Q-MELT AUTOMATIC EAF - LATEST EVOLUTION OF EAF CONCEPT FOR STEEL INDUSTRY*

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Abstract
DANIELI Q-MELT is the latest evolution of EAF concept to automatically control each stage of the melting process, from the electric power planning to the combustion optimization as well as the slag and steel metallurgy management for every operation required in the EAF cycle. The core of the automation system is the Melt-Model that automatically identifies deviations of the process control variables and corrects them to avoid losses or wasting of available energy sources. The real-time online off-gas analysis, via the in-situ laser system, promotes the process tracking and permits further optimization by a viable closed-loop control acting on fuel and oxygen post-combustion. A suite of supplementary stand-alone Technological Packages integrates the Q-MELT to further maximize the productive time and the utilization factor, supporting the operators to limit downtimes, avoiding misoperations and/or mistakes.
Keywords: Automatic EAF; Q-Melt; Melt-model; Technological packages; EAF control strategies; Steel making.

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1 Q-MELT AUTOMATIC FURNACE

The growing complexity of the EAF process in combination with increasing demands in productivity and reduced environmental impact requires control strategies taking into consideration the dynamics of the system requiring adaptation of the static preset operating points in real-time.
DANIELI Q-MELT has been conceived as an integrated process control supervisor. It automatically recognizes deviations from the expected behavior and re-tunes the melting program, acting on the electric power planning, on the chemical package, on the slag and steel metallurgy. Equipment constraints are integrated into the control action through functional diagnosis.
The Q-MELT Process Supervisor integrates basic automation and technological functions to enable EAF steel production in an effective and safe way, supporting each operation from the charging phase up to the tapping procedure. Thanks to its extensive sensor- and camera-based process monitoring, this new generation of machine pulpits can be installed in an arbitrary position and does not need dedicated windows to have a direct visual feedback from the process, increasing operator safety and process awareness (Figure 1).
A suite of supplementary stand-alone Technological Packages integrates the Q-MELT to further maximize the productive time, utilization factor and safety, through remotely controlled mechatronic units.

Figure 1: Thy Marchinelle's 3Q Automatic Pulpit

1.1 Melt Mode

The core of Q-MELT is the MELT-MODEL (Figure 2) that automatically identifies deviations of process controlled variables and corrects them to avoid material and energy losses.
"Melt Model" coordinates the data, collected in real-time by multiple on-board sensors, and the calculated process variables based on the preset static melting profiles. The MELT-MODEL coordinates a closed-loop control integrated by the Q-REG+ for the electrical power and the Q-JET for the chemical package.
Quick response off-gas analysis is ensured by in-situ LINDARC Gas Analyser. It provides the fast feedback information for the regulation of the oxygen injection during the refining stage, controlling the steel decarburization and limiting the bath oxidation at the same time.

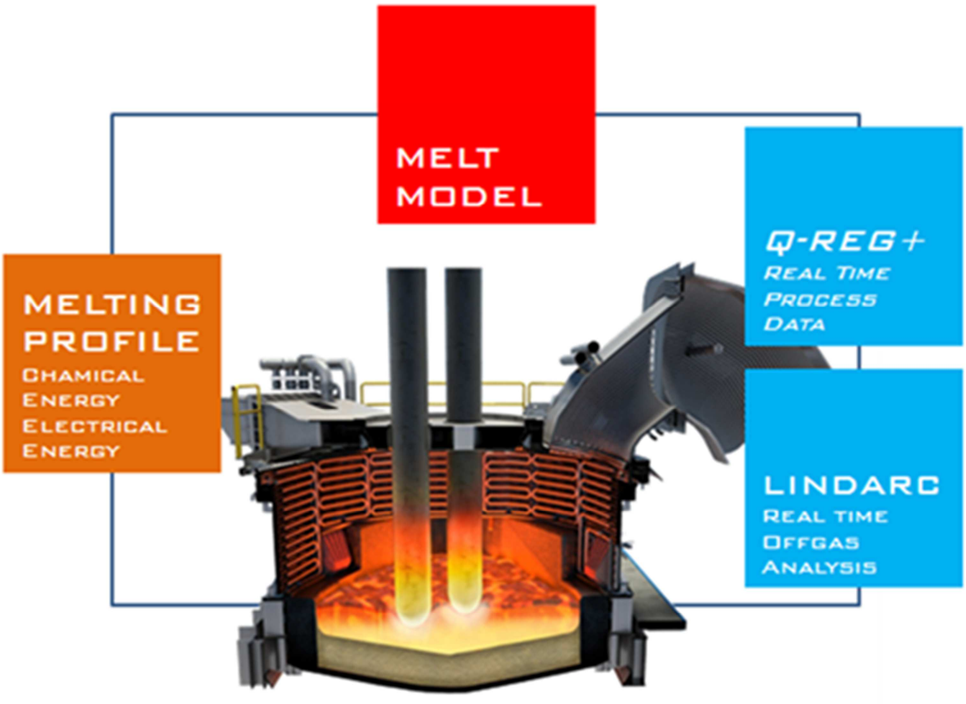

Figure 2: MELT MODEL – Step ahead in dynamic EAF close loop control.

Q3 intelligence is a powerful data mining engine that has been developed and specifically tailored for this control application. Relevant data variables are collected and automatically classified into structured relations.

Extensive statistical process analyses are applied to a massive quantity of information, discriminating from expected consistent behavior and anomalies. Persistent deviations from expected process conditions lead to continuous optimization of CO combustion and efficient use of fuel, by adapting the melting profile to the variable operational conditions. The integrated control of the melting process as a whole, together with the real-time tracking of the furnace variables outlining relevant deviations from expected process conditions, affords a significant opportunity to improve energy efficiency and productivity.

The main advantage over the majority of the existing systems is the capacity of the Q-MELT to adapt to continuously changing operating conditions keeping the EAF performance at top. The ability to react to the continuously changing operating conditions in the EAF (for example different charge mixes) cannot be achieved by means of non-dynamic set points. This is a significant progress if compared to conventional, rigid control diagrams based on time and energy. Additionally, the basis for a deeper understanding of the EAF steelmaking process and related pre- and post- processes is the usage of the latest measurement technologies and condition-monitoring solutions.

Q-MELT integrates a number of analysis technologies for slag detection (Q-SLAG) and off-gas analyses (LINDARC); together with a carbon mass balance, the supervision and analysis of all relevant input and output data is ensured.

As demonstrated in plant trials, the system can react to critical situations much earlier than operators can do based on dynamic and predictive control algorithms. So the critical situation can be prevented or at least the caused damages can be damped to a minimum. In this way the MELT-MODEL System (with the LINDARC and Q-REG+ technologies) also handles critical events of water leakages and massive arc radiation to panels.

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1.1.1 Melt model – Lindarc real-time off-gas analysis system

Lindarc laser off-gas analysis system is a very precise technology to obtain exact data for the various gas species in the EAF off-gas system resulting from the combustion and carbon injection within the EAF.

It performs real-time measurements of off-gas emissions (CO, O2, CO2, H2O) and temperature and ensures quick results (less than 2 seconds compared to more than 30 seconds of traditional extractive system) even with a very high dust content and high temperature in the off-gases.

Off-gas composition data allow the analysis of the current EAF practice efficiency and the formulation of possible optimization strategies for the EAF practice as well as real-time monitoring of water content values to improve safety and prevent explosions (Figure 3).

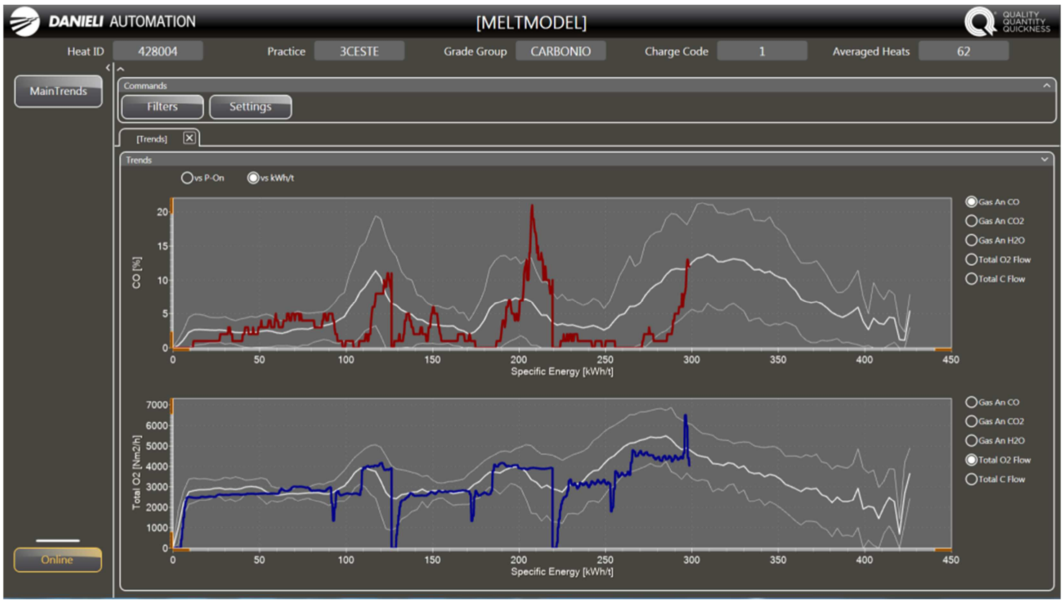

Figure 3: MELT-MODEL – CLC off-gas analysis trend

Data taken from the laser are elaborated by the MELT MODEL (Figure 4) that provides control and management of the entire melting process. Specific software has been developed to generate a Closed Loop Control (CLC) between the off-gas analysis technology and the burners / injectors / post-combustors. Oxygen / natural gas ratio of burners is dynamically controlled by the CLC, based on the CO2, CO and H2O readings. Oxygen flow through the post-combustor is also controlled by the CLC software with the aim of maximizing the post-combustion inside the furnace and saving electrical energy during scrap melting (Table 1).

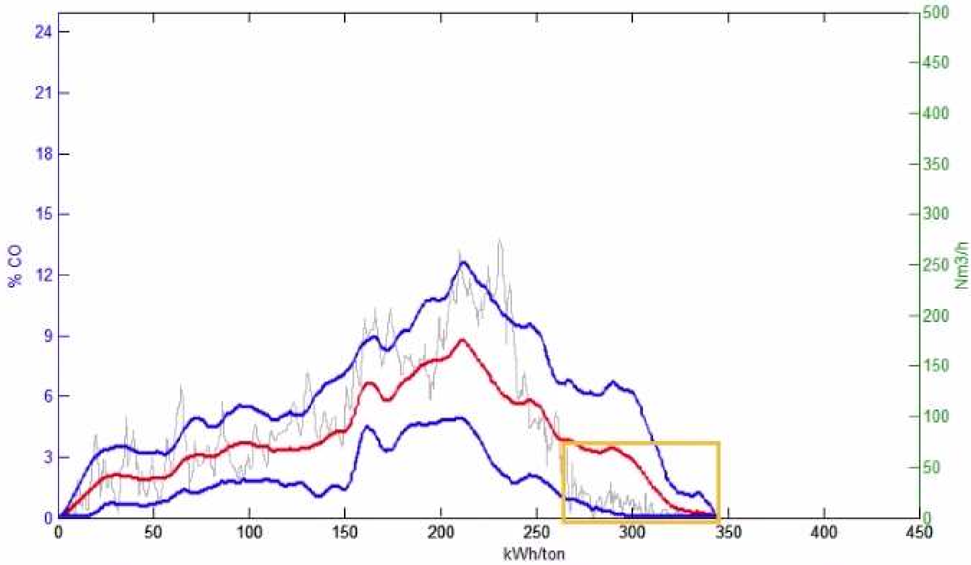

Figure 4: MELT MODEL – Real time trend analisys

On a single heat, as demonstrated in different steel plants, Lindarc and MELT-MODEL allow to foresee the liquid steel carbon content (%C) and temperature; these data are the input for dynamic model to manage Power and O2 injection with the aim of minimizing the superheating time, controlling at the same time the decarburization level. This control strategy allows higher process yield and machine efficiency.

Table 1: LINDARCTM average operational results from several plants installation [1].

LINDARC	**Avarage Result**
Electric Energy consumption	-5.0%
Oxygen consumption	-10%
Natural Gas consumption	-6.0%
Injected Carbon consumption	-10%

Table 2: LINDARCTM operational result in ABS Italy.

LINDARC	**Avarage Result**
Yield	+1.4%

Moreover, additional benefits are: reduced skulls (un-melted scrap) on the furnace walls, with consequent better scrap charging and a better knowledge of the furnace melting process.
By adopting the laser off-gas analysis, savings of 2 USD/t have been generated thanks to the precise control of all melting phases and the reduction of the overall transformation costs.

1.1.2 Melt-model – Q-REG+ advanced electrode regulation system

Q-REG+ is a highly sophisticated PAC-based electrode control system for AC-DC EAFs. The system uses high-performance algorithms together with intelligent measurement technology. The control strategy is based on fast data acquisition and MELT-MODEL processing, to manage both electrical and chemical power input of the EAF process.

1.1.2.1 Q-REG+ Dynamic electric energy regulation

Controlling the position of each electrode column, the system dynamically adjusts the electrical set-points to adapt to furnace and network current conditions and to achieve the highest possible active power input.

In this field, Q-REG+ main futures are: Fast-response hydraulic counter pressure control and touchdown function (lower electrode breakage risk), boring-down dynamic control (auto-regulation of the electrical working point, increasing the power as soon as possible), automatic supply voltage compensation (uniform operation and power inputs without operator intervention), transformer overcurrent and thermal protection with secondary insulation control (safe EAF operation) and Real-time irradiance supervisor (Q-RAY) for longer cooling panel and refractory lifetime (Figure 6).

Full-fledged customization tools allow interactive set-point input and visualization. Advanced diagnostic functions enhance process and machine monitoring. The circular diagram display features an interactive visualization of the furnace work area and work settings, to quickly check and modify the electrical working points.

Figure 5. Hydraulic Circuit Linearization.

The hydraulic circuit linearization function allows the automatic measurement of the positioning system response nonlinearity, to get a valve linear response for a specific lifting and lowering range (Figure 5). The dynamic regulation overview shows the current process status and electrical-chemical working points, while statistical analysis of process data is performed by Q-REG scope.

The innovative electrode irradiance supervisor (Q-RAY) evaluates the total radiative heat flux on the furnace panels to modify the electrical set-points, thus balancing the thermal loads on the water-cooled panels.

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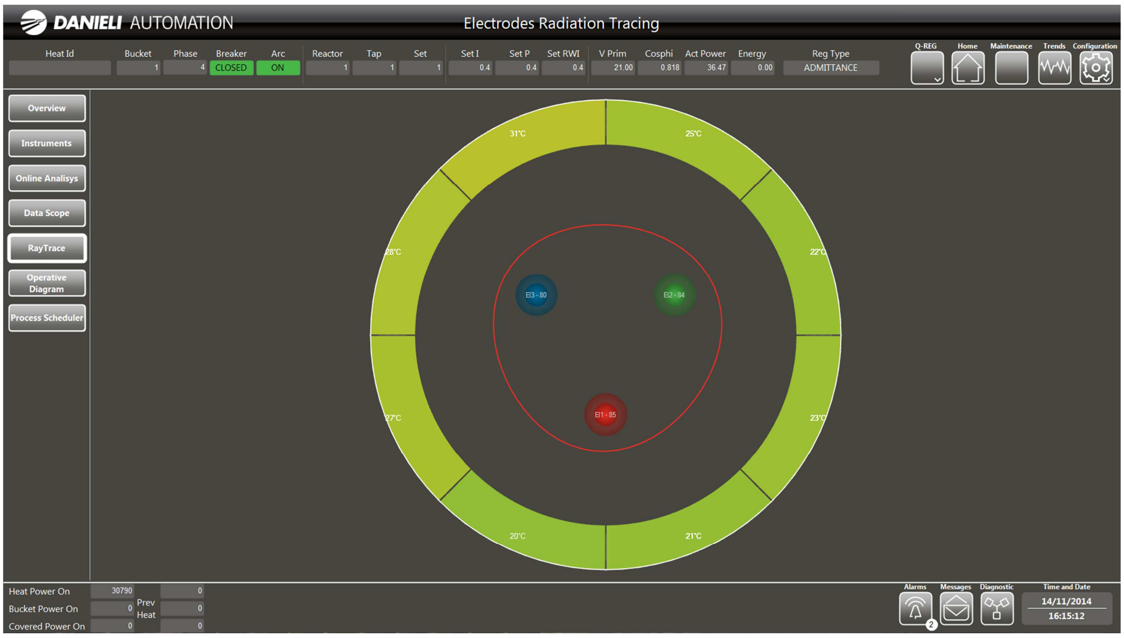

Figure 6. Q-RAY Arc irradiance supervisor.

1.1.2.2 Q-REG+ Dynamic foamy slag control

During the refining phase, arc coverage by the foaming slag is the key parameter to monitor the process. Q-REG+ continuously monitors the slag condition evaluating the Arc Coverage Index (ACI), a proprietary function based on arc V and I real-time analysis (Figure 7).

When the ACI exceeds a proper threshold, optimal foaming slag conditions are detected and the system automatically reduces the static C injection flow set-points. If the arc gets uncovered, the carbon flow is increased accordingly.

Towards the end of the process, dynamic regulation is applied also to lime-dololime injection, to recover proper slag basicity while optimizing slagging agent consumptions.

Toward the end of the process, dynamic lime injection counteracts the inherently unfavorable slag conditions while optimizing lime consumption.

The regulator control architecture was recently ported to a new unified control platform (DA-PAC), with an intense re-engineering activity which led to several advantages in terms of system setup time and machine operability. EAF operators showed positive feedback regarding the innovative interface and the radiation monitoring features, proving that a synthesis of significant process variables is an efficient approach to machine status display.

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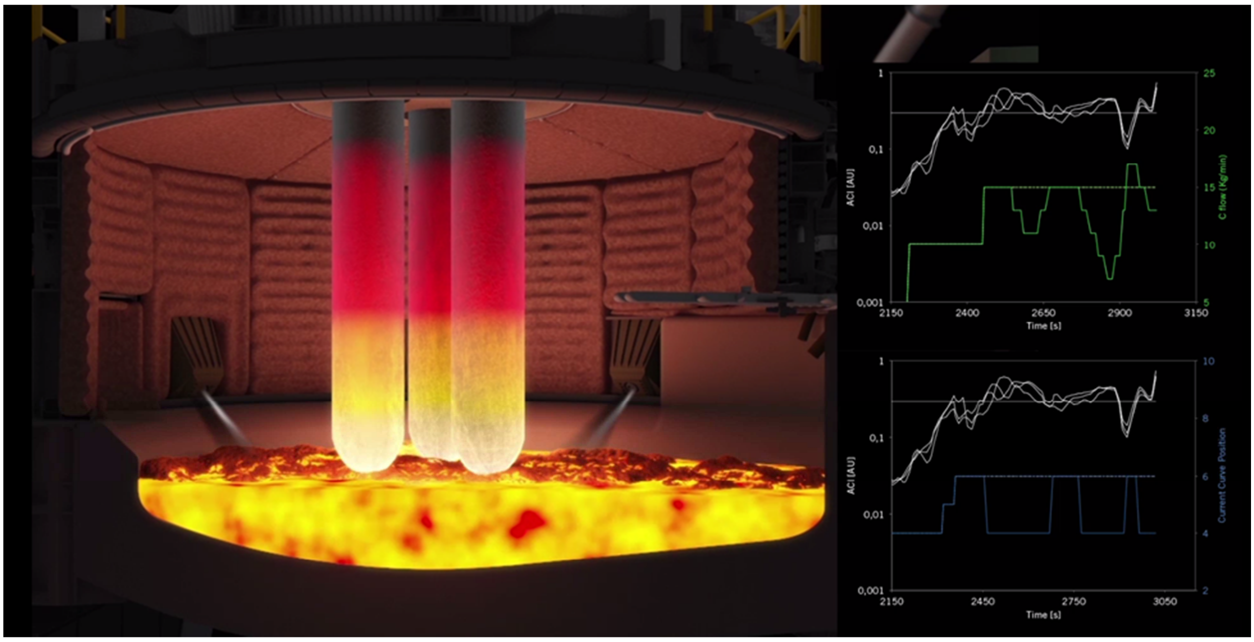

Figure 7: Arc Coverage Index (ACI)

Table 3: Q-REG+ average operational results from several plants installation**.**

Q-REG+	**Avarage Result**
Electrode consumption	-6.0%
Electrical Energy consumption	-5 Kwh\ton
Avarage Power consumption	+3.0%
Flicker	-10%

1.3 Melt-Model - Automatic Operations

MELT-MODEL manages the interaction of the electrical and chemical melting profiles to achieve energy use optimization, as well as slag and steel metallurgy control, involving, among other features, arc coverage by foaming slag management, post-combustion optimization, electrical energy consumption reduction, and oxygen and carbon consumption optimization

During the melting stages, several inputs are given to the system by Q-REG+ (Advanced Electrodes Control System) and Lindarc (Real-Time Laser-Based Off-Gas Analysis System), which will be continuously processed by MELT-MODEL.

Q-MELT Process Supervisor (Figure 8) controls all the technological functions to enable EAF steel production in an effective and safe way, from charging phase up to tapping procedure, permitting an increased flexibility on raw material charging in synergy with melting process.

A set of Technological Packages comprises the necessary equipment to automate manual operations in the EAF area.

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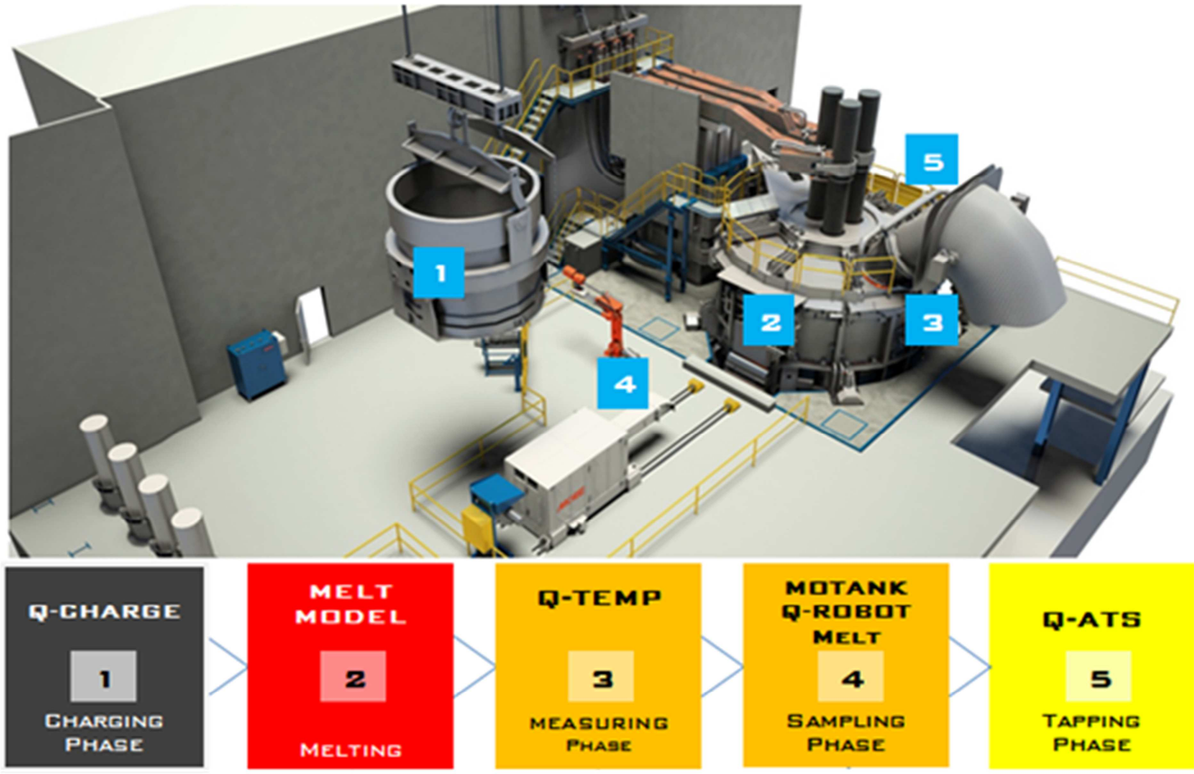

Figure 8: Q-MELT Process Supervisor

1.4 Q-Charge - Automatic Bucket Charging System

Q-CHARGE is a set of tools to manage the EAF charging process from the bucket recipe calculation to the basket unloading into the EAF. Charge recipe optimization (Figure 9) and automatic crane movement allow higher plant productivity, efficiency and output quality. Q-CHARGE features a least-cost charge calculation function to attain the tapping analysis targets respecting the maximum residual elements concentrations allowed. The main outputs of the algorithm are the total charge recipes, the individual bucket charge recipes and scrap purchase lists, for a FASTER and more reliable recipe calculation and a support to long-term production planning.

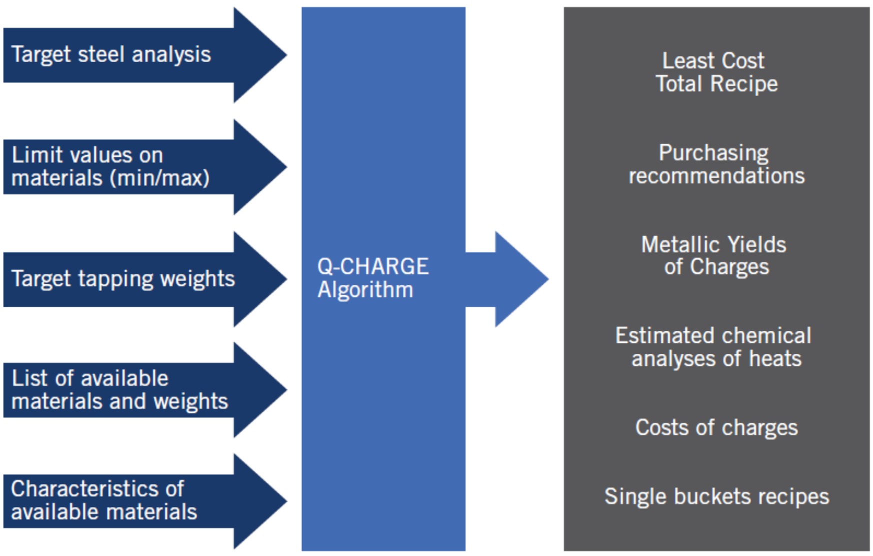

Figure 9. Q-Charge Algorithm.

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After operator request from the main EAF pulpit, a laser-based crane positioning system allows fully automatic bucket picking, movement and positioning over the EAF. When the bucket is discharged, the system automatically closes the EAF roof and the doghouse and delivers the empty bucket to the proper bucket car/parking position. Bucket identification is carried out by a camera-based pattern recognition system. Thanks to the integration with the EAF automation system, the movements of the doghouse door, EAF roof and crane hook are highly synchronized to minimize non-productive time and energy losses.

1.5 Q-Temp - Impulsive Contactless Temperature Sensor

Q-TEMP system provides a continuous liquid steel temperature reading, based on the readings of the pyrometer. This enables the operator to have a continuous perception of the evolution of the steel bath temperature along the melting phases, and to better manage the process itself.
The measuring process is made in real time (Figure 10), and the automation system proceeds to the necessary elaboration of the signal in order to identify the correct steel temperature.

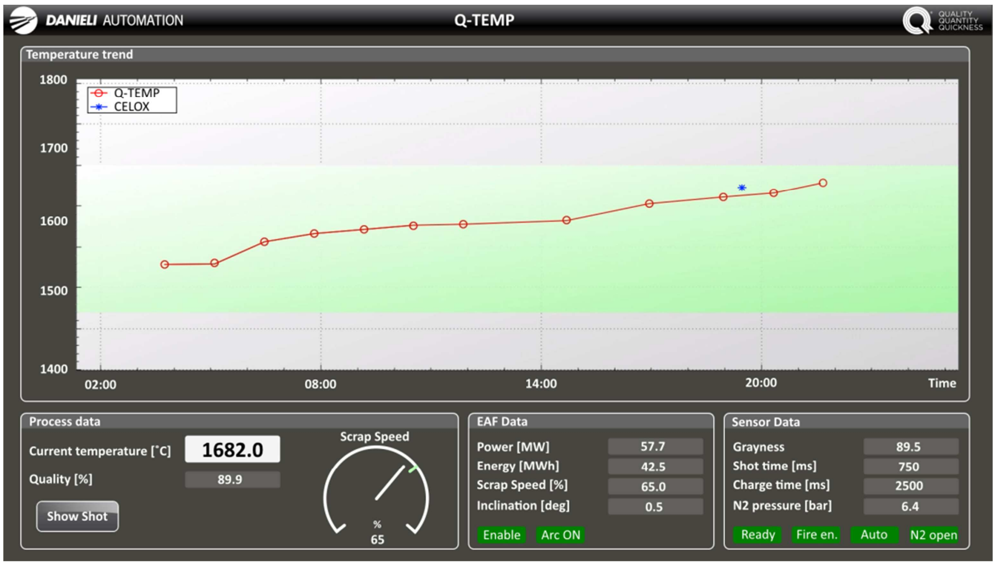

Figure 10. Q-TEMP Temperature interface.

In a continuous charging process (DRI or scrap), the Q-TEMP's algorithm evaluates if the material feeding rate is appropriate or, on the other side, requires a correction. Based on this interaction, and through intuitive dashboards, the operator receives suggestions regarding the increase or decrease of the material feeding rate. In this sense, the optimal DRI/Scrap feeding rate is met, optimizing the melting conditions along the process with positive influences on the stability along the production cycle, helping to achieve a high degree of leveled production.

Table 4: Q-TEMP average operational results from trial installation

Q-TEMP	Avarage Result
OPEX Saving (CELOX saving)	-4$\heat
Temperature measurement tolerance	± 0.5%

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1.6 Q-SmarTEC – Electrode Saving Tool

Q-SmarTEC is the new generation of electrode saving tools, consisting in a mechatronical valve stand and in optimized electrode cooling rings for a dynamic control of electrode cooling water.
The technological package is controlled in real time by the Q-SmarTEC Automation module during every phase of the process. For each electrode, the system controls the air / water flow rate and the pressure on the lines (monitoring the pressure drop), measures the conductivity and acts in order to maintain the perfect conditions regarding electrodes cooling. The operating profile of the electrode cooling system is automatically managed by a Central Unit, which is based on a Technological Data-Base, Pre-Set parameters and collected information from dedicated field sensors.
The whole process occurs in real time, for each step of cycle (pon and poff time). The result is an appreciable and significant improvement in electrode consumption, without any interference in the stability of the arc or any increase in electric energy consumption.

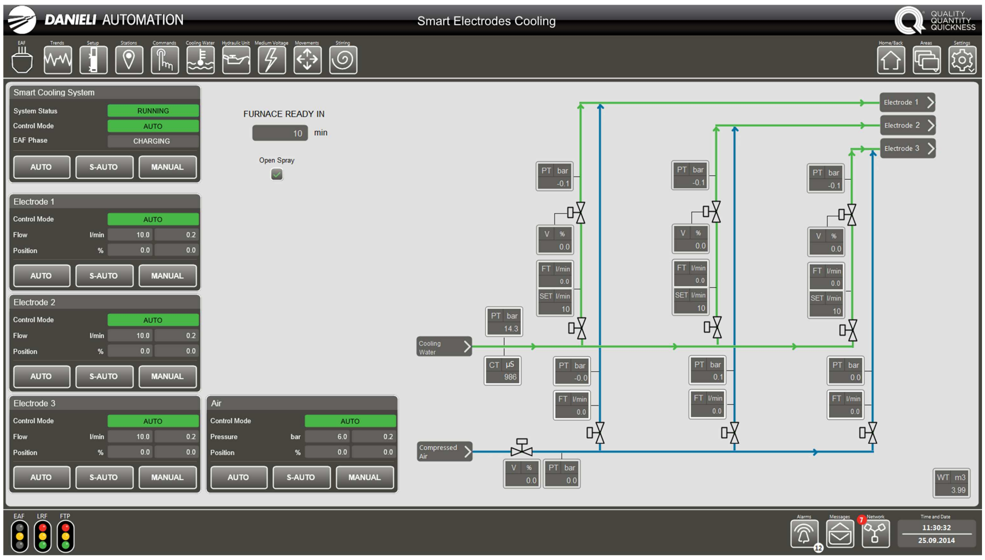

Figure 11. Q-SmarTEC 3Q Control interface.

Thanks to the new generation of Q-SmarTEC Cooling rings, the optimal combination of water flow rate and jets velocity is assured, enabling the optimal water flow range to cool the electrode in its maximum length, avoiding overcooling, which generates arc instability and increases energy consumption.

Table 5: Q-SmarTEC average operational results from plant installation

Q-SmarTEC	Avarage Result
Electrode consumption	up to -15%

1.7 Q-Ats - Automatic Tapping System

Q-ATS system is designed to automate and support the operator during the entire tapping process thanks to the synergy between Technological Packages and EAF functions.
The system is composed of the Q-ATS Automation module that coordinates Q-SLAG System for slag detection during tapping phase, the Q-EBY EYE which allows to have a full monitoring of the EBT tap hole condition during the entire process time,

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the Q-EBT SAND to automatically feed olivine on EBT tap hole. During the process, Q-ATS continuously performs the ladle preheating & temperature control, the ladle tapped weight control, the automatic tilting speed control based on ladle weight, the EAF thermo-camera-based tilt-back control (Q-SLAG – Figure 12), based on Q-SLAG image processing output, the ladle additions and stirring management, the EBT status monitoring (Q-EBT EYE), the EBT cleaning (Q-STAP) and the olivine charging (Q-EBT SAND).
Thanks to the Q-ATS the tapping procedure can be comfortably fulfilled in no more than 30” directly from the main control room without acting from the tapping pulpit, with benefits in terms of cost and time (the standard tapping procedure usually requiring 2 workers and some minutes) as well as in terms of safety since no operator is required for local actions.

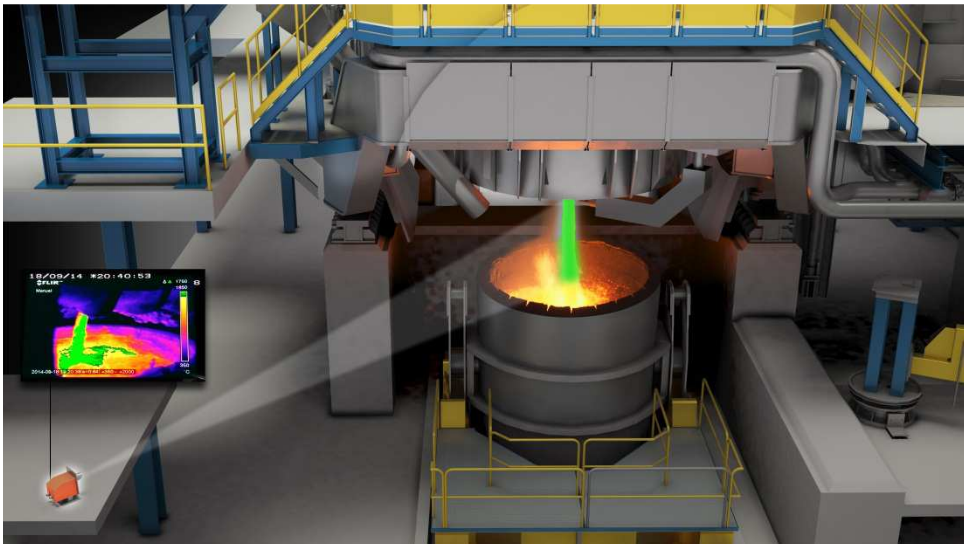

Figure 12. Q-ATS Slag Detection Module.

1.7.1 Q-ATS - Tapping time

During the entire tapping phase, the Q-ATS, by means of the Q-SLAG module (Figure 13), measures the amount of slag being transferred into the ladle and when the signal is higher than a specific limit, the command of back-tilting is automatically given. Automatic back-tilting controlled by a dedicated module reduces to a minimum the possible slag carryover which would possibly demand ladle slag raking, and improves the refractory lining lifetime at the slag line.
Higher consistency in steel quality as well as lower costs, ferroalloys consumption and ladle treatment time are proven advantages. The correct ferroalloy addition and stirring intensity is guaranteed by the Ladle addition management and stirring regulation module that allows the proper monitoring and control of this important process step.

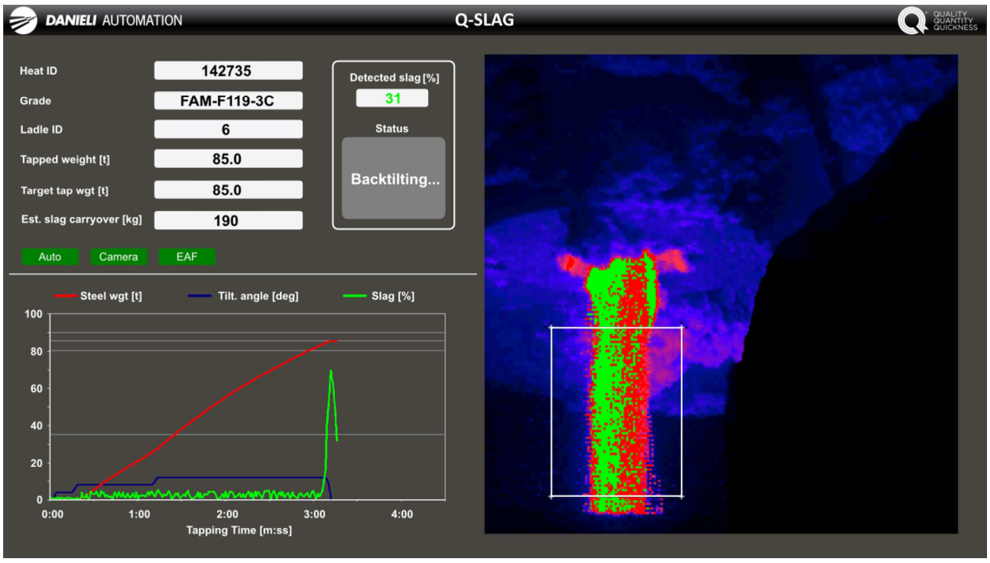

Figure 13. Q-ATS Slag Detection Module.

1.7.2 Q-ATS - Preparation time

After tapping, the operator can immediately assess from the main pulpit, thanks to the Q-EBT EYE camera, if the EBT hole is clean. EBT plate closing and olivine sand filling operations are then carried out by simply pushing a button controlling the sand storage bin slide gate valve (Figure 14).

The sand filling operation can be initiated immediately after the end of the EAF tilt-back, saving the time that otherwise would be spent on the local inspection and manual EBT sand filling.

Figure 14. Q-EBT Sand installation and sand discharging.

1.8 Q-MELT - 3Q Technology Automation

Danieli innovative approach to EAF process automation is a full package of modular solutions conceived for the process control and all the required operations in the production cycle. 3Q-EAF automation technology is the basis for Danieli philosophy of single-point coordination and full process control, which radically changes the role of the operator.

3Q Control Desk (Figure 15) improves plant performances, reducing dependence on the skill of operators. All the EAF operations are controlled and supervised from a single-point control room, which can be remotely located.

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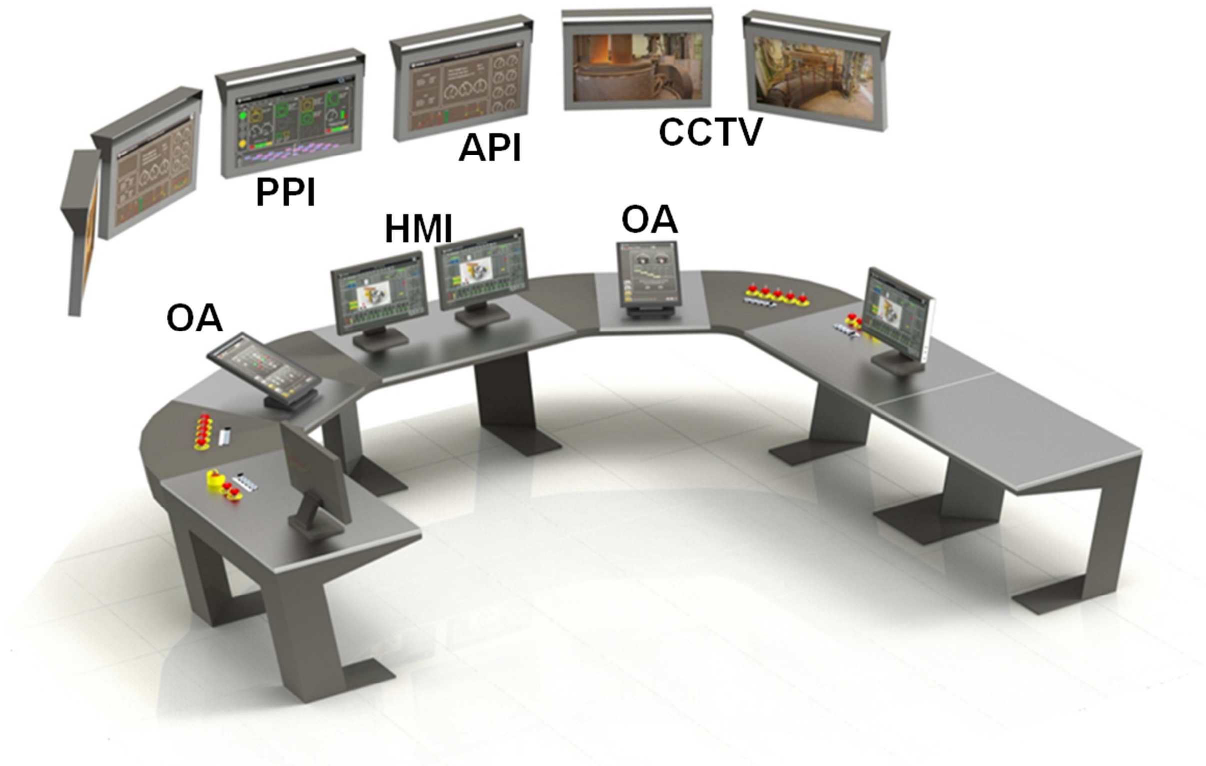

Figure 15. 3Q Control desk.

The knowledge-based approach consists in showing the operator only the useful information required for that precise process step.
One of the key points of 3Q Control Desk is the provision of a full Soft-Desk pulpit, totally based on touch-screen technology, through which the operator can both monitor the plant and operate it at the same time.

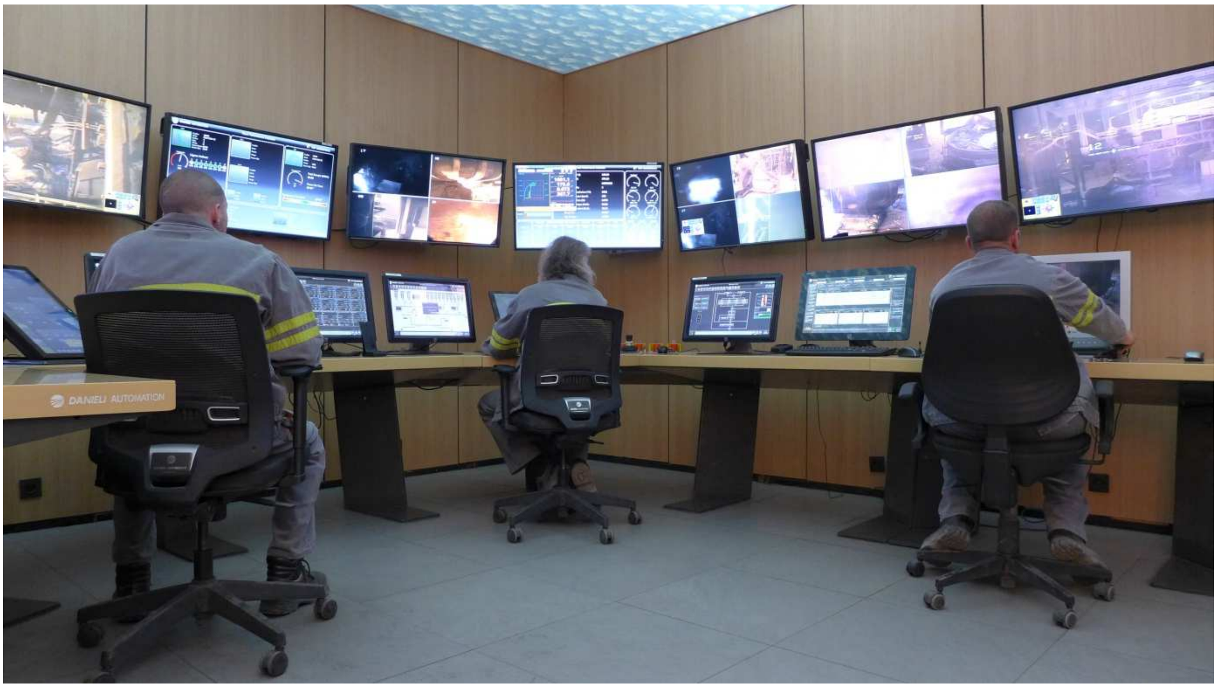

Figure 16. OA Operator Assistant.

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Coordination between different areas is natively embedded in the integrated architecture. Traditionally the operator gives commands and instructions to start the operating cycles.

With the 3Q approach the automation is responsible for the coordination of commands and instructions, with maximum overlapping and synchronization, while the responsibility of the operator is to supervise and decide on exceptions. When an exception in the standard operating cycle occurs, a dedicated interface asks the operator for his decision on the basis of a selected multiple choice based on the immediately subsequent action required in the sequence tree.

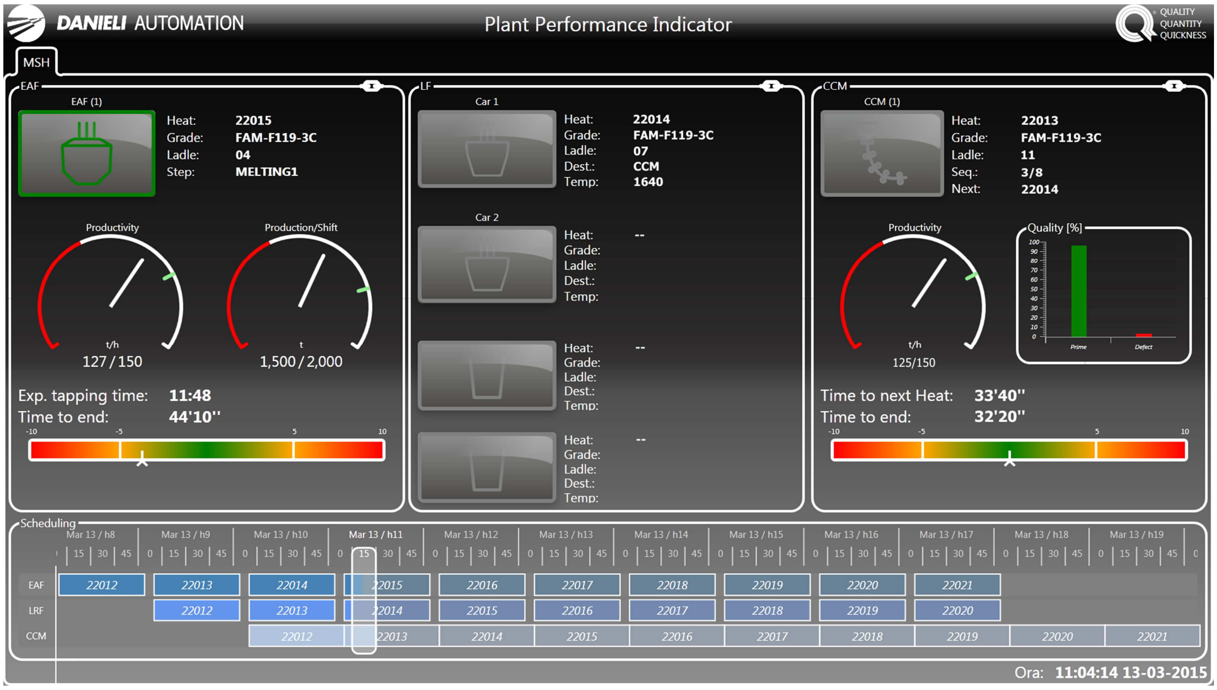

Figure 17. PPI Plant Performance Indicator.

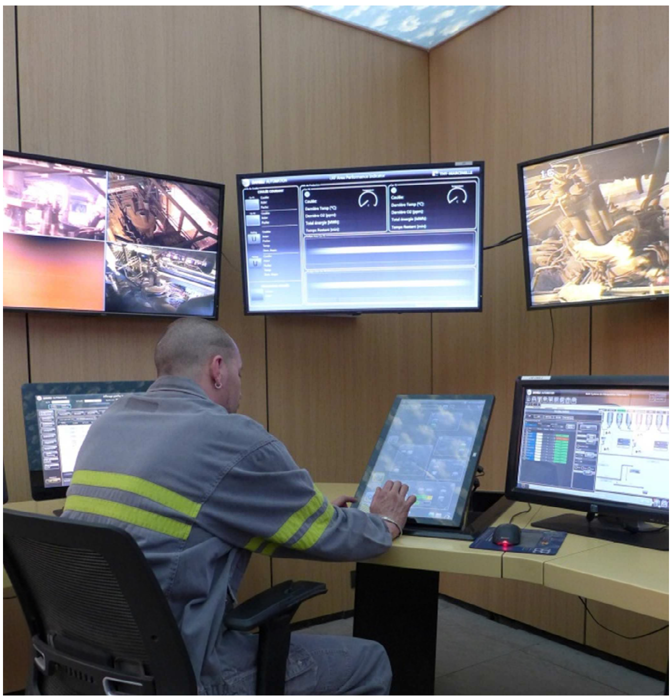

Figure 18. OA Operation Assistant.

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The Operator Assistant (OA) coordinates the machine commands ensuring the highest plant utilization and lower operator effort (Figures 16-18).
The Area Performance Indicator (API) provides real-time overall information on the process status and performances of the EAF area.
The Plant Performance Indicator (PPI) (Figure 17) supervises multiple technological areas, showing all significant variables to monitor the process status for the entire meltshop.

2 CONCLUSION

In the present market conditions, taking into account future market forecasts, competitive factors are always more demanding and are a differentiation factor across the steel industry. Increased efficiency and improved performances are the key factors for competitiveness and profitability.
The modularity of the Danieli's Automatic Furnace concept is based on these principles and gives to the steel makers the necessary flexibility to improve the EAF process, with proven results in Acciaierie Bertoli Safau, Gerdau Jacksonville and Thy Marcinelle, where the modularity concept increased plant flexibility and productivity.
Thy Marcinelle EAF results demonstrate that the implementation of advanced automation technologies like Q-CHARGE, Q-ATS Automatic Tapping, Q-ROBOT Melt and MOTANK equipment allowed the minimization of power-off. The observed result is a power-off of 8 minutes for a 2 bucket process (excluding delays), which is also obtained with minimization of workload and risk for personnel.
Moreover, thanks to the implementation of MELT MODEL and Q-SMARTEC in several steel plants, substantial benefits were demonstrated in terms of power consumption (-10%), electrode consumption (up to -15%) and metal yield increase (+1.4%).
Sustainable production is now achieved through the enhanced use of electrical and chemical energy, better utilization of raw materials, reduction of the non-productive times, decrease of the process variability, assuring a controlled quality of the produced goods.

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