SYNOPSIS:

Over the past few years, global steel industry has been in deep crisis. It was largely driven by a combination of several factors such as declining demand, overcapacity, tumbling steel price, high volatility of raw material market, etc. Although the market condition is getting better now, some fundamental issues are not completely solved. “Be vigilant in peacetime” - many companies have realized the significance of continuously improving cost competitiveness in order to prevent from another possible crises in future. However, some steelmakers may face great challenges while trying to cut cost. These challenges were identified and analyzed in this paper. Following key principles of Industry 4.0, a strategic planning and decision optimization platform was presented. It aims at helping senior managers of steel plants improve profitability by optimizing raw material procurement, adjusting operating parameters, balancing energy consumption and identifying value creating investment opportunities in a “integrated” and “intelligent” way. This system is able to make effective trade-off between cost control targets of different operation units so as to maximize company’s overall profit. Several industrial examples were discussed, which illustrated an annual cost saving of 2-6 Euros per ton of steel could be achieved.

**Keywords:** iron and steel, integrated optimization, strategic planning, raw material procurement optimization, cost savings, Industry 4.0

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1. Background

Over the past few years, global steel industry has gone through a deep crisis and faced with an extremely bad financial situation. Such an industry-wide poor performance was driven by the combination of many factors, such as declining demand, overcapacity, tumbling steel price, all-time high volatility of raw material market, etc. Fortunately some gratifying improvements have been observed since late 2016. China has been putting significant efforts, on one hand, to increase spending on infrastructure construction to boost domestic demand; on the other hand, to shut down illegal and inefficient steel mills that produce inferior products or cause pollution. These efforts helped balancing global supply and demand and provided strong support for the recent steel price rally. Although the market condition is getting better now, steel overcapacity has not been reversed fundamentally and today’s high steel price could result in production rebound as many steelmakers may operate at full capacity for profit taking. Nobody knows how sustainable the current market condition will be.

“Be vigilant in peacetime”. Many companies have already realized the significance of continuously improving cost competitiveness to prevent from another possible crisis in future. They put tremendous efforts, investments and resources for cost cutting. However, some of them had difficulties to achieve expected return of investment and hardly contribute to company’s cost competitiveness. From many visits to worldwide steel producers, we noticed that the following issues have often not received much attention, but they could notably devalue the above efforts and investments.

First of all, “focusing on cost control of each individual operation unit, but failing to capture cost interactions between operation units or between operation units and external market”. Steel production is divided into multiple independent operation units: coke plant, iron making, steelmaking and so on. In most cases, these units run independently like “silos” and don’t share their cost information to each other. While trying to reduce production cost, corporate management normally assign a cost control target to each individual unit without considering the potential cost interaction between them. Thus many considerable cost saving opportunities will be simply missed.

Secondly, "paying attention to market changes, but lacking of efficient tools to analyze and respond to the market changes quickly". With the increased volatility of raw materials and product prices, more and more companies started to pay close attention to market changes. Unfortunately, many of them are still at the level of using a few Excel files, either simple or very sophisticated ones, to manage and analyze market information. This caused many unavoidable problems: inconsistent and inaccurate data, time consuming for market analysis, lack of support of intelligent and advanced analytical tools, and so on. Steel companies are in great need of an integrated cost optimization system to suggest the best decisions to respond quickly to the changing market conditions.

Last but not least, “investing heavily in process and equipment improvement, but disvaluing the impact of managerial innovation”. Significant investments have been spent on massive process improvements to have the best in class of equipment and automation systems, whereas very few have been used to improve management decisions by taking full advantage of business intelligence or decision support systems. They are complementary to the existing MES or ERP system, and provide added value for senior management team to make informed decisions on important procurement and production strategies.

It won’t be an easy task to solve these issues quickly as it will touch many operation and management aspects of a steel company – production planning, operation improvement, cost control, performance assessment, investment and strategic development – just to name a few. With the new trend of Industry 4.0, some of its concepts and technologies can be borrowed to tackle
these problems. In this paper, three aspects are discussed: *Integration*, *Intelligence* and *Interrelation*. Following these principles, a strategic planning and decision optimization platform is presented together with some industrial case studies.

2. Inspiration and Impact of Industry 4.0 on Steel Manufacturing

“Industry 4.0” was originated in Germany with the intention to promote the new era of digitalization of manufacturing. The name is inherited from previous three industrial revolutions since 18th centuries, namely *1st revolution of machinery and steam power*, *2nd revolution of electrical power and automation* and *3rd revolution of computer and information technology*.

Under Industry 4.0, manufacturing is led by a number of so-called “cyber-physical systems”. It normally comprises of computers, networks and physical processes with embedded computation software, sensors and Internet connectivity. Such cyber-physical systems allow manufacturers to completely integrate the physical manufacturing with the virtual world through “Internet of Things”, in which computers and networks monitor and control the physical processes, with feedback from the physical processes impacting the subsequent operations. Up to now, steel industry hasn’t seen a true Industry 4.0 plant equipped with cyber-physical systems. However its concepts and technologies can already be applied to tackle today’s challenges.

*Integration* plays a central role in Industry 4.0. It aims at connecting all functions and data across the entire value chain, in both the vertical linkages in production processes as well as the horizontal linking of multiple functional systems that may be possibly beyond corporate boundaries. This concept is also very important in steel manufacturing. Figure 1 illustrates a steel plant with different operation units connected together through material, energy and capital flows to form a complicated process. To reduce production cost, one must consider this process as an integrated value chain and pay more attention to cross-operation decisions. For example: (1) what will be the optimal sulphur content in hot metal? (2) should cheaper coal be used to make high-S coke at low cost and thereafter leading to high-S hot metal, or vice versa to reduce desulphurization cost at steelmaking? (3) how will this optimal sulphur content be changed with different product mix determined by market demand? (4) what will be the best allocation of hot metal between multiple steelmaking shops depending on their different production capacity, steel grade mix, scrap price and availability? As one could see, these questions are not focused on individual operation unit, but all related to significant cost trade-off between different operation units or between operation unit and external market. Without an integrated viewpoint of entire value chain, it will be very difficult for steelmakers to identify these potential cost saving opportunities.

*Intelligence* is one of key technologies of Industry 4.0. It can be divided into two main themes: (1) “smart factory” focusing on intelligent equipment and production facilities, such as robots, 3D printing as well as distributed production networks; (2) “intelligent production” involving management and logistic decisions of entire enterprise – Big Data, machine learning and decision optimization technology all fall into this theme. Considering the above steel plant, it is no doubt a challenge to answer those cross-operation questions, especially when taking them into account simultaneously. It involves hundreds of decisions to make and can have impacts on many different aspects of the entire steel process. Solving these problems will largely rely on intelligence, for example, decision optimization technology can be used to construct a large-scale nonlinear optimization model and find the optimal combination of these decisions to achieve the minimum production cost.
Figure 1. A typical steel plant

Interrelation of human beings is also an important factor for Industry 4.0. As previously described, it is very common to see even at a very advanced steel plant that people at different operation units and functional departments work independently like “silos”: the communication between each other is not effective and the cost information is not shared transparently. Without breaking these “silos”, many cost saving opportunities cannot be exploited. Therefore a collaborative platform is a must-have, on which all stakeholders from procurement, production planning, cost control, operation and so on can cooperate, communicate and jointly find cost saving opportunities.

3. Integrated Decision Optimization for Cost Reduction

Following these principles, a Steel Cost Optimization (SCOOP) system has been developed and implemented successfully worldwide. SCOOP is an “integrated” and “intelligent” decision optimization platform. It covers the entire value chain of steel production, as shown in Figure 1, from raw materials procurement to end products produced at downstream facilities. SCOOP system is based on a sophisticated mathematical optimization model, which systematically considers all aspects of steel production, including raw material properties, mass/heat balance, intermediate and final product quality, as well as raw material prices, resource availability and revenue of products sold to the market. It recommends the best strategy to either minimize production cost or maximize company’s overall profit. Due to both technical and economic constraints being combined into one optimization model, SCOOP solutions are not only economically optimal, but also operationally feasible.
Figure 2 depicts SCOOP system’s functional diagram. It takes into account the market uncertainties from both supply and demand sides: the supply-side uncertainties exist in the market price and availability of raw materials; and those at the demand side come from the changes of market demand and price of final products. According to the company’s strategic goal, SCOOP system can choose from different objectives and suggests the best “all-in-one” solution for procurement, production and sales. Its four main functions are described in details in the following sections.

![SCOOP system functional block diagram](image)

### 3.1 Raw material procurement optimization

SCOOP system considers all types of raw materials, including coal, fuel oil and PCI, external coke, iron ore, lump ore, pellet, scrap, addition/flux, ferroalloy, external slab and coil. Instead of using traditional method of evaluating raw materials based on the “value of use”, which solely relies on raw material’s price and chemical compositions, SCOOP system proposed a new approach, *Limit Marginal Price* (LMP), to dynamically evaluate the true value of each raw material. In this approach the raw material evaluation also depend on many other aspects such as inventory, market supply and demand, operating conditions, equipment utilization, and final product mix.

The LMP of one raw material is defined as its purchase price plus attractiveness of the next ton of this raw material. The attractiveness means if one more ton of this raw material becomes available, how much it could contribute to overall company profit. This value can be positive or negative. A positive attractiveness indicates it is a valuable raw material and should be purchased more. The negative one implies this raw material has no value unless a lower purchase price less than its LMP can be negotiated. In short words, the LMP represents raw material’s true value under a specific operating condition.

Table 1 gives an example of SCOOP optimization results on selected coals available in the market. First of all, it suggested which coal to buy and the optimal quantity to buy. Then the LMP and attractiveness of each coal were calculated for each available coal. In this specific example, “RMS” and “NRF” both show positive attractiveness, which implied the procurement
department should purchase more of them for increased profit. If availability limit was reached (for instance 800kt in this example), the procurement department could even pay a higher price to obtain extra amount as long as the purchase price is not beyond the LMP.

Table 1. Raw material optimal procurement solution and LMP calculation

<table>
<thead>
<tr>
<th>Coal code</th>
<th>Optimal purchase volume (kt W)</th>
<th>Purchase price ($/t)</th>
<th>LMP ($/t)</th>
<th>Attractiveness ($/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAR</td>
<td>458.11</td>
<td>235.83</td>
<td>235.83</td>
<td>0.00</td>
</tr>
<tr>
<td>OAC</td>
<td>0.00</td>
<td>218.58</td>
<td>214.15</td>
<td>-4.43</td>
</tr>
<tr>
<td>OKN</td>
<td>0.00</td>
<td>225.85</td>
<td>220.83</td>
<td>-5.02</td>
</tr>
<tr>
<td>LOK</td>
<td>0.00</td>
<td>234.90</td>
<td>225.20</td>
<td>-9.70</td>
</tr>
<tr>
<td>RMS</td>
<td>800.00</td>
<td>244.19</td>
<td>257.40</td>
<td>13.21</td>
</tr>
<tr>
<td>MAF</td>
<td>230.66</td>
<td>262.13</td>
<td>262.13</td>
<td>0.00</td>
</tr>
<tr>
<td>NRF</td>
<td>800.00</td>
<td>194.64</td>
<td>196.52</td>
<td>1.88</td>
</tr>
<tr>
<td>MCL</td>
<td>533.98</td>
<td>232.98</td>
<td>232.98</td>
<td>0.00</td>
</tr>
</tbody>
</table>

3.2 Production resource allocation optimization

Through integrated optimization of all operation units across entire value chain, SCOOP is able to:

- determine optimal cost control target of each individual operation unit in order to achieve company’s maximum profit.
- determine the optimal operating conditions for each unit, including optimal blending of raw materials, optimal production level, intermediate product and/or by-product quality and their best allocation between operation units.
- determine process bottleneck, and identify equipment and process improvement opportunities with the high return on investment.

In order to achieve above function, SCOOP system developed a complete set of process models to represent mass and heat balance of each process, which contains hundreds of thousands of model equations. A portion of these models needs to be calibrated based on plant historian data.

3.3 Energy consumption optimization

SCOOP calculates energy balance along steel process chain. It suggests the best distribution and utilization of COG, BFG and/or LDG, and furthermore optimizes the usage of natural gas, fuel oil and electricity purchased externally from public grid. In addition, SCOOP also calculates SOx, NOx and CO2 emissions, and optimizes the company’s overall profit by taking into account the emission penalty cost if any.

3.4 Production level and product mix optimization

SCOOP optimizes production level and product mix based on Marginal Cost. It is able to assess and sort all products according to their profit margin, and therefore determine the priorities for sale orders.

The marginal cost of a product refers to the cost incurred to produce the last tonne of this product, which is completely different from the concept of average cost. When production level is low, all operation units have the best raw materials, and there is no production bottleneck. At this moment, the marginal cost is normally lower than product sale price and hence increasing production means getting more profit. However, with the continuous increase of production, all best raw materials could be consumed and certain equipment may hit its
bottleneck. As the result, alternative raw materials and/or alternative capacity have to be identified and utilized, which will lead to higher marginal cost. Actually the marginal cost is a monotonically increasing curve with the increased production level. When it meets the product sale price, the corresponding production level is the optimum.

SCOOP system can analyze marginal profit (which equals to marginal cost minus sale price) to determine which product makes the most contribution to company’s profit. As shown in Figure 3, the products labeled in green are profitable as their sale price is greater than its marginal cost. These products should be produced more to meet the maximum market demand. On contrast, the products in red are at a loss, and their production should be reduced to meet the minimum contract demand.

![Figure 3. Product (groups) profitability sorting based on marginal cost](image)

### 4. Case study

SCOOP system has broad applications in either an integrated steel mill or a mini-mill. As an intelligent decision optimization platform, it has been proven to be a very powerful tool to support the following decision-making processes:

- **Optimal procurement**: use LMP to dynamically evaluate the true value of all raw materials available in the market and determine the optimal purchase. LMP can also be used to negotiate price or volume to purchase with different suppliers.

- **Optimal blending of coal, iron ore and/or scrap**: SCOOP system suggests the best raw material blending by taking into account the possible changes of raw material quality and price, as well as market demand.

- **Optimal production planning**: optimize hot metal distribution between different steelmaking shops; or optimize product mix to focus on the most profitable products based on their marginal cost.

- **Optimal operating point**: decide the optimal process parameters, such as sulphur content and silicon content in hot metal, coke quality (with impact on PCI usage and productivity of blast furnaces), etc.

- **Optimal strategic study**: identify process bottlenecks and calculate ROI for new process improvements.

In the following sections, two industrial case studies are discussed.

#### 4.1 Optimal decision on raw materials procurement
When SCOOP system was used for annual budget planning, one company found a specific coal always showed positive attractiveness. Based on SCOOP suggestions, the coke plant started to increase the usage of this coal in the blend step by step. As shown in Figure 4, by the end of the year, the coal blend ratio has been completely changed – the usage of this coal was increased from 18.5% to 37.9%. Significant cost savings was achieved due to reduced coke production cost.

![Figure 4. Percentage of one specific coal in the blend](image)

### 4.2 Evaluation of impact of new PCI on slab cost

Under the ever-changing marketing condition, a carbon steel plant identified a possibility to use a low-price petroleum coke PCI, named CPATE. Although its price is low, it has relatively high sulphur content (i.e., 4.57%). This would impact on sulphur in hot metal, leading to higher cost of desulfurization at steelmaking shops. Should CPATE be used and if so, what will be the impact on slab cost? Integrated optimization makes SCOOP system a perfect tool to answer this type of cross-operation questions. To do it, CPATE was added into the model as a newly available raw material, together with its detailed chemical composition, physical properties, market price and availability. SCOOP optimization had given the following results:

- A new optimal blend ratio of PCI, which includes CPATE. This implies CPATE has positive impact on overall profitability.
- The maximum PCI rate was calculated as 150kg/t of hot metal.
- The sulphur content of hot metal produced by each blast furnace was given in Table 2, with comparison to the base case in which CPATE was not used.
- And most important, SCOOP calculated the economic impact of CPATE on slab cost. As shown in Table 3, the overall slab production cost was reduced by 7.34 €/t of steel, which is mainly contributed by decreased hot metal production cost of 8.71 €/t of hot metal and increased desulfurization cost of 0.66 €/t of steel at steelmaking.

<table>
<thead>
<tr>
<th>Sulphur content (%)</th>
<th>BF#1</th>
<th>BF#2</th>
<th>BF#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case without CPATE</td>
<td>0.041</td>
<td>0.040</td>
<td>0.044</td>
</tr>
<tr>
<td>New case with CPATE</td>
<td>0.081</td>
<td>0.079</td>
<td>0.082</td>
</tr>
</tbody>
</table>

Table 2. Economic impact of CPATE

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Difference</th>
</tr>
</thead>
</table>
Impact on hot metal production cost | - 8.71 €/thm
Impact on desulfurization cost | + 0.66 €/tsl
Impact on slab production cost | - 7.34 €/tsl

It can be concluded that CPATE is a very attractive PCI, which can make a significant improvement on the overall profitability. A further sensitivity analysis also revealed the change of slab cost with different consumption rate of CPATE. It determined the optimal usage of CPATE is 367 kt/yr. This will be the target set for procurement department to purchase.

5. Summary and Conclusions

Nowadays SCOOP has been successfully implemented in more than 15 steel production sites, including Aperam Stainless Steel, ArcelorMittal, CSN, Erdemir, Gerdau, NLMK, Severstal, Thyssenkrup CSA, Usiminas, etc. Past experiences showed SCOOP could help achieving annual cost savings of US$ 2-6 per ton of steel. The cost savings could come from one or more of the following sources:

- Integrated optimization of entire value chain from raw material purchasing to downstream facilities instead of considering local optimization of each individual operation unit.
- Better understanding of processes and complex impacts involving multiple operation units. As the result, decisions can be made based on appropriate trade-off to achieve maximum overall profit.
- Additional negotiation power gained by assessing true value of raw materials using LMP.
- Improved communication and information sharing of all stakeholders by breaking down internal “silos”.

On the journey towards the 4th industry revolution, SCOOP system well adopted some key concepts and technologies of Industry 4.0. It truly focuses on integration, intelligence and interrelation of human beings; helps steel industry identifying procurement and production strategies to maximize overall profit and improve company’s cost competitiveness.

References
