units of the production chain.

Quality Control System Functionality — Quality conformance checks are carried out by means of a specific rule system using production data. The results will be shown to operators and quality engineers, respectively, depending on the kind of quality issue and location in the plant. By means of the rule editor, TPQC offers a flexible method for quality checks, which paves the way for future adaptations and extensions without having to change any part of the system's source code.

Fig. 6 shows the principle of this process/quality checking. A green traffic light indicates all values (of a production unit) are inside the specified bounds. A yellow light expresses the presence of minor problems, requiring some further checks. A red light indicates more serious issues, which in most cases need a more complex remedial action and a final decision plan. What can be defined as minor and major has to be developed from the process experience and must be finally specified as expert rules, again an example of digitalization of know-how.

Figure 8



Root-cause analysis within the meltshop.

Deviation and Root-Cause Analysis —

Root-cause analysis (RCA) is a mandatory, method-based and structured type of problem-solving used to identify the real causes of faults or problems. TPQC provides a dynamic root-cause approach (Fig. 7):

1. In case of a detected deviation, a list of highly probable root causes is shown to the operators or quality engineers, depending on the plant location and organizational responsibility. People who are in charge of deviation management can automatically be informed which possible root causes can be excluded due to non-anomalous measurements.
2. Each root cause comes with a specific description for verification, in order to eventually remove any doubt in cases where more than one root cause might be possible.
3. After identification of the actual root cause, the responsible person places a check mark and thereby confirms the root cause for the given quality deviation.
4. The system keeps track of the root causes for any detected quality deviation and calculates a root-cause statistic.

In addition, a root-cause statistic can be calculated for an arbitrary time period, thereby enabling the calculation of trends over time. Hence, the root-cause statistic feature is a valuable aid to provide convincing evidence on the effectiveness of the quality management with respect to continual improvements. In particular, it is a useful tool for the plant manager, enabling a strict monitoring of deviation frequencies, in order to identify the most frequent and most costly deviations. These identified deviations may then be addressed by additional problem-solving methods and corrective actions.

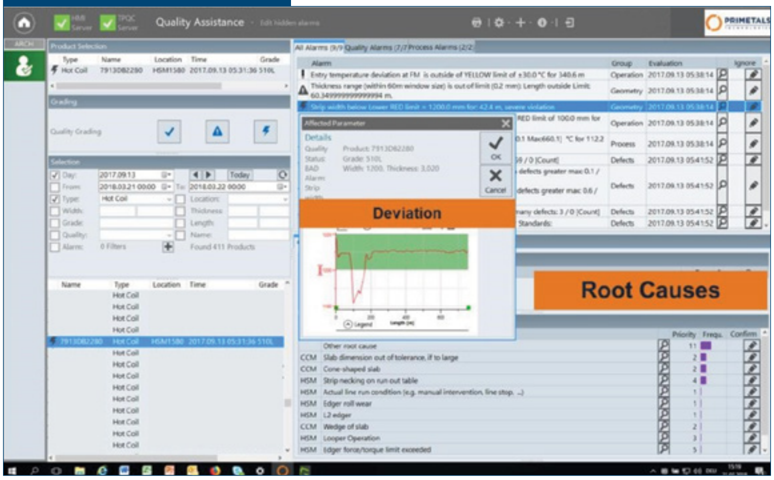
Corrective and Compensational Actions —

A corrective action can be defined as a set of actions to eliminate the cause of a quality deviation under specific conditions. Unfortunately, the production environment is subject to a large number of influences such as any kind of external disturbances, raw material unknowns, as well as the human factor and other non-deterministic events. Hence, it is seldom possible to eliminate the cause of a quality issue permanently. For this reason, the definition of corrective action has to be broadened insofar 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, e.g., by cutting out defective sections from a strip or by means of surface scarfing of a slab, as indicated in Fig. 8, etc. Because of the fact that the system provides guidance to operators and quality engineers, the tool can also be seen as a learning tool in that regard. It is a fact that people who are actively involved in root-cause analysis for some time will become more aware regarding quality-related influences, which allows them to take preventive measures even before a quality-related incident happens, that is without having to wait for root-cause suggestions at any rate and for any incident, respectively.

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. The example in Fig. 8 deals with quality issues in the meltshop.

Figure 9

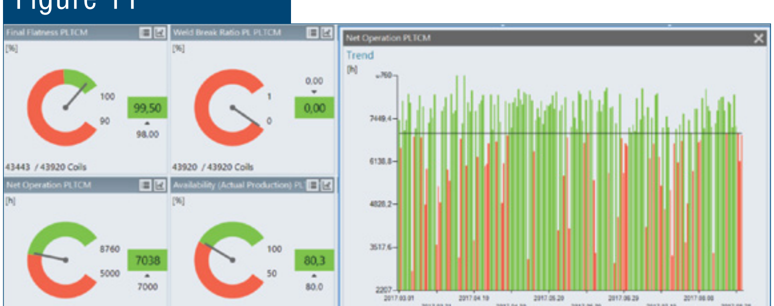


Root-cause analysis support as part of quality assistance.

Figure 10

Various surface defects scattered across a hot-rolled coil.

Figure 11



Key performance indicator visualization.

Fig. 8 illustrates the example of a produced heat, which is planned to arrive subsequently at a continuous casting machine. At the end of the basic oxygen furnace (BOF) process, the L2 system indicates a temperature of the liquid steel that violates the grade-specific requirements. In this case, TPQC evaluates the temperature by means of process-specific rules and records a quality issue. In addition, the TPQC system immediately suggests a reblow at the BOF. If this is confirmed by the operator, a message is sent to the continuous casting machine operator to reduce the casting speed. By reducing the casting speed, TPQC tries to compensate for the additional processing time caused by the reblow at the BOF, which otherwise would increase the risk of a sequence break or slab quality issues.

In addition, the system indicates again a list of likely root causes for this problem. In the example case, a new material was used for the material additions. The operators had not managed to update the L2 database with the new material data in time, which led to an inaccurate calculation of the L2 model for the BOF process and finally caused the temperature deviation.

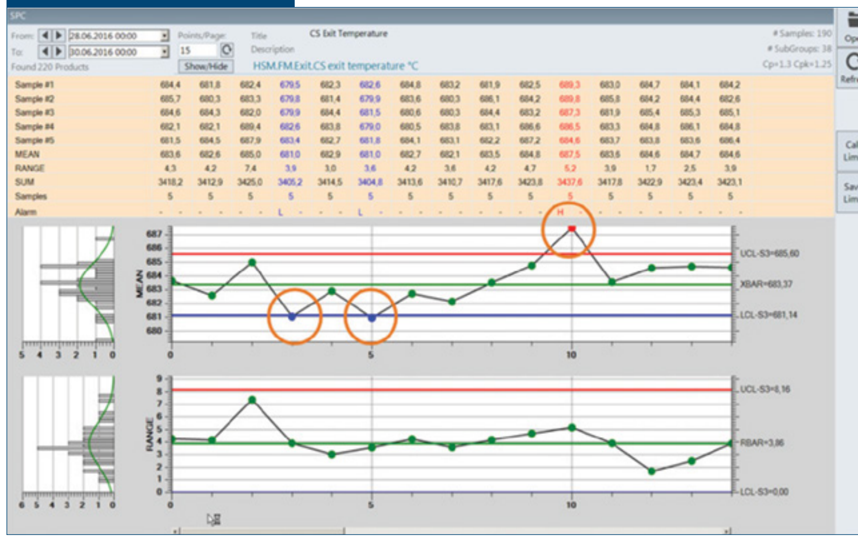
Fig. 9 shows a screenshot of how TPQC indicates root causes for recorded quality issues to quality engineers. The list on the left-hand side of the screen shows all semi-finished products for a given day (in this case filtered for heats). The selection of a heat with recorded quality issues (indicated by the call sign) shows all recorded quality alarms/issues. In this case, there are two quality alarms. By selecting a quality alarm, the instructions for verification as well as root causes are shown in the text window at the bottom of the screen.

Even though the given example shows a root-cause analysis for a single process unit, this kind of root-cause analysis is not restricted to single processes or plant areas (e.g., meltshop, hot strip mill, cold mill, etc.). By means of carefully specified rules for root-cause analysis, TPQC can also indicate root causes across process or plant boundaries. In this way, the system supports through-process root-cause analysis, which is especially useful in case of certain surface defects that can be tracked back to the liquid phase.

Automatic Product Grading — TPQC incorporates a rule-based module for coil grading. The coil grading module pre-processes, for example, surface defect maps (Fig. 10). Afterwards, the grading module performs an in-depth evaluation of the defect map in order to determine instantly whether a coil surface quality matches the pre-defined requirements of the end customer, and what action to take if this is not the case.

Key Performance Indicator Evaluation and Visualization — The centralized collection of data enables the generation of KPIs, which convey information about technical and business-related achievements and illustrate what progress has been made (Fig. 11). TPQC implements various types of graphical HMIs to support staff members from the quality and production departments, as well as top management executives, in monitoring and benchmarking production conditions with respect to specific targets that are in alignment with the KPIs.

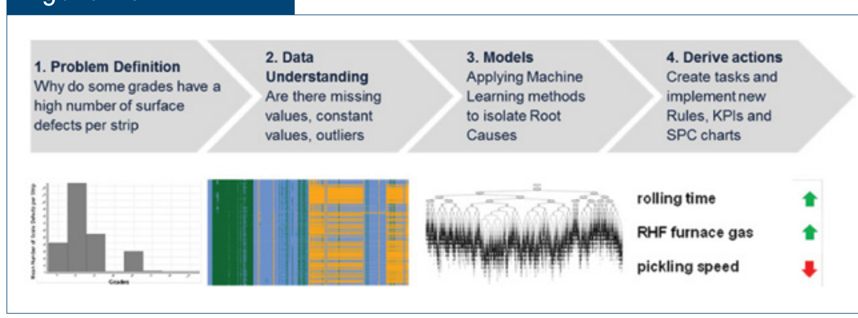
Figure 12



Typical statistic-process control diagram.

Statistical Process Control — SPC is a reliable and proven tool to provide statistical evidence that a production process stays within its pre-defined operational range and, therefore, behaves in a controlled way (Fig. 12). There are significant advantages of having this statistical process control applied to quality assurance processes, since sooner or later statistical significant deviations of process values will have an impact on the product quality. In general, SPC aims on sampling data, which is meant to be stable over a long period of time in order to allow for a reliable detection of an undesired process dynamic. TPQC can follow-up single process criteria and also combined calculated performance indicators and KPIs, and offers SPC charts for selectable material/product-related measurements or process data.

Figure 13



Example of data mining project and definition of actions.

Machine Learning Capabilities — The extraordinarily large amount of structured data in the TPQC system is perfectly suited for analysis with data mining and machine learning algorithms. A direct interface is offered to transfer data to state-of-the-art data mining platforms. All acquired data is automatically assigned to the correct products along the process chain (i.e., steelmaking heat, slab, hot-rolled strip, cold-rolled strip, galvanized strip) by the genealogy function in the TPQC. Data mining and machine learning in combination with TPQC have the following benefits:

1. Fast analysis for data quality and potential problems of measurements, manual inputs, etc.
2. Quick analysis of multi-variate problems, e.g., variation of mechanical properties by visualizing the raw data from TPQC.
3. Root-cause analysis of problems using through-process data and applying advanced data mining methods.
4. Predictions using machine learning methods for end-of-line properties of products or process stability.

Closing the loop by creating new rules, KPIs or SPC charts in TPQC can be based on the data mining results (Fig. 13). The data mining functionality of TPQC supports quality and process engineers in optimizing the product quality and stabilizing the production process. It is an extremely useful tool to increase the productivity of technologists and engineers throughout the process chain.

Conclusions

This paper presents how the co-action of digitalization and human expertise results in a deeper overall process understanding and how this co-action can be supported by a through-process optimization digital solution. The holistic approach, considering technical as well as socio-cultural aspects and the combination of metallurgical and operational know-how with an intelligent IT system, allows steel producers to improve their overall efficiency, achieving higher levels of quality and developing and maintaining their know-how basis.

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