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An Intelligent Maintenance System to Improve Safety of Operations of an Electric Furnace in the Steel Making Industry

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Steel making industry represents a sector in which maintenance can be considered a key process. In this paper the development of an intelligent monitoring system of the electric furnace of a steel making company is presented. The furnace is a relevant asset in terms of safety issues; due to the characteristics of the furnace – running continuously at high temperatures and in harsh environmental conditions –, many elements and components cannot be visually inspected, thus an intelligent maintenance system, with real-time monitoring capabilities, represents a proper solution to keep under control the asset health status. The intelligent maintenance system, herein presented, can be considered an E-maintenance tool, integrated within an existing industrial ICT infrastructure.

1. Research background

In steel making sector maintenance is charged with a wide responsibility and organizational involvement, encompassing also issues related to: i) asset lifecycle optimization, ii) safety and iii) environmental aspects. Asset management can be a better term to refer to, at least in order to represent the goals driving the maintenance processes and solutions adopted within such industry (see Amadi-Echendu, 2004, for proper discussion on physical asset as concept at the basis of Asset Management and Baglee et al. 2012 for the identification of the process of data management in the scope of Asset Management). Among the above mentioned issues, safety is of paramount importance in the sector, due to the typology of plants adopted and the severity of operations. Different approaches may be used to address the issue of safety. Supporting approaches and tools, namely CBM (Condition Based Maintenance) and Intelligent Maintenance Systems (IMSs), are worth to be considered as a lever to foster the achievement of good results in asset and maintenance management. Indeed, intelligent maintenance systems are often linked in scientific literature with the concept of E-maintenance. (Muller et al., 2008) stated that the term “E-maintenance” was not yet consistently defined in maintenance theory and practice. Engineers or scientists might consider E-maintenance as a concept, a philosophy, or a phenomenon, and so on. According to Djurdjanovic et al. (2003) such systems can save up to 20% in reduction of production losses, improved quality, decreased stock of spare parts: indeed they explicitly refer to CBM, speaking about e-CBM. Operational advantages and financial benefits of e-Maintenance can be also quantitatively assessed for investment appraisal (Macchi et al., 2012).

Nowadays, various E-maintenance solutions have been presented and scientific literature is plenty of even more innovative approaches, using detailed prognostic (Abichou et al., 2012) and mixed reality tools (i.e. Espindola et al., 2011 and Espindola et al., 2013) Beside these research frontiers, intelligent maintenance systems are progressively entering industry. This paper aims at presenting a proof of usefulness of such systems, discussing a practical implementation in the steel making industry, thus contributing to the

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scientific literature, providing evidences of the possibility of implementation of some of those research concepts, thanks to proper adaptation and IT architecture consideration.

The system has been developed directly in an industrial environment, at TenarisDalmine plant, located in Dalmine (Italy), with the objective of its practical adoption in the day-by-day operations, according to the direction of improvement of tools to be used in the plant (Rondi and Memoli, 2003). The tool is a kind of virtual inspector (shortly speaking, VI), capable to real-time supervise the health of the electric furnace (i.e. one of the key production equipment of the plant). This VI uses information sourced by the control system of the electric furnace, and develops additional knowledge of the production system behaviour thanks to an health monitoring algorithm. This means that proper parameters are identified to be input for the intelligent maintenance system. The parameters are the relevant ones for applying a condition-based operation of the furnace: if conditions are approaching risky situations, this can be identified thanks to the VI system, which reveals the asset health status, thus leading to subsequent operational decisions (like stopping the plant or planning for a stoppage in a short term). More specifically, the intelligent maintenance system, named Burnersys, aims at monitoring the parameters of the burning system of the furnace.

Four steps have been carried out to develop and implement the system: i) Hazard and Operability Analysis (HAZOP) to identify key parameters to monitor and map the asset behaviour, ii) definition of the reference signature representing good asset health conditions, iii) definition of the health assessment algorithm, iv) implementation and integration of the system in the existing ICT architecture of the plant.

The steps are presented and discussed through the following structure of the paper. Section 2 introduces the furnace and its key elements. Section 3 summarizes the use of HAZOP, as methodological approach aimed at formal specifying and structuring the analysis based on a "sound" language understandable by production process specialists and, in particular, process supervisors. Thanks to HAZOP, it was possible to identify the deviations in the process parameters and, thus, to select the signals needed in order to represent the asset behaviour for its degradations. These signals are then the relevant input for Burnersys. Section 4 presents the development of the algorithm for health assessment, namely the algorithm which has the task to compare the on-line monitored parameters of the process with a reference signature; the method adopted to identify such reference signature is also discussed. Finally, thanks to such algorithm, the system provides rich output information for the process supervisor in the control room: it displays not only an alarm signal, but also information about the importance of the faulty behaviour that is happening on the asset. Section 5 presents the implementation of the algorithm within the existing IT architecture which is adopted in TenarisDalmine plant, in order to i) properly connect the VI with the input signals, ii) properly realize the user interface that allows the operators to read the output information provided by the VI. From the point of view of the plant automation level, the developed system can be considered as a process monitoring tool, integrating some features typical of a SCADA (Supervisory Control and Data Acquisition) enlarged to health monitoring. Conclusions (in section 6) highlight the main remarks, together with the first results achieved by using the VI during the furnace operation.

2. Furnace description

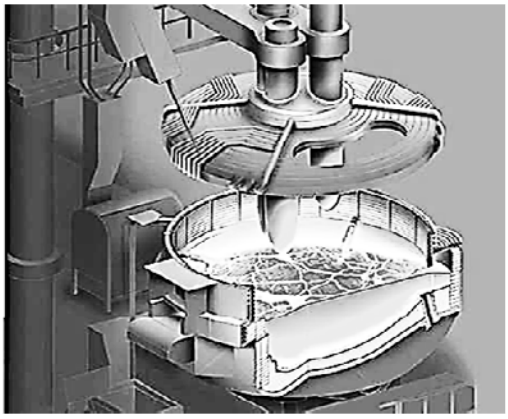

Figure 1: graphical representation of the furnace

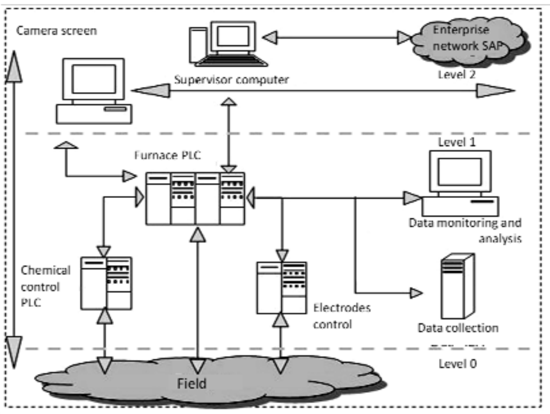

Figure 2: ICT architecture supporting the virtual inspector Burnersys

The electric furnace (Figure 1) is constituted by a lower sheet metal keel (lower-part) coated with refractory bricks, which serves to contain the liquid steel, and cooled by a cage, with a structural function, that supports panels cooled by a water circuit (Ferro et al., 2007). The upper part of the furnace encompasses, among others, three oxygen injection points, particularly relevant for the present research. In TenarisDalmine plant, there are two electric furnaces with the following characteristics: capacity 105 t, diameter 6.1 m, weight of the structure (considering also refractory bricks) 230 t.

The characteristics of each furnace allow to obtain 98 t of liquid steel, with an average power request of 67 MW per cast, and a maximum power peak of 89 MW. The casting cycle is around 38.5 min and this corresponds to a productivity above 150 t/h. The main contribution of energy needed for melting the scrap is supplied from the electricity for about 2/3 and for 1/3 by chemical energy supplied by the lances and the burners on board. In particular: melting 100 t of steel requires approximately 40 MWh of electricity; the chemical process is instead controlled by a system that monitors gases exiting the furnace and optimizes the injection by lances, providing oxygen; more specifically, the chemical system is a set of devices that provides multipoint injection of oxygen, methane and carbon.

3. Hazop analysis

The HAZOP technique uses a systematic process to identify possible deviations from normal operations and ensures that adequate measures are put in place to help preventing accidents, NSW Government Department of Planning (2008) provides useful guidelines and Labowsky et al. (2003) show an application case of HAZOP analysis to a real case. HAZOP adopts special adjectives (such as "more", "less", "no", etc..), in combination with process variables (speed, flow, pressure, etc..) to consider in a systematic way all the possible deviations. This approach has been proven to be useful when dealing with setup of monitoring and condition based maintenance system (Medina et al., 2012). Entire HAZOP table is herein neglected due to space constraints. HAZOP has provided the following benefits for the VI tool:

- Visual information sourced from HAZOP table is displayed by the VI Burnersys, allowing a better understanding of the behavior of the monitored equipment (i.e. the furnace);
- Identification of highly impacting risks from the HAZOP table is exploited to implement, through the VI, automatic disconnection of supply of oxygen under certain conditions.

4. Health assessment algorithm

The gas injection system works according to the set point values of the flow rate, set by a process expert through an user interface (Figure 2, level 2 of the architecture), then used by the field system to ensure that the flow rate follows the set-point value, independently from other factors (Figure 2, level 1). The “alerting” capability must be implemented through a proper analysis. An initial development consisted in associating the pressure in the line (process variable to "alert") with the flow rate (as “command” process variable). Indeed, according to the HAZOP, in most of the events it is not possible to deduce the asset health status by using the single evaluation of the “command” variable, if not relating it to an “alerting” variable of possible malfunctions. Firstly, by hypothesis, each line is considered "as good as new", thus the pressure drops are assumed constants and known: a single, unique pressure value corresponds to each flow rate value. Therefore, in case of leakage, equivalent to a decrease of pressure drop, one can expect to measure low values of both pressure and flow rate. Conversely, in case of a pipe obstruction, an increase in pressure drop is expected, detecting also two alternative phenomena: i) flow rate = set-point; ii) flow rate < set-point; the latter case, infrequent, already shows a mismatch between set point value and effective flow rate, so it does not require to analyse the pressure drop to detect an abnormal behaviour. Considering the need to analyse the pressure values to properly monitor the asset health status, it has been investigated what is the best method that allows to correlate the two variables in a precise manner, in order to quickly identify a deviation, considering i) the availability of certain parameters already monitored and ii) the impossibility to measure some variables in some, not accessible points of the asset. The methods seen as candidates for implementation are the followings: i) using a model based approach with the Bernoulli's law, ii) building control charts, iii) adopting systems based on Artificial Intelligence, or iv) developing a regression model.

As well known, flow rate and pressure are related by the Bernoulli’s law, in this case valid for compressible fluids. This method aims at developing a model based on a “white box” (the physical model), and can have some advantages if compared to “black box” approaches (Ierace et al., 2009). Black-box approaches – that use statistical and mathematical approaches, and are data-driven models – are the next options (either ii), iii) or iv)), and are later discussed. Applying a Bernoulli’s law based model was considered too costly and difficult for implementation in the industrial case; besides, this method is very sensitive to the variations in the geometry of the lines, frequent in the furnace burners in TenarisDalmine, which would finally impact the value of the pressure drops. This would require model updates in order to fit to the changes on the line, resulting in a not affordable extra-work. The second method involves the construction of control charts for each line, considering flow-pressure characteristics curves that, when implemented at Level 1 of the ICT architecture, would also allow the control of the gas injection system. Alike, this possibility, not expensive, was considered of low flexibility, and sensitive to changes, with need for continuous manual updates. The third method considers the use of systems of Artificial Intelligence like Artificial Neural Networks (ANNs); to this end, Fumagalli et al. (2011) show an application of artificial intelligence for fault detection on a dynamic process, another approach of artificial intelligence for CBM is discussed by Uraikul et al. (2006), while Korbicz (2006) describes an application of ANN technique for fault detection. But, because ANNs somehow hide the logic behind the calculation on data and for the difficulty to implement ANNs through proper software libraries in TenarsDalmine ICT system, this solution was excluded.

The fourth option, effectively chosen for the VI Burnersys deployment, is the method of least squares or polynomial regression. Often a variable y can be expressed as a polynomial of a second variable x, where, in our case, y and x are, respectively, pressure and flow rate. Once known a series of values (x_i, y_i), with $i = 1, \dots N$, for every x_i the value y_i can be obtained by the formula (1), once estimated values of A, B and C. After tests on plant data, the method has been verified to be applicable to the case of Burnersys. Values of plant operations were in fact collected (flow in Nm^3/h and pressure in bar) through a data acquisition campaign of field data, resulting in the coefficients of formula (1) – $A = 672 \cdot 10^{-9}$, $B = 451 \cdot 10^{-5}$ and $C = -0.392$ – and a coefficient of determination (formula (2)) $R^2 = 0.999375$.

$$y_i = A + Bx_i + C{x_i}^2 \tag{1}$$

$$R^2 = 1 - \frac{{\sigma_{err}}^2}{{\sigma_{tot}}^2} \tag{2}$$

${\sigma_{err}}^2$ is the sample variance of the estimated residuals and ${\sigma_{tot}}^2$ is the sample variance of the dependent variable. Considering that values of R^2 close to 1 mean that the regressors predict well the value of the dependent variable in the sample, the obtained result confirms that the method is effectively able to model the scenario considered for our asset. Further on, this method revealed to be inexpensive and very flexible, and it is deemed to be easily adaptable to any kind of future modification to the gas supply lines. The regression model so built allows then to obtain the signature of good working condition, namely the variables to be used as reference values for revealing proper functioning of the asset. Starting from the signature of the process in good working condition it is thus possible to develop an expert system in order to identify deviations, and then handle the alarms to the operator or activate safety mechanisms of the furnace. The expert system is based on an iterative algorithm. During each iteration it collects flow rate and pressure data from the field, and by using the formula expressed in (1) it computes the measured flow rate to obtain the expected pressure of oxygen injector. Keeping into account an appropriate tolerance threshold, the measured pressure is compared with the expected pressure, and the measured flow rate is compared with the set point flow rate. The results of these comparisons are the input of the next steps of the algorithm.

A troubleshooting scheme, developed thanks to the results provided by the HAZOP analysis, is then used to map the deviation of the asset behaviour and, if a fault is detected, it provides an output video alarm on the operator screen with a check list of operations to perform in order to solve the problem. For instance, a warning will be shown on the operator screen to notify a possible methane/oxygen loss if both the following conditions are true: i) the difference between the measured and the set point flow rate is comprised within a tolerance range and ii) the difference between the expected and the measured pressure is above a tolerance threshold. Moreover, the operator terminal will show a list of possible actions to do in order to solve the cause of the malfunction, listed from the most likely to happen till the less one; the following is an example of a such list: i) check furnace flexible pipe, ii) check pipe gaskets and joint, iii) check furnace rigid pipe, iv) check anomaly on the nozzle of injector, v) check pressure sensor. The possible lists to be displayed by the VI tool has been created thanks to the HAZOP analysis, that hence concurred to create a complete intelligent maintenance system for advising the maintenance operator with the proper actions to do.

5. Implementation of the algorithm within the existing ICT architecture

To understand the ICT architecture of TenarisDalmine systems, thus to understand Figure 2 representing the architecture of the VI Burnersys, the reader can refer to standard IEC 62264:2003 and the hierarchical levels therein defined. The gas injection system is equipped with the necessary sensors in order to ensure

the proper functioning of the algorithms developed so far: each line has both flow meter and pressure sensor. The definition of the deviations from good working condition, the reference signature analysis and health assessment algorithm are then implemented on top of the sensors (accordingly with what specified in sections 3 and 4). The system is now running as a real-time software, available to operators.
More precisely, the architecture of VI Burnersys, described according to the scheme of IEC 62264:2003, is the following. Field systems (Level 0) considered for Burnersys operations are all the sensors installed in the plant. The control system is constituted by a PLC committed to acquire all the signals coming from the field, and to control the load. In particular, the system controls the fully automatic operation of the furnace, both the control electrodes for electricity, and control of the chemical energy. The fast acquisition system is connected directly to the PLC (the software is customized for TenarisDalmine for data monitoring and analysis), allowing both to watch real-time, and historical, analog and digital signals.
For what concern the use and functionalities of the VI tool, the signals from the field (flow, pressure and valves position) are sent to Level 1. During the run of the furnace, Level 1 performs calculations using the appropriate interfaces of the PLC, that sends data to Level 2, which displays them on a graph and stores them in a database for future use. In the "real-time" application the PLC allows to monitor the progress of the furnace operation during the technological cycle; in this mode it is also possible to set the thresholds, based on which the VI will generate alarms. At the actual development stage, the algorithm, explained in section 4, is running and so practically supporting the health assessment activity. Thus, all the main variables of the furnace are collected; the maintenance operator is then able to access the information necessary to make a diagnosis, once the VI has highlighted the anomalies. The diagnostic analysis is supported by the information deployed by the HAZOP analysis, while HMI (Human Machine Interface) Systems and Information Systems (Level 2) are constituted by a system allowing to set the set-point: this is the interface where alarms and process variables are configured and displayed.
For what concerns the integration with the existing ICT systems, the VI tool has been developed according to the TenarisDalmine standard: it takes into account, besides the company graphical standards for user-interface, the paradigms for the development of Level 2, hence compliance and interoperability with other company's ICT systems; interoperability allows then to consult data coming from the VI Burnersys on other tool platform (such as e.g. production monitoring system) connected with Level 2. This integration with company's ICT systems represents one of the main constraint that had to be addressed to guarantee the effectiveness of the tool and its direct use in the company, besides the proper functionalities of the implemented algorithms.

6. Conclusions

Production processes in steel making industry involve many variables, and operators cope with the tasks of monitoring, control and diagnose the health status of the assets. Often, this results in high difficulties to effectively analyze the current assets' behavior, to detect and diagnose eventual process anomalies. This finally impacts on the capability to take quickly appropriate control actions. These considerations, and the experience gained by the TenarisDalmine maintenance staff, gave the foundations for initiating a novel approach, introducing the herein presented Intelligent Maintenance System. The system enables to detect incipient failures through monitoring of the burning system of the furnace, before causing a downtime, that may also bring disastrous consequences on people safety, integrity of assets and production cycle. The fact that the ICT infrastructure was pre-existent, as well as the importance of safety issues in such asset operation, represented good reasons for investing in such intelligent system as solution for the company, bringing innovation for maintenance. Today, the system is running and the following table summarizes the main information about its adoption in a period of eight months.

Table 1: summary of Burnersys performance from October 2012 to May 2013

Date of installation of the system	October 2012	Number of real anomalies detected	66
Test time of Burnersys	October 2012 – May 2013	Number of false positive anomalies	3
Number of performed casts	5856	Number of false negative (not detected anomalies)	0
Number of anomalies highlighted	69		

The main novelties of the research herein presented, considering both industrial and scientific point of views, are related to: i) the practical implementation of an E-maintenance tool within a real industrial environment and ii) the idea of a type of formalization of CBM/e-CBM system based primarily on operational risk, as result of an HAZOP approach. In particular, the Intelligent Maintenance System can be considered as a proof of practical results of implementation of research concepts – grown in the scientific field of e-Maintenance – applied to support asset management operation within an industrial company.

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References

Abichou B., Voisin A., Iung B., 2012, Choquet integral parameters inference for health indicators fusion within multi-levels industrial systems: application to components in series. 2nd IFAC Workshop on Advanced Maintenance Engineering, Service and Technology, A-Mest'12, Sevilla, Spain.

Amadi-Echendu J. E., 2004, Managing Physical Assets is a Paradigm Shift from Maintenance. IEEE Transactions on Engineering Management, Department of Engineering and Technology Management, University of Pretoria, South Africa.

Baglee D., Knowles M., Yau C.Y., 2012, Development of Techniques to Manage Asset. Asset Management - The state of Art in Europe from Life Cycle Perspective, by eds. Paulien Herder, Ype Wijnia and Telli van der Lei, 143-154, Springer, 2012.

Djurdjanovic D., Lee J., Ni J., 2003, Watchdog agent an infotronics-based prognostics approach for product performance degradation assessment and prediction. Advanced Engineering Informatics, 17, 109-125.

Espíndola D., Fumagalli L., Garetti M., Botelho S., Pereira C., 2011, Adaption of OSA-CBM Architecture for Human-Computer Interaction through Mixed Interface, INDIN 11 conference, Caparica, Lisbon, Portugal, 26-29 July 2011, 485 - 490.

Espíndola D., Fumagalli L., Garetti M., Pereira C.E., Botelho S., Ventura Henriques R., A model-based approach for data integration to improve maintenance management by mixed reality, Computers in Industry, Volume 64, Issue 4, May 2013, 376-391.

Ferro L., Giugliano P., Galbiati P., Memoli F., Giavani C., Maiolo J., 2007, The electric arc furnace of Tenaris Dalmine: from the application of the new technologies of digital electrode regulation and multipoint injection to the dynamic control of the process, 16th IAS Steelmaking Conference, 6th – 8th November 2007,Rosario, Argentina, 59-72.

Fumagalli L., Ierace S., Dovere E., Macchi M., Cavalieri S., Garetti M., 2011, Agile diagnostic tool based on electrical signature analysis, proceedings of IFAC 18th World Congress, August 28th – September 2nd 2011, Milan, Italy, 14067-14072.

IEC 62264:2003 Enterprise-control system integration.

Ierace S., Garetti M., Cristaldi L., 2009,Electric Signature Analysis as a cheap diagnostic and prognostic tool, Proceedings of WCEAM2009 (World Congress on Engineering Asset Management), Athens, Greece, 28th – 30th September 2009, 750-757.

Korbicz J., 2006, Robust fault detection using analytical and soft computing methods, Bulletin of the Polish Academy of Sciences, Technical Sciences, Vol. 54, no. 1, 75-88.

Labowsky J., Svandova Z., Markos J., Jelemensky L., 2003, Model-based HAZOP study of a real MTBE plant, Journal of Loss Prevention in the Process Industries 20, 2003, 230–237.

Macchi M., Barberá Martínez L., Crespo Márquez A., Holgado Granados M., Fumagalli L., 2012, Value assessment of an E-maintenance platform, 2nd Workshop on Advanced Maintenance Engineering, Services and Technology (AMEST 2012), 22-23 November 2012, Sevilla, Spain.

Medina Oliva G., Iung B., Barberá L., Viveros P., Ruin Y., 2012, Root Cause Analysis to Identify Physical Causes, Proceedings of PSAM 2011 & ESREL 2012, Helsinki, Finland, 25 – 29 June 2012.

Muller A., Crespo Marquez A., Iung, B., On the concept of e-Maintenance Review and current research, Reliability Engineering and System Safety, 93(8), 1165–1187, 2008.

New South Wales Government Department of Planning, 2008, HAZOP Guidelines, Hazardous Industry Planning Advisory Paper No 8, 2008.

Rondi M., Memoli F., 2003, Increase of Productivity in Dalmine Steel Plant through the Application of Innovative Electrical and Chemical Technologies, La Metallurgia Italiana (in italian), Oct 2003, Vol. 95, no. 10, 53-60.

Uraikul V., Chan C. W., Tontiwachwuthikul P., 2006, Artificial intelligence for monitoring and supervisory control of process systems, Engineering Applications of Artificial Intelligence Vol. 20 (2007), 115–131.