Expert Systems Controlling the Iron Making Process in Closed Loop Operation

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1. Introduction

1.1 Iron making

Since heavy industry is often big in physical size, loud and dirty, it is often considered as low technology. This applies also for the iron and steel industry, and here especially for the early phases of the production chain: Iron making, the process of turning solid iron bearing materials into liquid hot metal (typically 1500°C, 94.5% Fe, 4.7% C, 0.6% Si, some additional trace elements), is a process, which is known in its earliest form since thousands of years. It was improved over the centuries and builds still the starting point for about 65% of the world's steel production.

An average blast furnace, which is the predominant production unit for liquid hot metal, has an inner volume of about 3500 m^3 and produces about 8000 t of hot metal per day, thus consuming about 12000 t of iron bearing material and 4000 t of coke per day. In many plants one or two blast furnaces feed the processes down stream. Therefore, any problems immediately have consequences on the whole plant. The furnace should operate continuously 24 hours a day. Restarts after shutdowns are technically challenging and very costly.

Controlling a blast furnace is very difficult, because the properties of the used materials are not known exactly and are not stable over time. Control actions regarding the charged materials, the so called burden, take several hours before a reaction can be experienced. Moreover, such reactions are often overshadowed by other effects. Therefore, operating a blast furnace was for a long time considered somewhere between art and magic, and was entirely based on experience, but – as we will show in this paper – was turned over the last few decades into science.

Blast furnaces are fed alternating with layers of coke, produced in a coke plant, and iron bearing materials like lump ore, pellets or sinter. For the latter two special production units, namely pelletizing plants and sinter plants are required.

Coal cannot be charged into a blast furnace because it does not have enough physical strength to withstand the conditions inside of the furnace. Also, it is not possible to charge too many fine materials, because this would lead to a blockage of flow of the reducing gas. Therefore sinter plants are required to convert a mixture of iron carrier fines, coke and some additive materials into solid chunks of material with a Fe content of more than 60%.

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An alternative to the production route described above is the COREX® process. It produces liquid hot metal, just like a blast furnace, but can be charged with coal instead of coke, thus eliminating the need for a coke plant. Sinter is not required either, because lump ore or pellets are used as iron carrier feed material.

1.2 Automation systems

After starting of the automation age, blast furnaces were soon equipped with so called basic automation systems, in order to automatically control more and more parts of the furnace operation (sequence logic). However, the operational setpoints were determined by experienced engineers. Soon, the need was felt to take away the "magic" of determining setpoints and replace it with science.
So, one of the first such applications were charge models, which calculate – under the assumption that all input and output streams are known – based on material balance calculations, which materials have to be charged by which amount, to get the desired results, which are hot metal and slag with a certain chemical composition.
Following this example more and more process models were developed, initially used only offline in some computer centres, and then with the advent of cheaper and more powerful personal computers more and more online.
However, there was still a lot of art in controlling the blast furnaces, because it was not possible to find proper algorithms for the problems at hand, and so the experience of the operators and the engineers still had a major impact on the performance of a blast furnace.
In the 1970's and 80's artificial intelligence techniques were slowly finding their way from universities and research centres into the "real world". Rule based expert systems and later fuzzy logic based systems were the leaders of this development. Neural networks and other data based techniques soon followed. Steel producers were not shy to experiment with these technologies and investigated whether they can benefit from them (Gottlob & Nejdl, 1990).

1. 3 Expert systems

Medical diagnosis systems were developed to support doctors in their work (e.g. MYCIN, Buchanan & Shortliffe, 1984). The underlying ideas were adopted by the iron making industry and similar systems were developed by several different suppliers and researchers (Hörl et al 2006, Inkala et al 1994, Sato et al 1988, Sun et al, 2002) throughout the world.
Although they used different techniques and tools, they all shared the same goals, which are

- establish a diagnosis of the status of the blast furnace
- suggest corrective actions if needed (therapy)
- explain the reasoning behind diagnosis and therapy

When we look at all existing blast furnace expert systems we can see that there are three different types, which also comply with the historical development of these systems.

- Intelligent alarming and forecasting expert systems: Such a system uses the measured process data, evaluates them, combines different values to form more complex diagnoses, forecasts certain blast furnace events, gives an alarm to the operator and is able to explain its results (diagnosis).
  However, such a system could not lead to measurable changes in the blast furnace process stability, was not fully accepted by the operators and - most important - could not decrease the operation costs.

- Advisory expert systems: Almost any blast furnace expert system found in literature belongs to this group. Such a system goes one step further as the one mentioned before. In addition to just establishing a diagnosis, it also suggests control actions to be performed by the operator, but still the last decision is with the operator. Such advisory systems were very well accepted and gave useful suggestions, lead to a uniform control philosophy over all shifts, but could not decrease the operation costs significantly.

  Closed-Loop expert systems: The main difference to an advisory system is the automatic and simultaneous execution of corrective actions when necessary. E.g., when the coke rate has to be changed this also influences the Silicon content in the hot metal. Therefore such a change requires simultaneously a change in the burden basicity. Such combined actions, especially when the system is fine-tuning the process and performs many corrections, cannot be handled by the interaction between operator and advisory system.

  Only with a closed-loop expert system, a significant reduction of the production costs can be proven.

The systems, which are described further in this chapter are all of the third group. The product family is called SIMETAL^{CIS} VAiron. SIMETAL^{CIS} BF VAiron is the system dedicated to the blast furnace. Product names for the other iron making production units follow the same pattern. In this paper, the name VAiron is used for short.

1.4 State of the art

Although the starting point was establishment of diagnoses, it turned out that diagnosis is nice and interesting, but the real question is "what do I have to do to stabilize and further optimize the production?". Only answering this question allows the producers to save money and of course this is the ultimate driving force and justification of any such developments. Consequently, modern systems should be referred to as Therapy Systems instead of Diagnosis Systems.

Starting with simple if-then-else rules, blast furnace expert systems were enhanced step by step to increase their capabilities:

- Fuzzy logic rules were added because it was felt that this kind of reasoning is closer to the way how people think. Also, it is possible to express the vague, heuristic knowledge in a much more natural way.
- As mentioned in the beginning of this chapter a wide variety of process models were developed. These models can be used by human operators, but they can also be used directly by an expert system, thus turning a rule based system into a model based (or better model enhanced) system.
- Neural networks or also other learning techniques are common applications in the current automation field. Expert systems can for example call such a neural network to interpret patterns in data and then use the returned information for the further reasoning process.
- Optimising the blast furnace process does not necessarily mean that the overall production site is at an optimum as well (local optimum, i.e. blast furnace only, versus global optimum, whole ironmaking area). Therefore is important that production units upstream and downstream of the blast furnace are also considered. This is described in more detail in chapter 4 of this paper.

1.5 VAiron expert system

The VAiron expert system is fully integrated into the online process optimization package, which is now installed on many iron making production units world wide, thus being involved in more than 10% of the world's hot metal production.

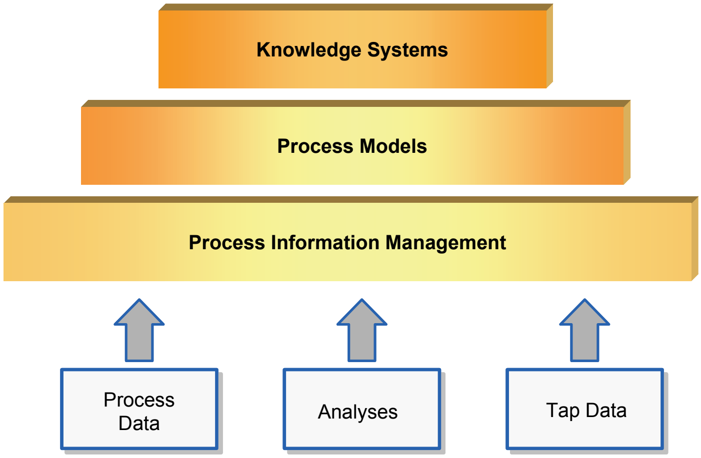

Fig. 1. VAiron Overall Structure

The top component "Knowledge Systems" is described in the following chapter.

2. VAiron expert system main modules

2.1 Data evaluation and preprocessing

2.1.1 Data handling modules

The purpose of the data handling modules of the VAiron expert system are to

- collect data from the different data sources, the main sources are continuous measurements , charging data (charging matrix setpoints and actual weights), cast data (timing information, hot metal temperature data, consumables, etc.), chemical analysis information for burden materials and hot metal and slag as well as plant status information (on/off conditions of the blast furnace and auxiliary plants)
- check whether used data are valid and provide substitutions if necessary and possible
- perform some auxiliary calculations

2.1.2 Data collection

Data used by the VAiron expert system are mainly measured values like temperatures, pressures or flows but also calculated tags like the gas utilization degree or the flame temperature. The measured values are read from the basic automation system with different scan rates which are corresponding to the rates of change of the underlying data points. The calculated tags are generated by various auxiliary modules of the VAiron system based on actual values and the history of process data.
The VAiron expert system needs actual values and the history of process data. Actual process data are taken taken from the memory of a dedicated VAiron system process. History data that are kept in the VAiron process database are read into memory of the

expert system whenever necessary. Target values are also stored in the VAiron database and may be maintained through graphical user interfaces at any time.
Charging data, cast data and plant status information are collected, processed and stored in the VAiron process database by dedicated VAiron system processes. These system functions are triggered by events generated in the basic automation system. Due to mechanical and operational reasons the handling of these data in the Level-1 system is different for every blast furnace but the final data structures in the process database which are accessed by the VAiron expert system remain the same.
Chemical analysis information for burden materials and blast furnace products (hot metal and slag) are important inputs to the VAiron blast furnace models and the expert system. The chemical analyses are either read from external systems (like Level-3, raw material handling, laboratory) whenever new samples are available or manually entered in the VAiron system through a graphical user interface. Again dedicated VAiron system processes for data handling guarantee that the final data structures in the process database which are accessed by the VAiron expert system remain the same for every VAiron installation.

2.1.3 Data validation

Data Validation methods are used by the VAiron expert system to find out if the raw values of process variables may be used in the expert system without further processing.
Data are checked whether they are up to date and whether they are reasonable from the process point of view. Such checks can be limit checks, rate of change calculations or the evaluation of simple formulas.
For example data which are checked whether they are up to date are the hot metal and slag chemical analyses because these data are used for thermal and quality control of hot metal and slag and have to be available for the VAiron expert system at least some time after the last cast is closed. A typical example for a consistency check based on simple formulas is the comparison between measured and calculated (based on blast volume and steam addition flow) blast humidity, and only the validated blast humidity is used for the blast moisture control module of the VAiron expert system.
In case missing or invalid data is detected, a message will be generated and displayed on the main screen of the user interface of the VAiron expert system.
In general the diagnosis and corrective actions of the VAiron expert system use different input data and need different quality of data. The decision whether all required input data for a diagnosis or corrective action are available and valid is made inside the diagnosis or corrective action. If data is missing or invalid for a diagnosis or corrective action the missing or invalid data and the violated checks are listed in the process overview log window, which is updated cyclically by the VAiron expert system.
The data validation checks of the VAiron expert system are highly configurable by using parameters for all relevant limits which can be maintained through graphical user interfaces.

2.1.4 Data preprocessing

Some diagnosis and corrective action modules of the VAiron blast furnace expert system require special auxiliary calculations. These calculation methods can be classified into the following groups:

- Time based statistics over arbitrary time spans (trends, mean values, standard deviations, minimum and maximum limits, etc.)
- Other statistics which combines different tags (for example mean values or arithmetic combinations of different tags)
- Additional calculations of high complexity which are provisional results of the respective expert system modules

For example the water leakage diagnosis of the VAiron expert system is interested not only in the actual values of the top gas H_2 analysis but also in the mean values, trends and minimum and maximum limits over some specific time spans. These calculations are provisional results of the water leakage diagnosis and thus can be performed by the diagnosis itself and do not have to be made available as tags for access by other modules of the VAiron system.
Another example for an additional calculation of high complexity is the computation of the change of SiO_2 content in the slag due to a change in hot metal temperature which is an intermediate result of the slag basicity corrective action of the VAiron blast furnace expert system.

2.2 Diagnosis calculation

2.2.1 Introduction

Diagnoses are established using fuzzy logic and conventional expert system (rule based) technology. The validated and preprocessed input data are fed to the fuzzy logic rule sets to establish an initial value for each diagnosis. Then additional process knowledge like actual actions of the operators or special situations are used to establish the final diagnosis results.
Usually the result of the diagnosis is in the range [-1,…,+1] using arbitrary units. The results of the diagnoses are visualized graphically on the main screen of the VAiron expert system using a kind of traffic light system with red, yellow and green zones for the diagnosis result ranges very low and very high, low and high and normal respectively. Additionally, a detailed description of the input data and results of each diagnosis are contained in the process overview log window of the VAiron expert system as part of the overall explanation.
The diagnosis rules are implemented relative to a configurable, and therefore easy modifiable, target value; absolute values are avoided at any time.

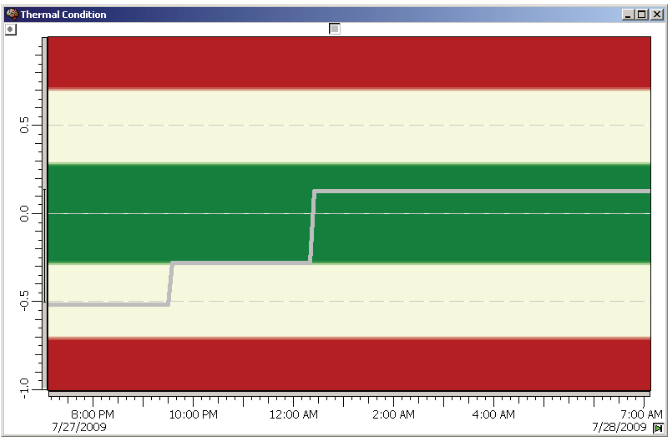

Fig. 2. Graphical Display of Diagnosis Result

2.2.2 Example of blast furnace scaffolding diagnosis

Scaffold build-up and removal (peeling) are permanent processes even in a smoothly running stable blast furnace. Whenever the build-up of scaffolds in a certain area exceeds a maximum limit for a longer time, the operators in the blast furnace control room have to pay attention on this phenomenon because a sudden removal of large scaffolds might have negative impact on the thermal level of the hot metal.

The scaffolding diagnosis of the VAiron expert system gives the operator a visual indication of the scaffold build-up and removal tendencies.

Initially two individual diagnoses are established, one for scaffold formation and one for scaffold removal, which are then combined into one diagnosis, which is displayed in the HMI. Depending on the cooling system of the blast furnace such diagnoses can be established separately for various sections of the furnace. Following is a list of input data. Note, that as described above, there are measured as well as calculated values used.

- Average heat flux over different time spans
- Normalized trend of the heat flux different time
- Average of the top gas utilization over different time spans
- Number of hot blast furnace cooling elements in the considered section, which is the result of a different diagnosis

The figure below shows the user interface screen which combines the scaffolding diagnosis results of all sections of the blast furnace which gives the control room operator an immediate overview of the ongoing build-up and removal activities and simplifies the identification of critical areas of the plant. When this screen dump was taken, the furnace was in a quite critical state, heavy scaffold formation was taking place in all sectors for several hours.

Fig. 3. Example Stack Visualization

The process overview log window of the VAiron blast furnace expert system contains the following explanation of the scaffolding diagnosis for a certain section:

```
Scaffolding - Middle Stack Quadrant 4: Peeling
 Heatfluxes: 7.01 [MW] Average: 6.86 [MW]  Trend: -0.01 [MW/h]
 Number of hot staves:        57.1[%]
 Top Gas Utilization:         47.21 [%]    Average:  47.08 [%]
```

2.3 Evaluation of corrective actions

2.3.1 Introduction

Corrective actions are proposals for the operating personnel to change some process parameters (setpoints). The VAiron expert system suggests one or more corrective actions out of a set of possible ones. Some of the corrective actions are provided qualitatively, that means the VAiron expert system suggests an increase or decrease of some process parameters instead of giving exact values to the user. Other corrective actions (e.g. fuel rate or slag basicity) are suggested quantitatively, that means the new process setpoints are calculated by the VAiron expert system.
Internally, the process of suggesting a corrective action is a two step procedure. First the actual situation is analyzed independently from other actions and also independently from the past. In a second step the history of the operation as well as of the process is taken into account. An example of such a post-processing step for the evaluation of the new setpoint for the coke rate is to take into account actual changes to the coke rate that were executed in the recent past shorter than the throughput time of the blast furnace.
Based on the configuration in the process database some corrective actions have to be acknowledged by the operators. The operators have to input a reason into the graphical user interface if they do not follow the expert systems suggestions and this corrective action is not executed. The entered reasons for rejecting certain suggestions are the basis for offline tuning of the expert system.
Explanations provide guidelines for the operators to understand why a certain corrective action was suggested or not. On the one hand the process overview log window of the VAiron expert system contains the status information for each corrective action and it is refreshed automatically every time the expert system runs. The following example shows the status information for the slag basicity corrective action and we see that finally no correction was required.

```
-- Rule 2: Slag Basicity
The slag basicity B2 of the previous tap {1568} was 1.154
(corr. value: 1.120 setpoint: 0.975 trend +0.0669 [1/h]
corr. trend +0.0669 [1/h]).
The HM temperature was 1534 [°C]
(corr. value: 1537 [Â°C] setpoint 1500 [°C]).
This results in a suggested change of -0.060.

From the previous basicity changes -0.017 are still active.
Therefore it is suggested to change the basicity by -0.043,
(maximum suggested basicity change is +/-0.050).

Because the tap number has not changed since the last suggestion,
NO suggestion is made.
```

Each explanation consists of two parts. The first one shows the current values of the most important process values involved in establishing the decision and the second shows the actions to be taken by the operators.

The following figure shows the graphical user interface for presenting a corrective action to the control room personnel. We see the detailed explanation of the suggested slag basicity change and the user has the possibility to reject the proposal of the VAiron expert system and enter a reason for this decision into the text box on the bottom of the screen. All data are stored in the process database and can be accessed offline for report generation and tuning purposes.

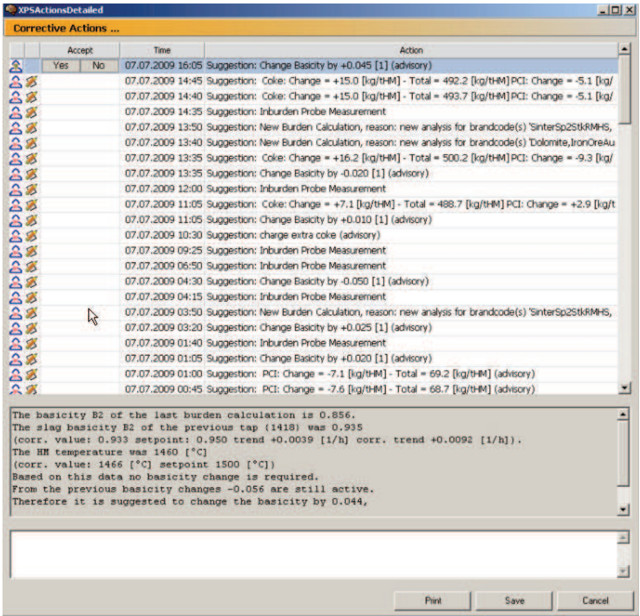

Fig. 4. Display Corrective Actions

The VAiron expert system knows two operation modes for a corrective action:

Advisory Mode (Semi-Automatic)

Closed Loop Mode

For operational safety and acceptance by the operators, all suggestions are displayed in the HMI. There is a configurable time span (typically 1 – 30 minutes) during which the operator can either confirm or reject the proposal. When the operator neither confirms or rejects, the action will be carries out if the setting of this action is closed loop, and it will be suspended if the setting is advisory mode.

For understanding of the two examples of the corrective actions suggested by the VAiron expert system we have to define what we mean by *active amount* of fuel or slag basicity. The *active amount* of a certain process variable is the sum of all changes of the process variable, which did not have time yet to produce a reaction of the blast furnace. Mathematically spoken it is a weighted sum of all changes of the process variable (i.e. changes of specific fuel rates in kg per ton of hot metal or changes of slag basicity) within the activation time span of the process variable.

The activation time span is different for different process variables. For example a change of the specific coke rate which is charged into the furnace from the top needs 5 to 8 hours to become metallurgically active whereas a change of the specific coal rate which is injected into the blast furnace tuyeres becomes metallurgically active within 1.5 to 3 hours. Therefore the VAiron expert system has to sum up the coke rate changes within the previous 5 to 8 hours and the coal rate changes within the previous 1.5 to 3 hours in order to compute the coke and coal active amounts respectively.

The question that remains is how the VAiron expert system knows the actual specific coke rate, the actual specific coal rate and the actual slag basicity at any time. This is done by the VAiron *Burden Control Model* which is triggered automatically when a new charging matrix which contains the material weight setpoints is activated on the Level-1 automation system. The result of this model are the specific (per ton of hot metal) rates of all materials (including coke and coal) and the complete hot metal and slag chemistry (especially the analysis elements which appear in the slag basicity definition).

2.3.2 Example of hot metal thermal control

The thermal stability of hot metal is an important objective of blast furnace ironmaking because it determines among other quality parameters the hot metal Sulphur content and the alkali balance.

The *Hot Metal Thermal Control* corrective action of the VAiron expert system calculates setpoints for the specific coke rate and the specific rates for the injected fuels through the tuyeres (coal, oil, gas) in order to keep the key quality parameters

- hot metal temperature and
- hot metal Si content

close to its target values.

The following input parameters are used by the VAiron expert system, in this example we assume that the reducing agents of the blast furnace consist of coke and injected coal (it could also be natural gas, oil or shredded plastics):

- Hot metal temperature of last casts, trend of hot metal temperature of last casts
- Hot metal chemistry (especially Si) content of last casts, trend of hot metal chemistry of last casts
- Target hot metal temperature
- Target hot metal chemistry
- History of the specific coke rate and the specific coal rate which are calculated by the VAiron burden control model

After the initial "calculation" of the required change of the specific fuel rate, we have to consider the active amounts of coke and. Then we have to split up the change of the specific fuel rate into changes of the specific coke rate and the specific coal rate. These changes are finally applied to the actual specific coke and coal rate in order to compute the new setpoints for the specific coke and coal rates.

All these intermediate calculation steps are presented to the operator through the graphical user interface of the VAiron expert system as we see in the following example:

Suggestion: Coal: Change = +6.1 - Total = 128.5 [kg/tHM] - 481.3 [g/Nm³] (advisory)

```
The current fuel rate is 565.5 [kg/tHM] (coke equivalent)
(coke=445.0 [kg/tHM] PCI=122.4 [kg/tHM])
The HM temperature of the last tap {1619} is 1460 [°C]
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(setpoint: 1500[°C] avg 1473[°C] trend -13.0 [K/h]).
The HM silicon of last tap is 0.373 [%]
(setpoint: 0.700 avg 0.436 trend -0.1175 [%/h]).
Based on the thermal condition a fuel rate change of +5.0 [kg/tHM]
is suggested.
Based on the HM silicon a fuel rate change of +5.0 [kg/tHM] is
suggested.
This leads to a suggested fuel rate change of +5.0 [kg/tHM].
(combination factors: 70.0 [%] temperature + 30.0 [%] silicon)

Since -1.9 [kg/tHM] from the previous changes are still active
(coke -1.9[kg/tHM],PCI 0.0 [kg/tHM], maximum total +/-15.0 [kg/tHM]),
a fuel rate change of 5.9 [kg/tHM] is suggested
(maximum suggested fuel rate change is +/-10.0 [kg/tHM]).

The following changes are suggested:
PCI: Change = +6.1 - Total = 128.5 [kg/tHM] - 481.3 [g/Nm³]
```

The VAiron blast furnace expert system automatically calculates a new charging matrix using the VAiron burden control model and sends the material weight setpoints to the Level-1 automation system. In other words the VAiron expert system prepares the new charging pattern automatically without further operator interaction.

2.3.3 Example of slag basicity control

The blast furnace slag basicity (defined as ratio of chemical compounds CaO/SiO_2, $(CaO+MgO)/SiO_2$ or $(CaO+MgO)/(SiO_2+Al_2O_3)$ depending on the raw material quality) has to be closely observed and controlled in order to keep the slag viscosity below a certain limit and to guarantee that the alkali compounds Na_2O and K_2O leave the blast furnace with the slag.

The *Slag Basicity Control* corrective action of the VAiron blast furnace expert system calculates setpoints for the charged material weights in order to keep the key quality parameters slag basicity close to its target value.

The following input parameters are used by the VAiron blast furnace expert system:

- Slag basicity of last casts, trend of slag basicity of last casts
- Target slag basicity
- History of the slag basicity which is calculated by the VAiron burden control model
- Target hot metal temperature and Si content as also used by the *Hot Metal Thermal Control* corrective action

The steps of execution are the same as in the thermal control described above. After the determination of the initial results, the active amount is considered to fine tune the expert system's proposal. Results are displayed in the HMI and also an explanation is provided. Triggering the VAiron burden control model a new charging matrix (and thus weight setpoints for the level 1 automation) is prepared and downloaded to level 1, where it can be used without any further operator interaction required.

It is important to mention that thermal level and the slag basicity influence each other which makes it difficult for the operator to keep control of these quality parameter because the hot metal temperature measurements and the results of the hot metal and slag chemical analysis for a certain cast are available at different times. The VAiron expert system has the ability to keep this overview and suggest the required corrective actions on time.

3. Savings and benefits

3.1 General benefits

3.1.1 Increase of operator know how

The VAiron Expert System generates textual explanations for the diagnoses and suggestions, allowing the operator to understand the situation in detail. Additionally, the user interfaces of the VAiron Expert Systems provide graphical information allowing for understanding the situation in brief. This combination of explanation facilities avoids the potential problem of high sophisticated automation solutions: the operational personnel looses its skills and get more and more dependent on the system. But permanent understanding the background of the system is more like an additional training for the operational staff, and even increases the skills of the operators.

3.1.2 Smooth plant operation

The earlier deviations from optimum conditions are detected, the earlier counter actions can be initiated. Moreover, this allows to apply small corrective actions instead of heavy ones. In a typical cycle time of five minutes, the VAiron Expert System checks:

- Several hundred measurement points from the Level-1 automation, and
- Related model calculations for internal process states which cannot be measured directly.

Even a high experienced human operator is not able to cope with this flood of information and therefore cannot identify process deviations as fast as the VAiron Expert System can do this. Also, no operator in the world can be constantly alert, but of course the expert system never gets tired.

In consequence, the main difference between manual operation and operation supported by the VAiron Expert System is that the later is characterized by more frequent, but smaller control actions. The resulting smooth operation of the blast furnace or the sinter plant avoiding heavy control actions and critical process situations leads to:

- Extended availability of equipment,
- Longer lifetime of equipment, and
- Reduced maintenance efforts and costs

3.1.3 Eliminating the human factor

Installing the VAiron expert system at a customer's plant goes in several phases. In a first phase the customer specific situation (raw materials, furnace geometry, equipment, operation philosophy, …) is analysed. Then the rules are adapted to the specific situation. Finally, during commissioning the rules are fine-tuned together with the customer.

This procedure has the following advantages

- High acceptance of the system, it is understood as their tool and not so much as some software which tells them what to do
- The customer's operation philosophy is followed 24 hours a day, 7 days a week.
- Consistent operation over all shifts, resulting again in a smoother operation

3.2. Specific benefits of VAiron blast furnace expert system

The general benefits mentioned in the previous section have long term character. An immediate advantage is not measureable, because reduced maintenance costs due to less wear and extended equipment lifetime appear only after years of operation with the system.

On the other hand, the VAiron Blast furnace Expert System gives also immediate benefits where the system pays back the investment costs starting on the first day of operation. The three main beneficial points in this respect are:

- Reduced specific fuel consumption and reduction of emissions.
- Increased productivity of the blast furnace.
- Stable hot metal quality even under usage of cheaper, low graded raw materials.

3.2.1 Reduced fuel consumption

A reduction of the fuel consumption leads to significant cost reductions for the blast furnace operating company and hand in hand to a reduction of emissions, especially of carbon dioxide. Depending on the original situation, and the magnitude of cooperation between the customer, voestalpine Stahl (GmbH) and Siemens VAI, the typical reduction of fuel consumption is between 5 and 15 kg fuel (mainly coke) per ton of hot metal. The following figure shows an example from a South African customer, where about 15 kg/t of hot metal have been achieved. The main factor for this excellent result was a very intensive cooperation between all parties:

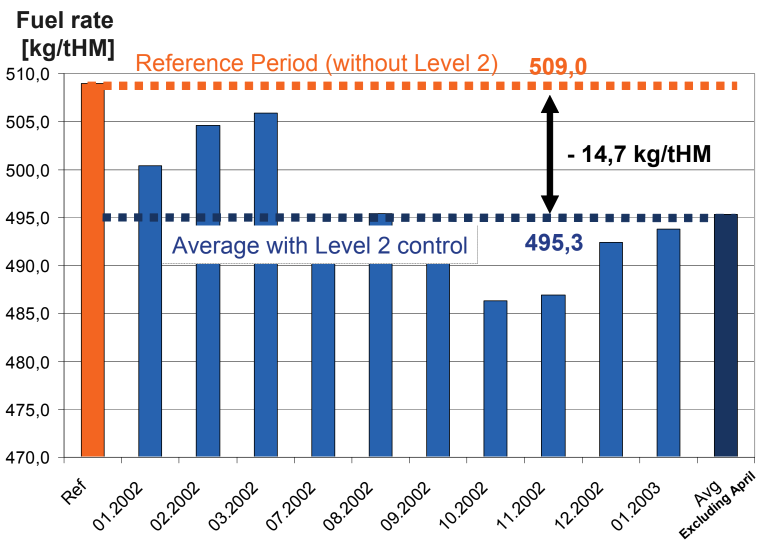

Fig. 5. Fuel Rate Savings Over Time

A severe incident in blast furnace operation is a freezing hearth. Therefore, operators tend to run a furnace warmer than required, giving them more safety in case of problems. By doing that, valuable coke is wasted. A closed loop expert system allows operating the furnace closer to its limits, therefore saving coke but still maintaining high operational safety.
Also, operators typically do not react immediately on incoming process data. If further data confirm the need of corrective action, quit significant corrective actions might be required. An expert system reacts earlier, and this allows typically smaller corrective actions.
15 kg/t of hot metal seem not to be a big saving, but considering a yearly production of 2 million tons of hot metal, the saving amounts to 30000 t of coke per year. With an average coke price of 200 €/t we end up with savings of 6 mill € per year!

3.2.2 Increase of blast furnace productivity

A further advantage of VAiron Blast furnace Expert System operation is an increase of productivity mainly resulting from stable operation avoiding process disturbances like e.g. hanging of the burden leading to reduced charging into the furnace, and therefore to reduced production. Additionally, the permeability control ensures optimum gas flow through the blast furnace, which also is a main factor for good productivity.

3.2.3 Stable hot metal quality

The VAiron Blast furnace Expert System receives the raw material and product analyses immediately from the laboratory. It reacts to deviations from optimum hot metal and slag analysis, and performs control actions to bring the quality parameters back to the setpoints. Fluctuations in raw material analyses are considered as soon as they are detected and the new optimum burden composition is calculated to avoid quality deviations in advance.
The control of fuel rate is keeping the thermal condition in the blast furnace hearth stable leading to stable hot metal temperature. Since there is a strong relationship between temperature and distribution of Silicon in hot metal and slag, the stable hot metal temperature implies stable Silicon content in the hot metal, which is an important requirement of the hot metal consumer, i.e. the steel plant.

3.3 Specific benefits of VAiron sinter expert system

Environmental regulations are rather tough in Western Europe and especially in Austria. To avoid problems due to exceeding emission thresholds, a special environmental diagnosis was introduced in the VAiron Sinter Expert System for voestalpine Stahl (GmbH) in Linz and Donawitz. This diagnosis warns the operational personnel as soon as the concentrations of dust or any other pollutant in the waste gas stack is approaching the threshold.
As in the case of the blast furnace system, the general benefits of the VAiron Sinter Expert System cannot be measured immediately. But the following specific benefits of the system allow for short term pay back of investment costs:

- Increased productivity of sinter plant.
- Reduced fuel consumption and emissions.
- Stable sinter quality.

3.3.1 Increase of sinter plant productivity

The usage of a higher percentage of sinter with stable quality in the blast furnace burden results in a further reduction of the blast furnace fuel consumption. Therefore, the increase of productivity of the sinter plant is a very important benefit of the VAiron Sinter Expert System. Typically, values between 2% and 5% can be achieved.
The VAiron Sinter Expert System was based on a former set of independent controllers for burn through point (BTP), return fines proportioning, coke addition, and for sinter basicity. The advantage of combining these controllers into a comprehensive expert system is the more general approach. The controllers do not act independently anymore, but their actions are connected by the system of rules. Additionally, the VAiron Sinter Expert System takes many more parameters into consideration, than the old controllers did. For example, while controlling the position of the burn through point parameters like harmonic diameter of sinter, actual return fines ratio, raw material mix, waste gas temperature, temperature on the cooler, etc. are also considered to prevent from short-sighted control actions, which would be done if only the actual position of the BTP is taken into account.

The gain in sinter plant productivity is mainly achieved by the rules and control loop controlling the BTP together with the optimum coke rate. Two independent control loops deal with BTP:

- The Classical (Longitudinal) BTP Controller, and
- The Transversal BTP Controller.

The classical, or longitudinal, BTP controller is basically watching the actual BTP position and adjusts the sinter strand speed in order to keep this point at the setpoint. The optimum position of the BTP (the setpoint) depends upon the specific plant. It is the optimum point balancing two phenomena: if the BTP is too close to the end of the sinter strand (the sinter machine speed is too fast), the sinter process is not yet completed, and a higher amount of return fines reduces the net production of the sinter plant. If the BTP is too far away from the end of the sinter strand (the machine speed is too low), then an increase of speed leads to an increase of sinter production.

Sinter plant productivity is a very good example for the interaction of human knowledge (customer and voestalpine Stahl (GmbH) process engineer evaluate the optimum position of the BTP) and artificial intelligence (the expert system takes care that the actual BTP is really at the optimum position).

The actual BTP is calculated from the average waste gas temperature in the wind boxes beyond the sinter pallet cars. It defines the mean position of the flame front. Since a sinter plant can be several meters in width, it is not clear, that the flame front is homogeneous, i.e. at the same position along transversal direction. A second control loop, the Transversal BTP Controller considers this situation. The following figure shows an inhomogeneous flame front at the left and a homogeneous one on the right.

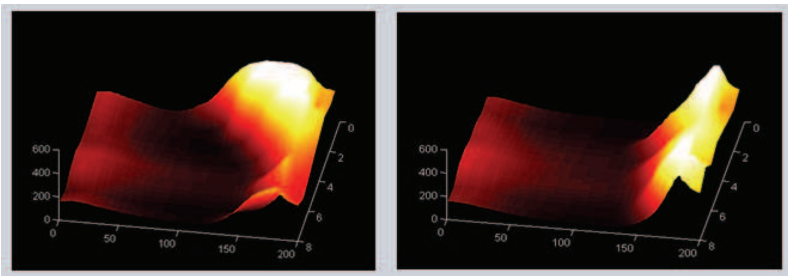

Fig. 6. Burn Through Point Position

3.3.2 Reduced fuel consumption

Similar to the VAiron Blast furnace Expert System, the VAiron Sinter Expert System reduces the fuel consumption of the process. Besides the immediate monetary benefit for the customer due to less expense for fuel, the positive environmental effect of less carbon dioxide emission is important. In the future this carbon dioxide effect will be an economical issue as well.

3.3.3 Stable sinter quality

The stable sinter quality is achieved by special quality controllers considering incoming sinter analyses from laboratory and performing counter actions, if deviations in one of the following quality parameters from the setpoint are detected:

- Harmonic diameter of sinter
- Sinter basicity
- Sinter SiO_2 content
- Total sinter Fe content

Additionally, fluctuations in raw material analyses are detected and the new optimum raw mix composition is calculated immediately, downloaded to the level 1 automation system and executed there. Obviously this is much faster than waiting to see effects in the produced sinter.

4. The next step: VAiron productivity control system

The VAiron Productivity Control System is a new development started by Siemens VAI together with voestalpine Stahl (GmbH). Target is the implementation of a powerful automated production control system for the various plants involved in the iron making process (i.e. coke oven plants, raw material yard, sinter plants, blast furnaces)
A superimposed expert system ensures a fully automatic linkage of the interacting plants. Thus an overall optimization of the complete plant network is realized instead of independent optimizations of the single plants which often do not represent the best solution.
This approach features essential benefits:

- Transparent and traceable production decisions
- Optimization of the complete plant network instead of independent single optimizations
- Reduction of costs and increase of production

4.1 Basic situation

At voestalpine Stahl (GmbH) hot metal is produced by three blast furnaces. Sinter and coke, which are input materials for the blast furnaces are produced in a sinter and a coke oven plant. Additionally other external material brands may also be bought in if needed. The involved plants are equipped with enhanced level 2 software automation system based on advanced process models and closed-loop expert systems.
Yet, there was the requirement for a superimposed system integrating the complete plant network. This missing overall link was the reason for the development of the VAiron Productivity Control System:

- Production control was done offline, decentralized and manually
- The necessary information were retrieved from different sources
- The executed measures were not fully traceable in the sense of quality assurance

4.2 Target situation

Target was a coordinated production control and an automated execution of the plan data by specifying setpoints which are sent directly to the level 2 automation systems of the involved plants.
The coordination of the production control is by an expert system considering actual deviations and evaluating production, resulting in optimized production setpoints.
The following targets were defined:

- Transparent and traceable plan data and planning decisions based on a clear identification and storage of all production plan data.
- Implementation of an authorization concept

- Automated production control with optimized production increase and cost reduction
- Control of the produced amounts and qualities in particular for the sinter plant, the blast furnaces and the coke oven plant

4.3 Implementation

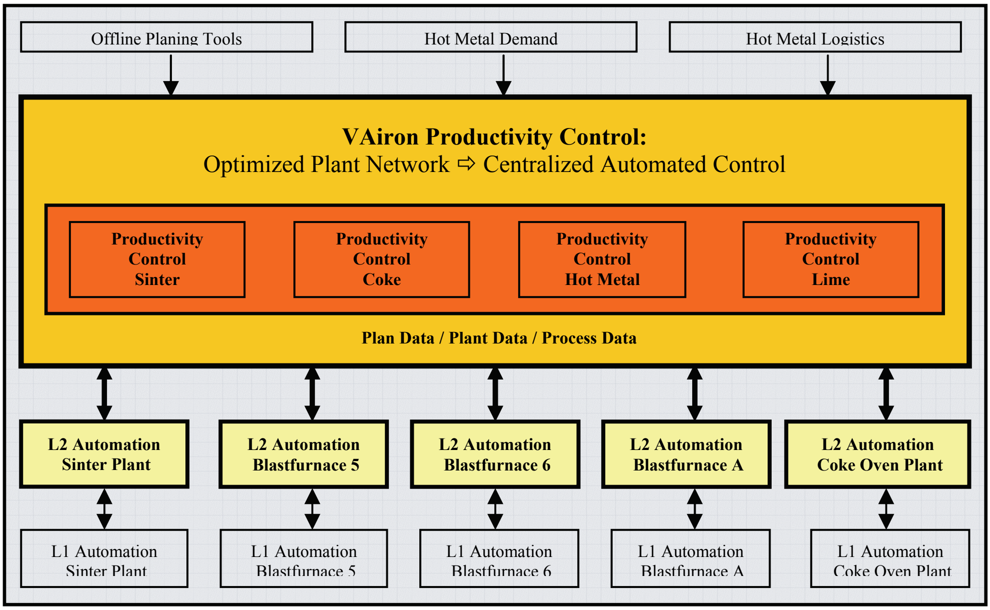

Fig. 7. VAiron Productivity Control System Concept

To meet the requirements the concept for a integrated solution package was defined (refer to Figure 7).

- A superimposed expert system ensures the overall optimization of the complete plant network and a centralized automated control
- The actual plan data provide the framework for this expert system
- The actual plant status data and the process data of the involved plants provide the input data for this expert system
- Fully automated interfaces between all interacting automation systems allow the exchange of all necessary data in all directions
- The optimized measures evaluated by the superimposed expert system are executed online by specifying setpoints which are sent directly to the level 2 automation systems of the involved plants. There, these setpoints are processed by local expert systems.
- Based on the measures finally resulting from the local expert systems, setpoints for the level 1 automation systems are preset and executed.

4.3.1 Production plan data

The actual production plan data provide the framework for evaluation of the optimized figures by the expert system. Therefore the recording, administration and implementation of the plan data is an integrative part of the system:

Annual plan data:
Planning done once per year for the next financial year.
Operation plan data:
Deviations from the annual plan data during operation are recorded separately in the system.
Detailed plan data:
Short-term deviations from the operation plan data resulting from current influences (actual plant status, process data ...) are handled using detailed plan data. The detailed plan data represent the latest and most binding plan data.

The system covers various features for the handling of production plan data:

- Recording of the actual plan data using a process database and a graded authorization concept
- Administration of annual plan data, operation plan data and detailed plan data
- Data exchange of plan data figures with other systems using automated interfaces
- Supply of up-to-date information about the currently needed and available amount and quality of the burden materials using automated interfaces to the involved plants and the raw material yard
- Automatic target-actual comparison of plan data and actual process data

4.3.2 Production control

A superimposed expert system is the kernel of the VAiron Productivity Control System. This expert system performs the production control by presetting the optimized target figures to the automation systems of the involved plants.

The expert system is charactarized by fully automated online processing:

- The overall optimized target figures are evaluated automatically by the superimposed expert system based on the actual plan data and the actual process data of all involved plants.
- These setpoints are preset directly to the level 2 automation systems of the involved plants.
- Local expert systems included in the level 2 automation systems apply the setpoints recieved from the VAiron Productivity Control System to evaluate detailed corrective measures.
- The setpoints resulting from the evaluation of the local expert systems are finally preset to the level 1 automation systems of the single plants.

A modular structure allows to extend the system in defined steps during the further development. Two modules are already integrated in the superimposed expert system, the production control of the sinter and the production control of the coke.

Target of the production control of sinter is the coordination between the sinter production in the sinter plant and the sinter consumption by the blast furnaces.

Basically for the operation plan the material mix of the sinter burden und the blast furnaces burden is calculated so that the produced amount of sinter minus process losses equals the sinter amount consumed by the blast furnaces. Anyway in real operation there are deviations of the sinter production as well as of the sinter consumption. These deviations are buffered by the sinter stock.

To ensure an operation with a defined sinter stock level a control of the sinter consumption of the blast furnaces is implemented by evaluating and presetting the target sinter basicity figure for the sinter plant.

Target of the production control of coke is a defined stock level of coke produced in the coke oven plant in Linz. Therefore this module evaluates the optimum ratio of the coke brands charged at the blast furnace and readjusts the setpoint.

4.4 Further actions

A first version of the VAiron Productivity Control System implemented with the described functionality is in use at voestalpine Stahl (GmbH). At the moment the actually implemented modules are fine-tuned and optimized.

For the future the gradual integration of further modules in the existing expert system is planed. Ideas are e.g. an optimized distribution of the available oxygen between the blast furnaces, the control of the slag quality for better utilization or the control of the hot metal amount.

5. Conclusions and outlook

It was shown that a powerful automation system based on expert system technology, ensures that the know-how and experience of the best operators and engineers are executed 24 hours a day, can lead to tremendous cost savings. These savings by far outnumber the costs of such a system.

Although reduction of costs is the predominant reason for installing such systems, there are also other benefits, that can not be quantified, but are worth mentioning, as there are for example

- Fewer process disturbances
- Smooth consistent operation in all shifts
- Early detection and therefore early reaction on any process changes or upcoming problems

Basically all developments were driven to reduce the final cost of the hot metal. It has been shown in more than 100 references that Blast Furnace and Sinterplant expert systems can significantly contribute to reduce the production costs. As the next step to further optimize the complete Ironmaking process, we are confident that the VAiron productivity control expert system will give us the desired result.

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