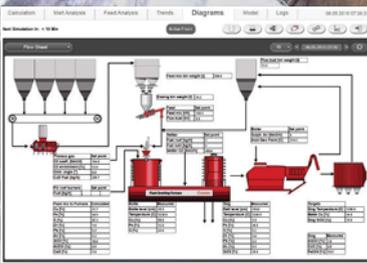
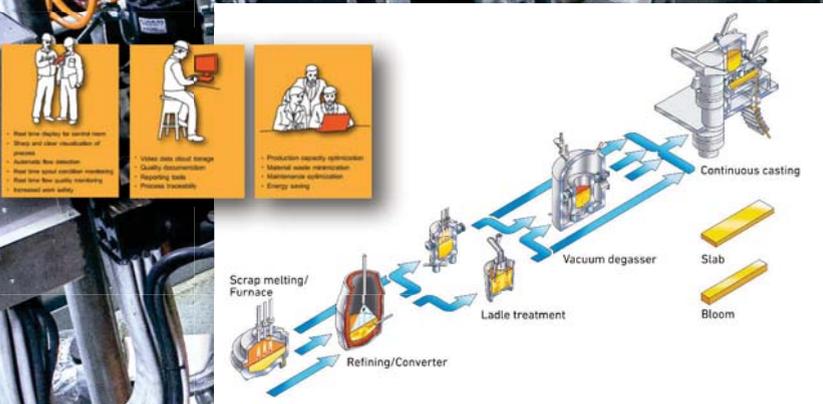


## SIMP – SYSTEM INTEGRATED METALS PROCESSING

2014 –  
2017



**DIMECC**

FINAL REPORT 4/2017

# SIMP – SYSTEM INTEGRATED METALS PROCESSING

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## CONTENTS

<b>DIMECC FOREWORDS</b>	
Ülo Parts: Digitalization and processing of metals .....	4
<b>PROGRAM MANAGER'S REVIEW</b>	
Ingmar Baarman: Co-creation in SIMP.....	6
<b>INDUSTRIAL REVIEW</b>	
Mikael Jåfs, Jarmo Lilja, Mikko Ylitalo: The DIMECC collaboration platform is of fundamental importance to the future of the Finnish metal industry .....	9
<b>RESEARCH INSTITUTE'S REVIEW</b>	
Timo Fabritius, Mari Lundström: Fostering the new generation for innovative Finland .....	12
<b>DIMECC SIMP in nutshell</b> .....	14
<b>Flexible copper plant operation with a wide range of raw material quality</b> .....	15
Tools 1–17 .....	37
<b>Dynamic multiphysics modeling for steel production</b> .....	54
Tools 1–11 .....	80
<b>Advanced quality monitoring methods for steel production</b> .....	91
Tools 1–24 .....	121
<b>Decision support of metallurgical processes</b> .....	145
Tools 1–22 .....	166
<b>System modelling to optimize low-carbon footprint fuel usage in the Finnish metallurgical industry</b> .....	188
Tools 1–14 .....	215
<b>Appendix: Graduated PhD students in DIMECC SIMP</b> .....	229
<b>Appendix: International co-operation partners</b> .....	231

# Digitalization and processing of metals

We are living in the age of digitalization. Digital change and opportunities have a high priority in the public sector and especially in business. Digitalization is often seen as a cost-cutting and efficiency asset for companies. However, there are many more opportunities: manufacturers are providing product and service combinations by taking a holistic view of customers' needs. Furthermore, the biggest changes will happen when the whole value chain in digital disruptions is re-designed, potentially by completely new competitors. This is clearly visible in consumer businesses. Similar changes are in the air in manufacturing, where servitization and platformization will change company boundaries by transforming business-to-business relations toward business for business.

The DIMECC SIMP program has taken challenging targets to bring benefits from digitalization to the metals and metals production industry. The program focused on the digitalization of highly complex process chains by modeling, simulations, and analysis, which, in the end, will enable real-time predictive control in the plant environment. Those have a clear impact on production and resource efficiency for one of the biggest export sectors in Finland. Such an approach provides a different angle compared to the general discussion in digitalization.

The success of the program shows, once again, a good collaboration culture within Finnish metals and metals production companies in pre-competitive areas, together with excellent research groups. One of the great examples has been visits and seminars by doctoral students in factories to see actual facilities where research results will be applied, and to get direct information from factory personnel, including not only R&D staff but also the operators controlling the processes.

The DIMECC SIMP team has achieved great results in the program, and these are summarized in this final report. I want to thank the whole team for good work on the program, and also the program preparation team for their visionary work. In addition, special acknowledgements are made to program manager Ingmar Baarman, for facilitating efficient cooperation between industry partners and leading researchers.

The program report at hand describes a summary of the SIMP program results. When reading the report, you will get insights for future

development needs and, somewhat surprisingly, you will see new innovative product and business opportunities, which are according to the main lines of digitalization described at the beginning of this foreword.

We at DIMECC are pleased that good progress has been achieved through our programs. While reading, you will also note that, obviously, there is still a lot of R&D work needed in the future – DIMECC together with a strong ICT partner network could comprehensively support those needs in digitalization.

Good reading!



**Ülo Parts**

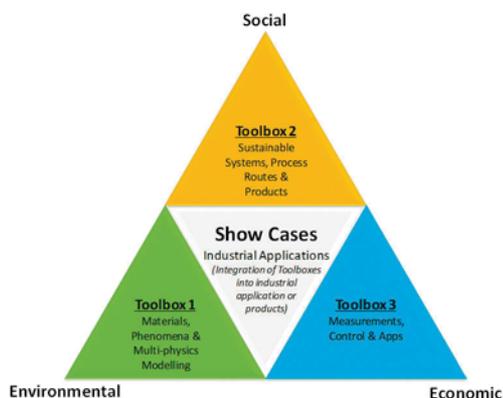
Executive Vice President,  
Operations

### Co-creation in SIMP

“SIMP” in DIMECC’s SIMP program stands for System Integrated Metals Processing. Some people say that this is the digitalization project of the metals processing industry in Finland. This is true, but honestly, the digitalization of the production processes is no new thing to metals producers in Finland. Instead, I would want to emphasize “System Integration” in SIMP.

New and innovative models and measurement technologies have been developed in the program to optimize the production processes. The aim, throughout the program, has been to integrate these innovative models and measurement technologies as far as possible into the control systems of the production processes. Only by this system integration can the full benefit of the models and measurement technologies (the tools) be achieved. In the best cases, the tools have already been piloted in full-scale production tests, leading to significant improvements in economic, environmental, and social terms. In the years to come, we will realize the full benefit of this system integration, when even more tools originating in SIMP are developed for production use. So far, we have only scraped the surface, or demonstrated the feasibility of the system integration concept.

We have divided the tools into toolboxes to structure the program. Toolbox 1 contains the models, materials, and phenomena. Toolbox 3 contains the measurement systems, controls, and apps. Toolbox 2 contains the tools for integrating the models and measurement systems in the processes and control systems.



**Figure 1. Program overview that shows Show Cases as the gravity point, fed by the (generic) toolboxes (TB 1 to 3) embedded within sustainability principles (social, environmental, economic)**

By defining the tools and dividing them into toolboxes, we promote the sharing of knowledge (i.e. tools) across the boundaries between the projects in the DIMECC SIMP program, or the Showcases, as we have called them. Most of the tools are described in the one-pagers following each chapter of this report, and as you will see, there are several examples of tools that have been successfully utilized in more than one project in SIMP. This sharing process will continue far beyond the finalization of the SIMP program.

Developing the tools into systems that can be integrated into a live and continuous metals production process has been an exercise in cooperation between people with a wide range of competencies. Forcing researchers to cooperate with industrial staff, including operators in the production process, is very educational for all parties.

In addition to the purely scientific cooperation between industry and academia in SIMP, we have had efficient collaboration in the administration of the Show Cases. PhD students, post docs, professors, and other researchers have worked seamlessly together with the industrial and SME partners in the different administrative groups. Efficient administration has helped us focus on what is important: generating tangible improvements for the industrial processes.

DIMECC runs the two largest and most significant industrial doctoral schools in Finland: SIMP and Breakthrough Materials. The 41 PhD students in SIMP have received special attention. The idea has been to ensure that they develop a network among themselves, as the future decision-makers in the metals industry in Finland. We have also given them an opportunity to get to know the major metals producing processes. Since the beginning of the program, our PhD students have visited Outokumpu Tornio Plant and Kemi Mine, Boliden Harjavalta, Norilsk Nickel, Ovako Imatra, Boliden Kokkola, and SSAB Raahe (May 2017). All the visits have been combined with seminars and education, which has been backbone of the Doctoral School of SIMP.



**Figure 2. The SIMP PhD students at Outokumpu Tornio 2014 and Boliden Harjavalta 2015**

Another aspect of collaboration that is emphasized in the program is international collaboration. Around 9% of the resources in SIMP have been dedicated to research with international partners. During SIMP, we have collaborated with more than 49 international research institutes and companies, compared to the 31 originally planned. The high level of international cooperation is a good indicator of the quality and attractiveness of the research that has been conducted in SIMP. Additionally, it has provided a means to ensure that we do not invent the wheel once again – we utilize the knowledge that is already available, regardless of whether it is domestic or abroad. The extensive international collaboration in SIMP has led to several RFCS and H2020 projects and even more applications. In some cases, this international collaboration has been a direct result of the SIMP excursions that we conducted to RWTH Aachen, JKU Linz, and Politecnico di Milan.

The efficient and seamless cooperation (or you can even call it “system integration”) between academia, SMEs, and industry is not only a result of DIMECC SIMP. It has been exercised since 1984 in programs like Teräksen Jatkuva Valu, SULA 1, SULA 2, Metallurgian Mahdollisuudet, NewPRO, and FIMECC ELEMET. Personally, I have been very fortunate to have the opportunity to be part of SIMP and this R&D community, and I hope it will continue to prosper in the next DIMECC programs. I think that this report will also demonstrate how important and beneficial this particular R&D community is to maintaining the competitiveness of the metals processing industry in Finland.



**Ingmar Baarman**

DIMECC SIMP program manager

## The DIMECC collaboration platform is of fundamental importance to the future of the Finnish metal industry

The DIMECC SIMP program enabled the extraction of heaps of data from industrial operations that, together with data from several industrial-scale pilots, enabled the development of modeling and simulation tools for the optimization of production. This was possible thanks to the high level of knowledge utilized through the DIMECC network. Research-based long-term financing was also essential when testing techniques that have no previous industrial references. In this work, SMEs played a key role in the introduction of novel technologies and innovations.

More than 80 tools were developed during the program. These tools are available for both industry and the R&D network, for utilization in process control and further development. The ideas behind many of these tools originate from previous DIMECC programs. Without the DIMECC platform, long-term collaboration between industry and academia would not have been possible. It is of fundamental importance to the future of the Finnish metal industry that this collaboration continues and all the benefits of the developed tools can be exploited.

At SSAB, the introduction of pulverized coal injection (PCI) at blast furnaces has been a success story in which new measurements and processes models developed within SIMP have been integrated into process control systems. Together with improved raw material quality-control methods, carbon consumption at blast furnaces decreased by 15 kg/t hot metal and CO<sub>2</sub> emissions by 120 kt/a during 2016, corresponding to an annual saving of €7M. SIMP also contributed to the fast start-up of the PCI plant and shortening of the €60M investment payback time. Testing of bio-materials and modeling of processes showed that a considerable reduction in CO<sub>2</sub> emissions in metals production can be achieved by utilizing biomass as a reductant. The use of domestic raw materials would create new job opportunities and boost the circular economy.

Potential annual operational cost savings through minor investments at the Boliden Harjavalta smelter reached €1.5M based on the immediate findings from industrial-scale sampling campaigns. Further benefits are estimated to be achieved soon through optimizing electrorefinery operations through models predicting anode quality based on raw-material analysis, optimization of slag cleaning will increase impurity and side-stream recoveries, and through an increased flexibility to treat a broader variation of feed stock.

Fundamental and prediction modeling was piloted in many processing phases, from liquid steelmaking down to cold rolling processes at Outokumpu. A great success was achieved when the simulation results of a generic AOD-model were converted into new optimal AOD practices. Approximately €3M in annual savings could be recorded because of this model alone. Deep understanding of solidification phenomena in continuous casting has resulted in better quality and decreased slab-grinding work. Prediction modeling and FEM modeling were used to find the root cause of a severe sticking defect in hot rolling. The potential of a dynamic SAF model and a library of quality prediction models in hot rolling is still being verified.

In addition to the direct annual savings, a number of novel measurement techniques were piloted at ten different locations at Outokumpu and at Boliden Harjavalta, of which half have proven to have the potential for investment in the required industrial platforms. To name a few of these: the Luxmets innovative measurement system at the electric arc furnace in Tornio indicates more accurately when the melt is ready, thus saving costs and increasing capacity. A sensor for a similar purpose was piloted by Outotec at the Boliden Harjavalta smelter for faster feedback from the Flash Smelting process. Machine vision was successfully piloted in the hot-rolling mill at Outokumpu to measure the sideways movement of hot strip, and Outotec piloted the use of machine vision for melt level detection in continuous smelting processes. In liquid steelmaking, quality-monitoring functions were implemented in a platform, developed by one of the SME partners, that significantly stabilized the process, and in the hot-rolling area a new tool is being tested to predict quality indexes for each coil, using advanced statistical methods.

These above-mentioned single projects in DIMECC SIMP have alone led to annual cost savings of more than €11.5M during the time span of the program. Additionally, there are even more sub-projects and tools in SIMP, that are, for the moment, in the piloting phase, that will increase the savings substantially once they are introduced into industrial use. While the total budget of SIMP is €24M, this means that the payback time of the program will be less than a year. By any R&D standards, this is fast.

Another good indicator of the importance of the conducted research is that much of the work initiated in SIMP will continue through the next systemic DIMECC programs and smaller projects (e.g. EIT Raw Materials KIC, Horizon2020, RFCS). The savings already reported form only the tip of the iceberg, as many new leads for process improvements have been identified. The work done in DIMECC SIMP will, in a few years, also reach other producers in the metals and mining industry, through commercialization by Outotec and SMEs, and will thus have a large impact on sustainable metals production on a global scale.



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### Fostering the new generation for innovative Finland

**F**inland is a country that successfully combines high education and high technology. In particular, we have been focused on innovations in metallurgical technologies for decades. For example, one of the world's leading innovations in the metal industry, the flash smelting furnace, is globally used in major parts of all copper production. In addition, the metallurgical industry is inherently driven toward metal recycling; for example, our steel and stainless steel production is largely based on secondary raw materials, so that it has one of the lowest specific CO<sub>2</sub> emission levels in the world. Strong co-operation between research institutes and the Finnish metallurgical industry, combined with a limited population and short distances, not only encourages but also requires a very integrated and successful collaborative approach.

We, as professors at Aalto University and the University of Oulu, have had the privilege to see the new DIMECC SIMP generation of Master's and doctoral students grow along with the SIMP program. One of the challenges in involving talented students in work in academia over the years has been related to the temporary nature of funding. In this respect, the SIMP program has provided continuity and the possibility for a number of students to choose to deepen their knowledge and support industry in academia, before continuing in industry after graduation. Already in the short term, but more specifically in the longer term, this benefits both industry and academia. As one successful example of solid academia–industry collaboration, the spinoff company Luxmet Oy (founded in 2014) has developed its optical emission spectroscopy-based products during SIMP.

An important impact of the DIMECC SIMP program has been its support for fundamental and academic research in the many areas of metal making. Not only has this been crucial in several niche topics, such as reduction metallurgy, hydrometallurgy, phase equilibria, and thermodynamic simulations, but equally in other simulation and modeling techniques and methodologies, as well as their implementation in the industrial processes. The close linkage provided by SIMP has enabled the metallurgy research groups in Finnish universities to profile their activities and avoid overlaps, thus maximizing their skills coverage at the national level.

Even if DIMECC SIMP has efficiently promoted fundamental and academic research, the objective in SIMP has also been to apply the research results in industrial pilots and full-scale tests. The industrial orientation of SIMP has brought several additional challenges to the research, which would never have been confronted in the laboratory or on the researcher's desktop computer. The demands on the stability of the

models and the measurement techniques are completely different in an industrial environment. Integrating models in an industrial environment also provides several constraints in the form of specific hardware and software utilized in the production process. The new models and measurement techniques need to be transferred into user interfaces that the operational staff can understand and manage. These are only some examples of the challenges that our researchers confront in SIMP. The industrial environment brings new challenges to our research, which significantly raises the level of complexity. As the complexity increases, at the same time it fosters our researchers to become more multi-skilled from both a scientific and a social point of view.

Although the number of academic KPIs cannot sufficiently describe the impact of research carried out in the universities, they are an inherent part of academic work. In the SIMP program, 19 Doctor of Science and 276 scientific publications have been produced. This not only supports industry, but also emphasizes the importance of metallurgy as a research field among the other less applied research areas in academia. Many of the theses and publications are based on profound interdisciplinary joint research between natural sciences and different fields of technology. The interest in the SIMP program has been international; for example, the European copper industry has been interested in the wider impact of the achieved results. Moreover, Finnish academia has also collaborated with several international universities, including the Central South University (China), Bandung University (Indonesia), RWTH Aachen (Germany), and Politecnico de Milan (Italy), to name just a few. The strong and in-depth scientific know-how generated in SIMP has enabled the academic research groups involved to participate in nearly 10 Horizon 2020 and Research Fund for Coal and Steel (RFCS) projects. This is what we call a positive systemic spillover effect, and the impact is relevant not only to the DIMECC innovation ecosystem players, but more to economic and qualitative growth in Finland.



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# DIMECC SIMP in a nutshell

## Program Key Characteristics

### Company partners (Pcs.): 13

Boliden Harjavalta Oy, Feedstock Optimum Oy, Indalگو Oy, Nortal Oy, Outotec (Finland) Oy, Outokumpu Chrome Oy, Outokumpu Stainless Oy, Ovako Imatra Oy Ab, SSAB Europe Oy, Sapotech Oy, Savcor Oy, SW-Development Oy, Sustainable Energy Asset Management Oy

### Research institute partners (Pcs.): 6

Aalto University, Lappeenranta University of Technology, Tampere University of Technology, University of Oulu, VTT Technical Research Centre of Finland Oy, Åbo Akademi University

### Volumes:

Duration: ..... 1.1.2014 – 30.06.2017  
Budget: ..... 24,2 M€  
Company budget: ..... 12,7 M€  
Research institute budget: ..... 11,5 M€  
People involved: ..... Approx. 275 FTE

### Results:

Number of publications: ..... 276  
Number of doctoral theses: ..... 19  
Number of other theses:  
    LicSc: ..... 1  
    MSc: ..... 37  
    BSc: ..... 8  
  
Research exchange months: ..... 272 (9,0 % total work)  
International Co-operation partners: ..... 49  
Volume of spin-off projects: ..... 16,4 M€

# FLEXIBLE COPPER PLANT OPERATION WITH A WIDE RANGE OF RAW MATERIAL QUALITY

SHOWCASE  
1

Mikael Jåfs/Outotec (Finland) Oy  
Petri Latostenmaa/Boliden Harjavalta  
Jari Aromaa, Mari Lundström, Pekka Taskinen, Rodrigo Serna/Aalto University  
Tuomo Sainio/Lappeenranta University of Technology  
Matti Vilkkö/Tampere University of Technology

## Overcoming the raw-material challenges of the copper-refining industry through digitalization – from chemical phenomena to system integration

The non-ferrous metals industry faces several challenges: an ageing workforce and reductions in targeted education; ore bodies are becoming more complex; and grades are declining causing processing challenges, especially in relation to impurities. This has led to increasing production costs while productivity has simultaneously been in long-term decline. The depletion of high-quality resources has accelerated over the past decade largely because of China's rapid economic development and the strain on mineral commodity production that it has fostered. The second development adversely affecting productivity, costs, and prices is the decline in the pace at which new, cost-reducing innovations arise and diffuse in the metals industry. In the past, new technology has offset the cost-increasing effects of mineral depletion. In the future, this might not be the case as ore grade depletion is becoming more severe and the technological advances have been made.

To address the aforementioned challenges, work has been focusing on improving the energy and materials efficiency of copper plants by digitalization, including adopting advanced mathematical tools and process simulation, developing interaction and communication between models, and using control theory, as well as new software and control architectures. System integration is needed to increase the resource efficiency of copper plants and enable processing of the range of complex raw materials derived from the increasing demand to process secondary raw materials as part of the feed, as well as the weakening grades in the primary raw material. The optimization of production processes in modestly instrumented batch-continuous mixed-mode operations is the main challenge in enabling a resource-efficient process along with the impact of impurities and their distributions and manageability in the processes. The project has focused on two challenges: digitalization of processes and impact of complex raw materials.

The main areas of research in Toolbox 1 covered the development of simulation models for flotation, determining fundamental data (e.g. distributions and, in particular, impurity distributions), and real-time analysis tools for smelting, solvent extraction, and refining. In Toolbox 2, the research focused on the development of an optimization architecture for the process chain and, in particular, for the smelter environment, together with research into slag cleaning, which is an integral part of the total recovery of metals from the smelting process. Toolbox 3, on the other hand, focused on the treatment of data available from the processes, especially for the solvent extraction route. The research conducted also emphasizes the fact that pyrometallurgical and hydrometallurgical unit processes are integrated into copper and precious metal production, and they inherently complement each other and do not compete against each other as often is depicted in the literature.

During the program, it was decided to realign the focus to tasks reinforcing system integration and toolboxes, and bringing applications to be applied in industry, while some tasks related to certain processing areas were removed in comparison to the original research plan. In light of the aforementioned, the main goals in the revised research plan were well met, although some tools could not be validated on an industrial scale due to the short time schedule of the program.

### HIGHLIGHTS OF SHOWCASE 1

A vast amount of new thermodynamic modeling data (32 publications) was developed to enable improvements in impurity management and recovery of valuable trace elements.

New models were developed through sampling campaigns, which resulted in approx. 1.5 MEUR annual savings after small investments at Boliden Harjavalta alone.

Process unit models and algorithms were developed to enable the building of a scheduling and optimization tool for a batch-continuous mixed-mode processing chain.

World-leading conductivity models for copper electrorefining electrolyte were developed. These models help copper producers to decrease energy consumption.

Through the use of sophisticated mathematical tools, new information was extracted from existing online analyzer data.

## Setting the scene

The production route of copper is described in general in Schlesinger et al. (2011) and can be summarized into the flowsheet in [Figure 10, Showcase 1](#). Copper is most commonly present in the earth's crust as copper-iron-sulfide and copper sulfide minerals, such as chalcopyrite ( $\text{CuFeS}_2$ ) and chalcocite ( $\text{Cu}_2\text{S}$ ). The concentration of these minerals in an ore body is low. Typical copper ores contain from 0.5% Cu (open pit mines) to 1% or 2% Cu (underground mines). Pure copper metal is mostly produced from these ores by concentration, smelting, and refining. Copper also occurs to a lesser extent in oxidized minerals (carbonates, oxides, hydroxysilicates, sulfates). Copper metal is usually produced from these minerals by leaching, solvent extraction, and electrowinning. These processes are also used to treat chalcocite ( $\text{Cu}_2\text{S}$ ). A third major source of copper is copper and copper alloy scrap. Production of copper from recycled used objects is 20% of mine production. In addition, there is considerable re-melting/re-refining of scrap generated during fabrication and manufacture. Total copper production in 2014 (mined and from end-of-use scrap) was more than 22 million tonnes, of which 14,2 Mt was primary fire-refined and electrorefined, 4.07 Mt primary electrowon, and 3.91 Mt secondary copper (Brininstool, 2016).

Non-ferrous metal production is a complex industrial operation in which low-grade raw materials are converted into high-purity metals. The global megatrend includes a decrease in the raw materials grade with a simultaneous increase of complexity and never-before treated raw-material feedstocks (Lehner & Stål 2012). The average concentrate grade has decreased from about 30% Cu to 25% Cu since 2003. This means higher amounts of slag and off-gases, and higher consumption of energy and oxygen. The tendency toward higher matte grades has increased the impurity level of anode copper (Wang et al. 2016).

The industrial paradigm is to maintain a high production rate and a predictable product quality in the future business environment, when raw material quality and its impurity levels become less and less favorable. This requires advanced analysis and control of the production stages, such as interactively from flash smelting to refining and electrolysis. Intelligent control of impurities in the material streams and novel coordination between the control and plant DCS software require a system-integrated physical model and approach. The handicaps, such as lack of direct measurements in hostile industrial environments, sensors, and linking different phases (from aqueous, particulate, gaseous, and multiphase to high temperature molten metals and slags in excess of 1300°C), contribute to the complexity and explain the difficulty in providing a harmonized data input and modelling basis for achieving the goal.

## Beneficiation

As the run-of-the-mine ores present a low concentration (i.e. low grade) of valuable minerals, the first processing step aims to treat the ore to produce concentrated materials that can be smelted or refined in an economical way. In these preliminary steps, generally called “ore beneficiation” or “dressing”, concentration is driven by the physical separation of valuables from gangue. Beneficiation processes can also be used to remove mineral components that can be problematic in the subsequent pyrometallurgical or hydrometallurgical processes. Consequently, the proper understanding and control of ore beneficiation processes is a fundamental part of the mineral production chain, as the refining strategies and their associated economic parameters are based on the quality of the concentrate produced in the mineral beneficiation step.

Among the various mineral technologies currently used for ore beneficiation, froth flotation is one of the most widely used, particularly for concentration of Cu. Briefly, froth flotation is based on the separation of hydrophobic mineral particles into a froth phase produced by mixing air bubbles with mineral slurry in a stirred tank. Froth flotation is a chemically complex system, as it requires a series of additives to operate efficiently. Typically, these are: i) “collectors” to selectively render a mineral species hydrophobic, ii) “frothers” to control and stabilize bubble size and froth phase; iii) pH-control agents; iv) “activators” to promote collector adsorption on specific mineral surfaces, and v) “depressants” to prevent the unwanted mineral fraction from reporting to the froth-phase. As seen, this results in a complex chemical system that is difficult to model.

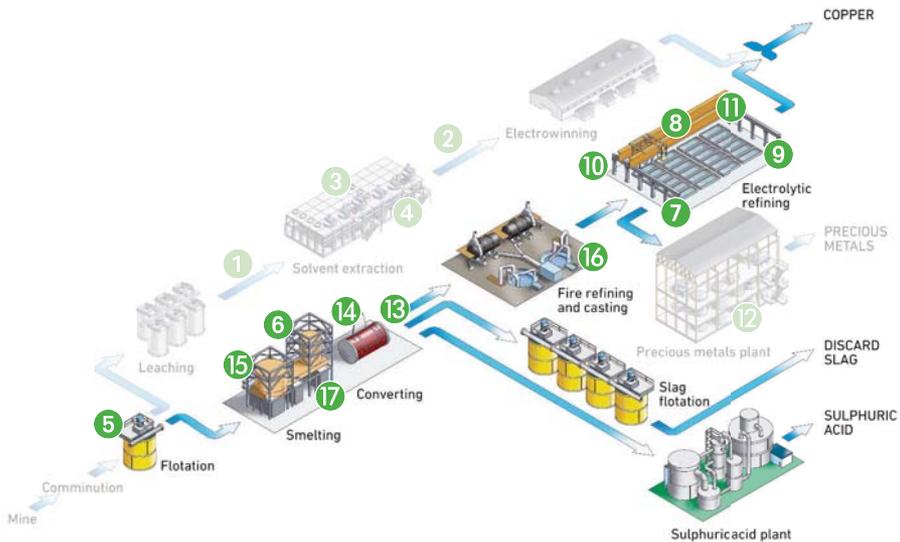
The degree of mineral liberation and the bubble-particle contact time are known to have a strong influence on the performance of a flotation cell. Due to the complex nature, it is necessary to have reliable methods to study bubble-particle interactions in an efficient manner under conditions relevant for industrial practice [MJ1].

Within the scope of this work, an instrument capable of correlating the probability of particle attachment to a bubble as a function of contact time was developed. Such correlation aims at establishing the influence of contact time on flotation efficiency under a specific chemical environment and particle characteristics. Since bubble-particle attachment time is influenced by the physical and chemical operating variables in a flotation cell, it represents a parameter that enables a holistic understanding of this separation process. The uniqueness of this device is that it enables the recovery of particles attached to the bubbles for further characterization to determine, for example, particle size distribution and mineral liberation. A detailed description of the equipment developed in this work and some preliminary results can be found in the attached documents ([Tool 5, Page 41: AN EXPERIMENTAL INSTRUMENT DEVELOPED TO PREDICT CHANGES IN ORE FLOATABILITY](#))

The possibility to determine attachment time under physicochemical environments relevant in industry results in models that can be implemented in simulation software for the design of flotation circuits. In addition, understanding of the influence of operating conditions on attachment time provides a new dimension on control strategies for efficient operation of a froth flotation concentration plant.

### The smelter and refinery route

After ore has been processed into concentrate, it is further processed into sellable cathode copper using typically either the “smelter and electrorefinery” or the “solvent extraction and electrowinning” route. This is, however, just an artificial categorization, and in reality the process routes and technologies used at plants are often intertwined and utilize the needed parts from each other to enable the efficient processing of each concentrate. A typical example of this is the concentration of impurities into smelter bleeds with subsequent hydrometallurgical treatment.



**Figure 1. The typical route of pyrometallurgical copper production with main discard and by-product streams**

A typical smelter-electrorefinery plant consists of feed preparation, homogenization and drying, a smelting and a converting stage, fire refining, and casting and electrorefining to produce cathode copper. The auxiliary processes include typically at least off-gas and slag treatment plants and, in connection with the refinery, a precious metals plant.

The main challenge in recent years has been the rising impurity levels, causing environmental and process efficiency challenges, and combined with the decreasing size of the capable workforce, this means that new solutions are needed. For this, digitalization can be an efficient tool.

The digitalization of pyrometallurgical processes relies on reliable thermodynamic descriptions and models, process simulation, and online instrumentation. A good example of this is how a prediction of anode quality can now be made based on concentrate analysis [Tool 16, page 52: ANODE QUALITY CORRELATION WITH SMELTER DATA].



### Industry impact

“We are now able estimate anode quality from smelter feeds more accurately and easier than before. The new anode quality estimation model uses a smelter history database in feed mixture planning.”

*Petri Latostenmaa, Boliden Harjavalta*

### Improving valuable metals recovery by thermodynamic modeling

The digitalization of sulfide smelting relies on reliable thermodynamic descriptions of the fluxing chemistry, which allows calculation of phase boundaries of the slags in various conditions of the smelting, as well as its auxiliary operations, such as converting, anode furnace refining, and slag cleaning. The thermodynamic databases used for that purpose are developed using the Calphad technique, which permits and ensures consistency for the data from small to large systems, and from one pure component to another.

The assessed data in various extensive databases (e.g. FactSage or MTDATA) have been extracted from multi-component systems, but often without any knowledge or with limited experimental information of the binaries. This very fact disables extrapolation capabilities of the databases when the low-order systems are only ‘the best available approximations’ and not based on experimental measurements.



### Industry impact

“In smelter and in refinery impurity, mass flows and distributions are better known than before, and possible ways to control some impurities have been identified.”

*Petri Latostenmaa, Boliden Harjavalta*

In this sub-project of SIMP, the following sub-systems of the copper and nickel smelting slags have been studied experimentally, using a novel equilibration technique [Tool 17, page 53: NOVEL PHASE DIAGRAM DATA FOR COPPER SMELTING] in which the chemical compositions of the phases were measured directly after quenching from high temperatures, without the need to separate them from each other prior to the chemical analysis. The focus was on liquidus data with well-defined constraints. The numbers behind the system refer to the list of publications at the end of this review.

BINARIES	BaO-Al <sub>2</sub> O <sub>3</sub> [18]	TERNARIES	Al <sub>2</sub> O <sub>3</sub> -Cu-O [11, 28, 30, 31]	QUATERNARIES	CaO-ZnO-Cu-O [2]
	BaO-CaO [4]		Cr <sub>2</sub> O <sub>3</sub> -Cu-O [5]		Al <sub>2</sub> O <sub>3</sub> -CaO-Cu-O [1]
	BaO-MgO [26]		CaO-Cu-O [19, 20]		Al <sub>2</sub> O <sub>3</sub> -SiO <sub>2</sub> -Cu-O [24]
	BaO-SiO <sub>2</sub> [4, 12, 16, 29]		MgO-Cu-O [14, 27]		ZnO-SiO <sub>2</sub> -Cu-O [22]
	BaO-SrO [4]		ZnO-Cu-O [13]		CaO-Al <sub>2</sub> O <sub>3</sub> -Cu-O [15, 21]
	CaO-ZnO [3]		SiO <sub>2</sub> -Cu-O [10]		
	MgO-ZnO [6]		BaO-Al <sub>2</sub> O <sub>3</sub> -SiO <sub>2</sub> [8, 25]		
	Na <sub>2</sub> O-SiO <sub>2</sub> [9]		Na <sub>2</sub> O-SiO <sub>2</sub> -TeO <sub>2</sub> [7, 23]		
	SrO-SiO <sub>2</sub> [4]				
	ZnO-SiO <sub>2</sub> [17]				

**Figure 2. Non-ferrous slag systems studied in the DIMECC SIMP program**

A large majority of the studied systems were without any previous phase diagram observations. A few binaries and ternaries were used as initial tests for the accuracy of the experimental technique and analytical methods used. During the project, there has, in addition, been extensive cooperation through Outotec with research teams at the University of Queensland, Australia, regarding thermodynamic modeling. The thermodynamic assessments at Aalto, which are based on the new experimental data started in 2016, partly using other resources. External funding from Finnish Metals Producers' Fund, Central South University (Changsha, PRC), and the Indonesian Government has been obtained in 2014–2016.

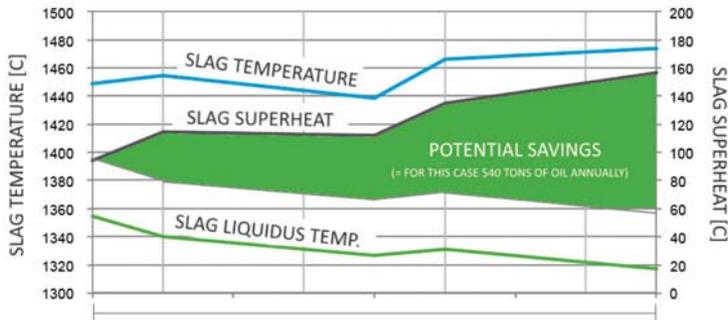
*32 publications and 9.4 FTE international exchanges in thermo-dynamic research*

### Algorithms increasing the intelligence of sensors

The challenges in measurements of sulfide concentrate processes typically relate to high temperatures, dust, acid formation, and generally the difficult and varying behavior of the material and gaseous flows inside the vessels. The extraction of additional status information from the process is necessary to enable better and especially faster control of the processes and is the enabler of optimization and scheduling. This addi-

tional data can be extracted through soft sensors using data analysis and algorithms to extract more out of the current signals. Often, however, this is not sufficient and new sensors need to be developed.

As thermodynamic modeling is an offline tool for the optimization of processes and especially their slag systems, the focus was on the development of sensors and new online in-situ measurements from the process. For this purpose, a sampling probe [Tool 6 page 42: NEW SAMPLING PROBE FOR SMELTERS ] was developed and industrially trialed for determining liquidus data of an industrial slag. The sampling probe provides data so that an algorithm can be used to determine, among other things, the liquidus temperature of the melt. This can then be utilized as online process feedback, which enables the minimization of the slag superheat, meaning the excess heat of the melt, and thus decreases the need for auxiliary (often fossil) fuels and/or decreases oxygen consumption, which is the major electricity consumer of the smelting and converting processes.



**Figure 3. A new sensor added understanding of how much energy can potentially be saved through controlling the slag temperature based on actual liquidus temperatures rather than operator feel**

Another novel measurement technique was field tested at one of the PS converters at Boliden Harjavalta, where optical emission spectrometry was tested for the determination of the off-gas temperatures. The results of the tests seemed promising compared to the current temperature measuring practices.

### How linking process models enables a step change in productivity

To enable plant-wide scheduling, models for all unit process are needed. The models should describe the most important interactions and dominant dynamics of the systems, but at the same time should be sufficiently

simple to enable very short calculation times. In this project, three parallel approaches have been used. The first approach is to formulate the process work-flow. The second approach is to start from the differential equations and develop a simulation model. The third approach is to simplify existing models and shorten their calculation time.

The case problem takes into account the continuously operated flash smelting furnace and three batch operated Peirce-Smith converters. The scheduling solution [Tool 13 page 49: OPTIMIZATION AND SCHEDULING OF COPPER PRODUCTION] has to be available for daily operator use, and as such results should be presentable quickly and should also consider longer time horizons. A continuous time formulation is chosen to keep the number of variables low, and mixed integer linear programming is used to enable fast calculation.

The converter batches use a predetermined sequence of tasks consisting of a slag-making blow and a copper-making blow, in which blow times are defined from converter configurations and a predetermined matte grade (%Cu in feed to converter from the smelting furnace). For example, nine converter batches use almost 300 variables and almost 900 inequality constraints, but the problem is still typically solvable in under a second.

The second approach used in the project is the development of a dynamic Peirce-Smith converter model [Tool 14 Page 50: A DYNAMIC MODEL OF THE PEIRCE-SMITH CONVERTER FOR MODEL BASED OPTIMIZATION AND CONTROL] based on differential equations available in the literature. A dynamic non-equilibrium model concept of the P-S converter was developed for real-time operation optimization and scheduling purposes. The copper-converting operation involves minimizing copper loss to slag through gas feed end-point prediction and control of slag properties, and removing minor elements that affect product quality. Efficient simulation of phase composition and temperature trajectories also enable the use of robust predictive control strategies under uncertainties in input material composition. The model is based on the main reactions in the gas-liquid interactions, liquid-liquid mass transfer kinetics, and energy balance. An approximative model for the internal liquid phase conditions was implemented to avoid time-consuming thermodynamic equilibrium calculations. The resulting model enables faster computations while maintaining the capability to model interactions beyond the two main reactions of the process. Test simulations of actual industrial converting batches compared with analyzed samples of produced material indicate that good prediction capabilities are achievable. Inaccuracies in the model parameters affect especially the transition between slag and copper making. Future work would involve incorporation of minor element volatilization and proper treatment of recycled copper skim into the model.

The third approach was based on an existing HSC Sim model for a flash smelting furnace (hereafter FSF). The HSC Sim models for pyrometallurgical applications are mathematical process models based on mass and energy balances, and include empirical knowledge to control the equilibrium state. These models are already successfully used in strategic planning of metal processing. The drawback of these models is the iterative calculation needed to reach the equilibrium state, which is too slow to be directly used in online process optimization.

The objective of this study was to develop a method for converting iterative output controlled balance models to direct calculating models for the purpose of process scheduling. Here, the case study is a FSF HSC Sim model used in copper smelting process line scheduling to optimize the total process chain operation in the smelter.

The basic idea is to form a symbolic system of equations based on the FSF HSC Sim model, and to solve this group analytically in software, including symbolic computation to achieve causal outputs as functions of inputs. The solution is possible due to the empirical knowledge included in the control sheet of the FSF HSC Sim model. The advantage of the approach [Tool 15 Page 51: FROM ITERATIVE BALANCE MODELS TO DIRECTLY CALCULATING EXPLICIT MODELS FOR REAL-TIME PROCESS OPTIMIZATION AND SCHEDULING] is that even though the length of the functions disable model maintenance in function form, functions can easily be resolved after updates in the HSC Sim model are done. In this analytic approach, the model is greatly simplified, as input elements include only copper (Cu), iron (Fe), nitrogen (N), oxygen (O), sulfur (S), silicon (Si), and other content (Ot). The distributions of the elements between the output stream settler gas, settler fume, settler dust, slag, and matte are in line with the FSF HSC Sim model. To enable an analytic solution with the symbolic software, the equation group has to be exactly determined. This study utilizes the Symbolic Toolbox in the Matlab software. A comparison of the analytical solution of the symbolic calculation with the iterative HSC Sim solution shows good uniformity.



**Figure 4. The furnace operator and the researcher taking samples from the PS converter during slag skimming**

Boliden performed a large sampling campaign (over 240 slag and matte samples) at the most challenging (varying) process step at that time in the smelting line (PS converting). The reason for the campaign was to get better understanding of the variations between batches, and to reduce variations to enable optimization of the whole line. The campaign resulted in several improvements in PSC operations.

Tampere University of Technology (TUT) participated in the campaign and collected lists of process measurement points that are utilized in plant-wide optimization. TUT also monitored the workflow of the operators and recorded the work phases, such as FSF tappings, PSC charging matte for a new batch (including crane operations), slag blow schedules, slag pouring and PSC re-charging, copper blows, and AF loadings. The recorded work flows are used in the development of a plant-wide scheduling algorithm. The scheduling solutions take into account the continuously operated flash smelting furnace (FSF), the three batch-operated Pierce-Smith converters (PSC), and the batch operated anode furnaces. The schedule generation uses a linear mass transfer model with predetermined matte grade (%Cu). The scheduling algorithm is capable of generating solutions quickly (<1s), even when a time horizon of three days is considered. When the scheduling solution is implemented in the operator's control system, the schedules can be presented to operators and engineers as an advisory tool to enable improved production control.

A more detailed differential equation-based dynamic model was developed for PSC. The model is based on the main reactions in the gas-liquid interactions, liquid-liquid mass transfer kinetics, and energy balance. An approximate model for the internal liquid phase conditions was implemented to avoid time-consuming thermodynamic equilibrium calculations.

During the BOHA sampling campaign, the manually collected workflow data was integrated into the data stored in BOHA's information system. The merged dataset was used to calibrate and validate the developed model.

In the latest version of the plant-wide scheduling algorithm, the differential equation-based model is used to describe the dynamics of PS converters. Efficient simulation of phase composition and temperature trajectories will provide useful information for operators, but will also enable the potential use of robust predictive control strategies to optimize converter operation.

### **Optimizing smelter operations from the perspective of capacity constraints in trace element treatment**

One of the trending impurities in copper smelting is the increasing content of nickel, which is a primary raw material in itself, but in the copper

processing it is considered an impurity. Traditionally, nickel management in copper smelting and refining is done by removing nickel from the copper refinery bleed stream. Nickel removal capacity at the refinery has set internal nickel constraints for the smelter. Therefore, research was done into the trace element distributions at the smelter, and data was evaluated and analyzed. For example, a comprehensive study of complex dust streams was done during the project. Based on the element distribution evaluation, effort was put into improving the PS-converter model. Studies were also done into the separation of elements from the slags on a laboratory scale. These resulting streams were then modeled with HSC Sim. In addition to the nickel, the improved PS converter model provided a more stable converting operation, and this model is now in use at the smelter.



## Industry impact

“A comparison of slag-cleaning process alternatives helped us to focus on the existing process. With slag-cleaning process modeling and test work, we have identified bottlenecks in capacity and metal recoveries.”

*Petri Latostenmaa, Boliden Harjavalta*



**Figure 5. Studying trace elements on ppm levels of a 20-ton sample can be like searching for a needle in a haystack**

Based on the comparison of two different slag-cleaning processes, a selection for further development in slag flotation was made at the beginning of the project. An improved flotation simulation model was built with the HSC Sim tool. To gather data and to identify the kinetic parameters

for the simulation model, several flotation and grinding tests were carried out. Based on these, the model was used for the identification of bottlenecks in capacity and in the recovery potential of the existing plant set-up. Similar bottleneck and potential studies were also done for the grinding circuit. Based on the flotation and grinding circuit study findings, two plant-scale test runs in slag flotation will be carried out at Boliden Harjavalta during 2017.

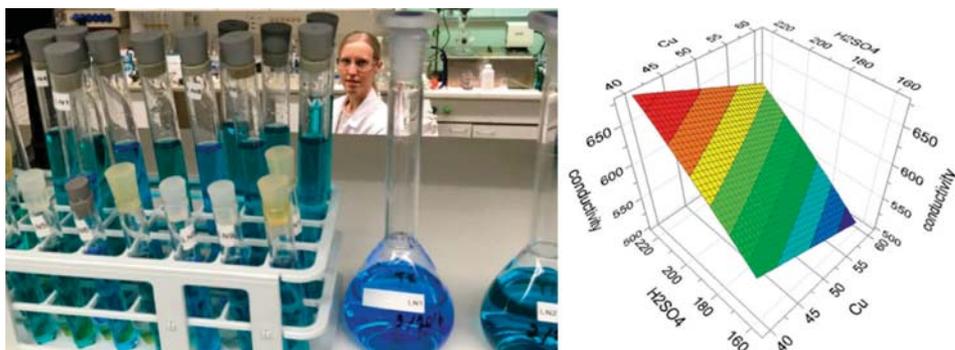
### Optimizing copper electrorefining and decreasing energy consumption

The challenge of declining ore grades and increasing impurity levels is also seen in copper electrorefining. Due to higher copper grades in smelting and an increasing amount of secondary raw materials, several impurity metals, such as As, Bi, Sb, Ni, Fe, Zn, Pb, Au, Ag, Pt, Pd, and Se, end up in copper electrorefining. Especially the levels of As, Bi, Se, Pb, and Ni in anode copper have increased in the 2000s (Moats et al. 2016). To maintain uninterrupted production, the electrolyte impurities should not cause a decrease in cathode quality due to metal co-precipitation or slime inclusions, nor should the anode impurities lead to the formation of adherent anode slime and passivation. Furthermore, the electrolyte composition and temperature affect the electrolyte conductivity and thus the energy consumption.

The physicochemical properties of the electrolyte affect the production rate and energy consumption of electrorefining. The electrolyte composition and temperature affect the conductivity, viscosity, density, and diffusion coefficient of  $\text{Cu}^{2+}$ . The physicochemical properties were already investigated several decades ago, and the models developed at that time are still applied in industry. However, the models are not valid for the increasing range of impurities, and those models rely on the computational power characteristic for that time, and cannot predict, for example, the combined effect of parameters in copper electrorefining. In the SIMP project, Aalto University completed an extended series of modeling of conductivity, viscosity, density, and diffusion coefficient of  $\text{Cu}^{2+}$  using copper, nickel, arsenic, and sulfuric acid concentrations and temperature [Tool 10 page 46: TOOL FOR PREDICTING CONDUCTIVITY OF COPPER ELECTROREFINING ELECTROLYTE and Tool 11 page 47: TOOL FOR PREDICTING DIFFUSION COEFFICIENT OF CU(II) OF COPPER ELECTROREFINING ELECTROLYTE]. In addition, preliminary industrial validation of the models was conducted.

Electrolyte conductivity has a strong influence on cell voltage and thus on specific energy consumption. Approximately 50% of the electricity consumption in copper electrorefining originates in the resistance of the electrolyte. The developed conductivity models indicate that increas-

ing temperature and sulfuric acid concentration will increase conductivity, whereas increasing the concentration of metals will decrease conductivity [Tool 10, page 46: TOOL FOR PREDICTING CONDUCTIVITY OF COPPER ELECTROREFINING ELECTROLYTE].



**Figure 6. Doctoral student Taina Kalliomäki (Aalto University) made a major contribution to building the world-leading conductivity model for copper electrorefining**

To increase the electrochemical deposition rate of copper, it is necessary to improve the mass transport of copper ions in the electrolyte. This can be done by maximizing the diffusion coefficient of  $\text{Cu}^{2+}$  and minimizing the electrolyte viscosity.

The developed models show that increasing the temperature increases the diffusion coefficient, increasing the arsenic decreases significantly, but increasing the copper, nickel, and sulfuric acid decreases the diffusion coefficient only slightly. Increases in the concentrations of Cu, Ni, As, and  $\text{H}_2\text{SO}_4$  were found to increase both viscosity and density, whereas temperature was shown to decrease both viscosity and density.

In copper electrorefining, the impurities can create three types of anode slime. The composition and formation of these solid particles, namely bottom, floating, and adherent anode slimes, is highly dependent on the impurity levels in the anode and electrolyte. The adverse effect of slime is dependent on the viscosity and density of the electrolyte affecting the slime falling rate. In the SIMP project, methods for characterization of anode slime [Tool 7 page 43: CHARACTERIZATION OF ADHERENT ANODE SLIMES IN COPPER ELECTROREFINING] and equipment for sampling anode slime were developed. Furthermore, equipment for measuring the current density distribution on electrodes [Tool 8, page 44: MEASURING CURRENT DENSITY PROFILE IN A COPPER ELECTROREFINING CELL] and a methodology for estimating anode passivation tendency were developed [Tool 9, page 45: TOOL FOR PREDICTING PASSIVATION OF COPPER ANODES].



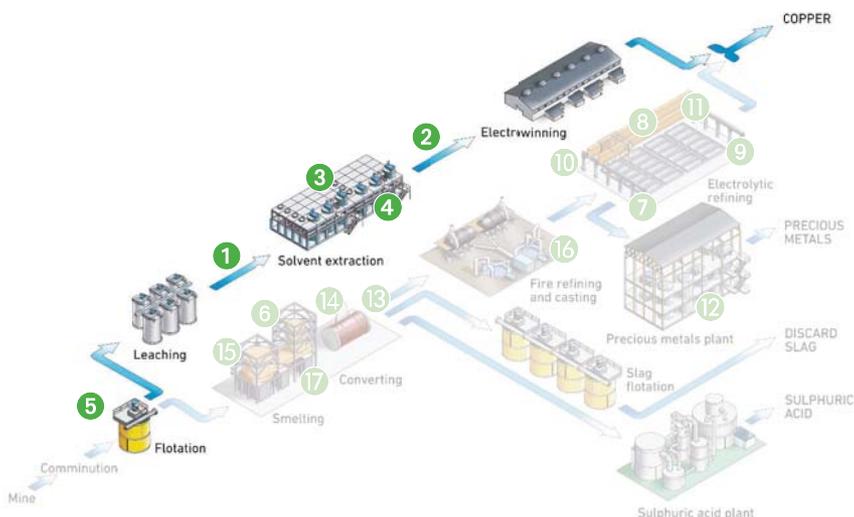
## Industry impact

“I was myself conducting hands-on conductivity measurements in the Boliden Harjavalta tankhouse with a doctoral student from Aalto University. As a result of collaboration between Aalto University and Boliden Harjavalta, a world-leading copper electrolyte conductivity model was developed.”

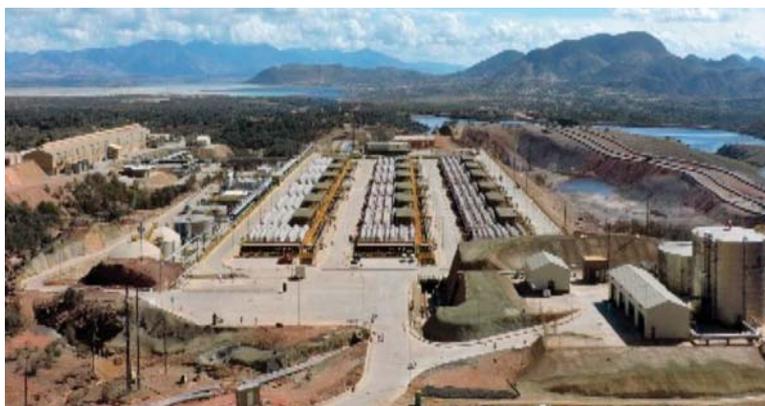
*Petri Latostenmaa, R&D manager, Boliden Harjavalta*

## The solvent extraction and electrowinning route

Approximately 20–25% of copper globally is produced via the hydrometallurgical route. This route involves leaching of metals from the ore (or concentrate) either in a large heap or in a leaching reactor, purification by solvent extraction/stripping, and recovery as copper cathodes by electrowinning. Typically, this hydrometallurgical route is preferred when the raw material is of low grade, the deposits are relatively small, or the capital costs are to be minimized. No  $\text{SO}_2$  is produced from sulfide ores in this route, which means that the plant can operate as “stand-alone” without a sulfuric acid plant. A major advantage of the use of chemical agents in the hydrometallurgical leaching and purification steps is that it gives more degrees of freedom to control the process. Higher flexibility to react to variations in the copper content and the impurity profiles is needed, as the general trend is toward lower grade ores. Fully responding to this challenge requires new online process analytical data, and advanced process monitoring and control tools. Increasingly complex raw materials also call for more accurate dynamic simulation tools for flowsheet development and process optimization. In other words, the hydrometallurgical processes of tomorrow need a higher level of digitalization.



**Figure 7. The typical SX-EW route to copper from concentrates**



**Figure 8. Copper SX-EW plant Grupo Mexico ESDE III Cananea, Mexico**

### **Data is nothing. Information is everything.**

Digitalization of hydrometallurgical processes means increasing the amount of process analytical instrumentation, as process control relies on accurate and up-to-date measurements. This is particularly important in the solvent extraction stage, in which the aqueous and organic phases are complex multicomponent mixtures. An example of successful online process analytical equipment in copper hydrometallurgy is the use of X-ray fluorescence spectroscopy (e.g. Outotec Courier Analyzer). The currently available commercial implementations exploit only selected wavelengths, however, and not the entire XRF spectrum is analyzed. In this showcase, new tools were developed for extracting more information from such an XRF analyzer by using multivariate calibration (chemometrics).

The presence of Fe, which is the main impurity in typical copper processes, was found to significantly affect the predicted Cu concentration, rendering the calibration unreliable in multicomponent mixtures. Several methods were tested for eliminating the matrix effect. A new algorithm, termed the spectral interaction method, was found to be suitable for this task. Using the new algorithm, PLS calibration was shown to predict copper concentrations with good accuracy without recalibration, even when several impurity metals were added to the solution. It was shown that treatment of the complete spectrum from an XRF analyzer enables identification of the accumulation of impurities or the drift of the process outside the normal (acceptable) operating region. More specifically, the Co impurity peak was recovered and identified under Fe spectra in a multi-component mixture without information on its presence being included in the calibration model. [\[Tool 1, page 37: MORE INFORMATION FROM INDUSTRIAL ANALYZER IN COPPER HYDROMETALLURGY\]](#). This is important because, in conventional laboratory analy-

ses, disturbances such as new impurities are often not detected unless they are specifically looked for.

Increasing online instrumentation means that a large number of process variables should be monitored simultaneously. The use of multivariate statistical data analysis methods was investigated using industrial plant history data from the copper solvent extraction and electrowinning stages. The benefit of multivariate methods is that they can transform data from all the available sensors into information that can be summarized in a single control chart. A procedure was developed to define normal operating conditions and to issue warnings for new types of disturbances that occur. The main advantage of the procedure is that it separates structural variation in data from noise, such as incorrect measurements, which are not uncommon in plant data. Advanced mathematical treatment of online process analytical data can issue warnings even for new types of disturbances that have not been encountered before. Once a warning has been detected, the algorithm reveals with which process parameter the disturbance is associated.

A tool [\[Tool 2, page 38: MULTIVARIATE METHODS IN STATISTICAL PROCESS MONITORING OF COPPER SX-EW\]](#) was developed for monitoring the efficiency of electrical current usage in copper electrowinning. The multivariate calibration model enables online detection of current inefficiencies that increase the energy consumption per ton of copper produced. When integrated within a production management system, the tool could be used as an automated solution to enhance the energy efficiency of copper electrowinning circuits.

### **A closer look at rigorous models**

The statistical methods described above treat historical data or data from an existing process. In order to reach the goal of Showcase 1, which was to guarantee flexible operation over a wide range of raw material qualities, it is necessary to understand the complex chemical interactions involved in the process solutions. Therefore, new equilibrium data on the extraction and stripping stages of the hydrometallurgical copper process were also produced [\[Tool 3, page 39: NEW FUNDAMENTAL DATA AND MODELS FOR CU SX\]](#). The new data spans such a large range of concentrations that it shows the influence of thermodynamic non-idealities in both the aqueous and the organic phases.

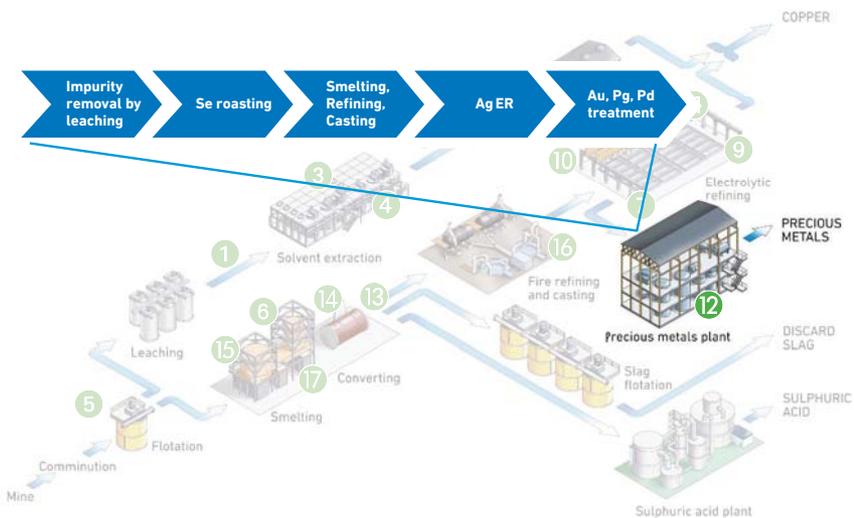
Detailed mathematical models were developed to describe the equilibrium data. These include the speciation equilibria in concentrated sulfate solutions of copper and iron, and the concentration dependency of the equilibrium constant of the extraction reactions. An unconventional rate-based approach was used to ease and accelerate the numerical solution of the equilibrium models. For predictive models, it is important

that the parameters estimated from experimental data are well identified and reliable. A Markov chain Monte Carlo (MCMC) algorithm was used to ensure the reliability of the models.

Such mechanistic modeling and equilibrium-based simulations show the thermodynamic limitations of process operation and give an estimate of the steady-state of the process under given operating conditions. In order to account for interfacial mass transfer between the aqueous and organic phases, the two-film theory and Fick's second law were used. The hydrodynamics in the settler were described with a surrogate model for simplicity. While the work was done with Matlab, the models can be implemented in any other computation platform. These process models can be used in operator training or when generating process control algorithms.

### Precious metals

Anode slime treatment is important to the economics of a copper smelter, since most of the gold, silver, and PGM in copper concentrate is deported to anode slime. Nevertheless, anode slime treatment has some challenges. Impurities present in the copper concentrate end up in the precious metal plant through smelting and electrorefining. Achieving high recovery, in particular for gold, silver, and PGM, is essential in anode slime processing. In the copper smelter, substantial amounts of silver, gold, and PGM are locked up in the process. Copper electrorefining itself takes 2-3 weeks for the completion of a single anode batch. Thus, faster recovery of valuable metals in the anode slime treatment (precious metals plant) will increase the competitiveness of the plant. The precious metal plant consists of several unit processes, shown in Figure 9.



**Figure 9. Example of unit processes in a precious metals plant, treating anode slime**

Impurities have an effect on precious metal recovery. In the SIMP program, several models were built to integrate precious metal plant operation in the primary copper plant production optimization. It was proven that substantial amounts of Cu, Ni, and Bi can be leached out from the slime. In silver electrorefining (Ag ER), it was found that high current density, meaning improved process kinetics, can be applied to anodes with less than 10% of Au. Models for optimizing the energy consumption in silver electrorefining were built: silver electrolyte conductivity, density, and viscosity [Tool 12, page 48: MODELING THE PHYSICO-CHEMICAL PROPERTIES OF SILVER ELECTROREFINING ELECTROLYTE]. The area of silver electrorefining has previously been poorly scientifically published. The work carried out at Aalto University provided totally novel models, increasing international interest in Finnish metallurgical knowledge.

### "Tying the knots"

Through novel measuring techniques and one-off sampling campaigns, the development of suitable and adaptive models for online control enable the scheduling and optimization of process units and subsequently also the entire processing chain. Reliable measurements coupled to the simulation of the ideal state help us to reach for the theoretical baseline and increase the productivity and footprint of processing operations. Coupling the behavior of impurities with the constraints of the plant enable the optimization of recoveries and production costs actively, instead of in the traditional reactive manner. The research work in this showcase has developed a vast amount of new information that can and will be utilized in the further work needed to continue the step change in productivity, enabling the sustainable processing of increasingly complex raw materials by adding flexibility to the current processes and equipment used at existing smelters.



### Industry impact

"The generic tools from the SIMP program enable the development of digital products targeting a productivity increase at Outotec customer operations, and thus the work in this program greatly affected the sustainability of copper production on a global scale."

*Mikael Jåfs, Outotec (Finland) Oy*

## The future beyond DIMECC SIMP

As the world is never finished and the development of platforms in the form of data analytics, simulation, and modeling is continuously improving, there is a great opportunity to continue the work done under the DIMECC SIMP Showcase 1 umbrella. Much of the research embarked upon in this project will either continue or serve as the starting point in developing commercial applications to enable a resource-efficient and sustainable, system-integrated, copper processing plant.

The work done on scheduling and optimization of the process chain in the pyrometallurgical case will continue and develop further with Horizon 2020 SPIRE funding. The new project, called Coordinating Optimization of Complex Processes (COCOP), is coordinated by Tampere University of Technology. In COCOP, Outotec will develop advanced process control methods that will be applied to a Boliden pilot case. The development is focused on advisory features that are based on the optimization of unit process operations and on the coordination of the solutions toward optimal overall plant operation.

The extensive sampling campaign at Boliden during the project proved to be successful. Based on the results, a new project has been set up to further develop trace element management at the Boliden Harjavalta smelter. On the same theme, Outotec will continue efforts in developing new sustainable treatment methods and outlets for impurities arising from both secondary raw-materials and increasingly complex concentrates.

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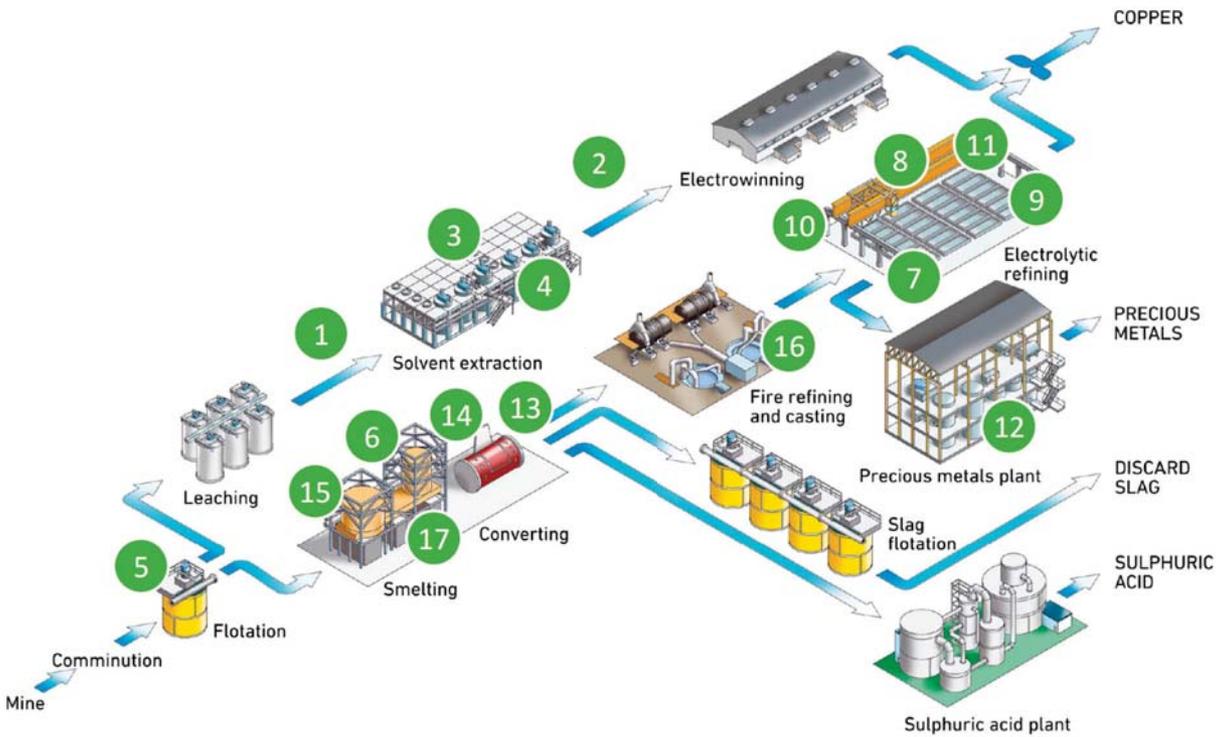
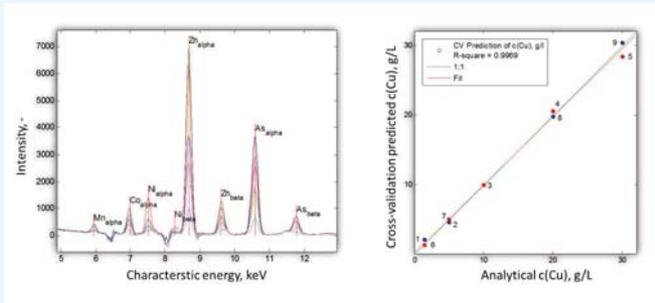


Figure 10. The numbered bullets in the process scheme represent the tools developed in Showcase 1. The tools are described in the following pages

## SHOWCASE 1



### Description of the tool

An example of successful on-line process analytical equipment in copper hydrometallurgy is the use of X-ray fluorescence spectroscopy (e.g. Outotec Courier Analyzer). The currently available commercial implementations exploit

only selected wavelengths, however, and not the entire XRF spectrum is analyzed. In this showcase, a new tool for extracting more information from such an XRF analyzer by using multivariate calibration (chemometrics) was developed. Treatment of the complete spectrum enables identification of the accumulation of impurities or the drift of the process outside the normal (acceptable) operating region.

The presence of Fe was found to significantly affect the predicted Cu concentration. A new algorithm, the spectral interaction method, was found to be suitable for identification and elimination of so-called matrix effects that render the calibration unreliable in multicomponent mixtures. Besides analysis of Cu content, the feasibility of the procedure was proven by demonstrating that the signal of an unknown impurity in a multi-component mixture (e.g. Co) can be recovered under the Fe spectrum with multivariate methods.

### Application

The tool was developed with data acquired with an industrial elemental analyzer, and it can be applied in various hydrometallurgical processes.

### Technologies

The multivariate algorithms were implemented in Matlab but, in principle, any platform with linear algebra packages could be used.

### Scope of application

The tool shows potential as an easily implemented automated solution for industrial energy-dispersive X-ray fluorescence analyzers, as it does not require additional measurements of side-effects and correction procedures. This reduces the time required for laboratory analyses of liquid process samples.

#### Contact persons – Inventors

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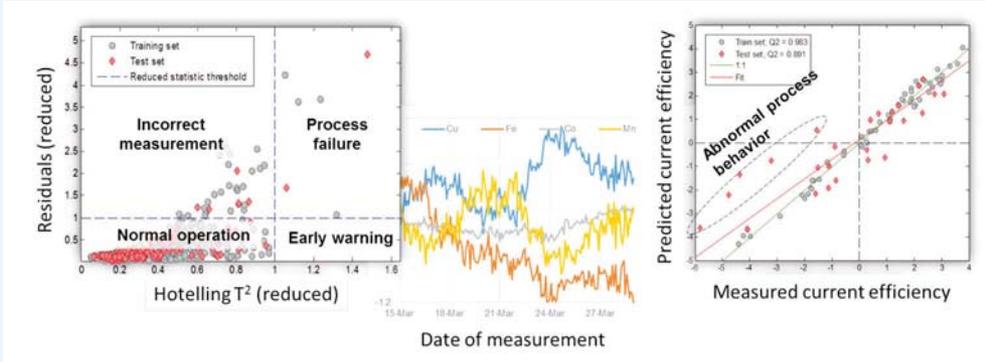
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2

MULTIVARIATE METHODS IN STATISTICAL PROCESS MONITORING OF COPPER SX-EW

SHOWCASE 1



Description of the tool

In order to ensure high production rate and product quality in hydrometallurgical copper production, a large number of process variables should be monitored simultaneously. The benefit of multivariate statistical data analysis is that information from all available sensors can be summarized in a single control chart.

Application

When integrated within a production management system, the tools can be implemented as an automated solution for early detection of abnormal process behavior, thus enhancing the energy efficiency of copper SX-EW circuits.

Technologies

The multivariate algorithms were implemented in Matlab but, in principle, any platform with linear algebra packages could be used.

Scope of application

The tools were developed using data from an industrial copper process, but can be used for any process.

Contact persons – Inventors

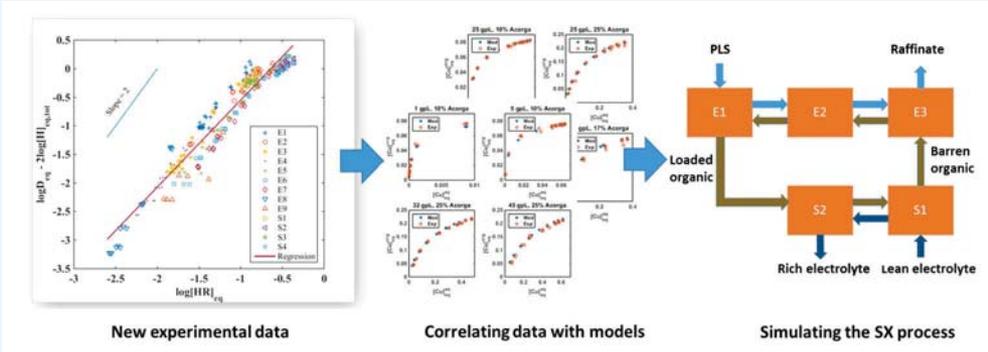
Tuomo Sainio, tuomo.sainio@lut.fi, +358 403578683, Lappeenranta University of Technology; Kirill Filianin, kirill.filianin@lut.fi; Satu-Pia Reinikainen, satu-pia.reinikainen@lut.fi; Mikael Jäfs, Mikael.jafs@outotec.com, Outotec (Finland) Oy

Additional Information/ Publications

Filianin K., Reinikainen S-P., and Sainio T. Detection of Current Inefficiencies in Copper Electrowinning with Multivariate Data Analysis, in the Proceedings of IEEE 7th International Conference on Intelligent Control and Information Processing, December 2016.

Filianin K., Reinikainen S-P., Sainio T., Helaakoski, H., Kyllönen, V., Detection of Abnormal Process Behavior in Copper Solvent Extraction by Hotelling T2 Control Chart, in the Proceedings of IEEE 7th International Conference on Intelligent Control and Information Processing, December 2016.

SHOWCASE 1



Description of the tool

Mechanistic modeling enables accurate prediction of complex non-linear behavior of hydrometallurgical copper processes in a wide range of operating conditions. Equilibrium-based process simulation shows the thermodynamic limitations of process operation and gives an estimate of the steady state of the process under given operating conditions.

Considering the aim of SC1, flexible operation over a wide range of raw material qualities, new equilibrium data of extraction, and stripping stages of copper SX were produced for a wide range of operating conditions (Cu up to 45 g/L, Fe up to 25 g/L, and extractant up to 25 vol-%). The data were used for calibration and verification of mechanistic models developed for the prediction of phase equilibrium in loading and stripping stages. The models account for non-ideality of both aqueous and organic phases, and for the presence of the most important impurity (Fe).

A tool for equilibrium-based simulation of copper SX circuits was developed by combining the models for the loading and stripping stages. The tool enables fast design of process flowsheets and the evaluation of steady-state compositions of the streams.

**Application** The tool has not yet been applied in industry.

Technologies

The modeling and simulation work was done in Matlab, but the models can be implemented in any other platform. Non-linear regression analysis was used for fitting model parameters. A Markov chain Monte Carlo (MCMC) algorithm was used to test and prove the reliability of the models.

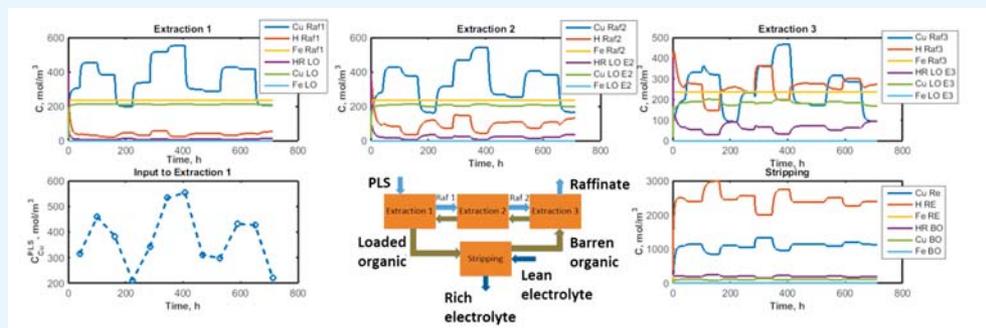
Scope of application

The developed models and the flow-sheet tool can be used for the design, optimization, and control of Cu SX processes.

**Contact persons – Inventors** Tuomo Sainio, tuomo.sainio@lut.fi, +358 403578683, Lappeenranta University of Technology; Fedor Vasilyev, fedor.vasilyev@lut.fi; Sami Virolainen, sami.virolainen@lut.fi

**Additional Information/ Publications** Vasilyev, F., Virolainen, S., Sainio, T., Modeling the phase equilibrium in liquid-liquid extraction of copper over a wide range of copper and hydroxyoxime extractant concentrations, December 2016.

## SHOWCASE 1



## Description of the tool

Besides accurate and up-to-date information on the process state, process control relies on effective and efficient control strategies. Model predictive control can be successful only with a model that is sufficiently rigorous but can be solved in a short time. A dynamic simulation model for the Cu SX process was developed here, using process thermodynamics and kinetics. A rigorous phase equilibrium model was coupled with two-film theory and Fick's second law to model mass transfer between the aqueous and organic phases. Non-ideal flow in the settler was described with series and parallel combinations of ideal stirred tanks. The dynamic model is able to simulate an entire circuit of the Cu SX process and predict propagation of composition disturbances in the extraction process.

The main benefit of the model is that it enables predicting the composition of the aqueous and organic phases over a wide range of operating conditions.

## Application

The numerical methods and algorithms can be implemented in dynamic simulators to design hydrometallurgical processes.

## Technologies

The modeling was done in Matlab, but the model can be implemented in any other platform. A rate-based approach was used to accelerate the solution and eliminate difficulties in the iterative solution of non-linear equations.

## Scope of application

Model-based design, optimization, and control of solvent extraction circuits in copper hydrometallurgy.

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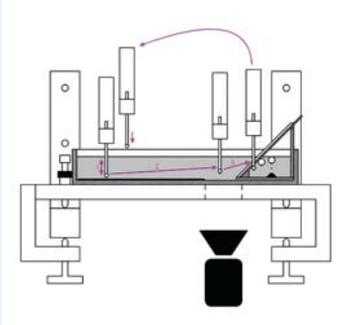
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## 5

## AN EXPERIMENTAL INSTRUMENT DEVELOPED TO PREDICT CHANGES IN ORE FLOATABILITY

## SHOWCASE 1



## Description of the tool

The prediction of flotation efficiency requires a deep understanding and careful measurement of various relevant chemical, physical, and mineralogical variables. Within the scope of the SIMP project, we developed an instrument capable of measuring floatability as a function of bubble-particle contact time. The effect of contact time on flotation efficiency has been acknowledged in the past and has been associated with relevant operating parameters, such as mineral liberation and hydrophobicity. The uniqueness of this device is that it enables the recovery of particles attached to the bubbles for further

characterization. Consequently, the impact of a number of different parameters on flotation can be obtained by applying the developed instrument and measurement procedure. Furthermore, the device is transportable and can be taken on-site to processing plants to measure the mineralogical system directly in its processing environment. Lastly, the automated measurement cycles provide a reliable statistical analysis with hundreds of bubbles measured in a short period of time.

1. Bubbles are formed at the tip of a series of six needles and pushed against the particle bed for a specific contact time. All parameters of the vertical movement are controlled and recorded.
2. Bubble-particle aggregates are transported to a viewing window above the digital microscope for imaging. Bubble size and attached particles are determined from the obtained pictures.
3. The bubbles are taken to the sample collector and detached from the needles. The particles are thus captured inside the container.
4. The needles are lifted above the surface and flushed with air to remove moisture and bubbles stuck at the tip of the needle simultaneously, when moving horizontally.
5. The needles are lowered into liquid above an untouched spot of the particle bed for the next measurement cycle.

## Application

The tool has not yet been applied in industry.

**Contact persons  
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Rodrigo Serna, Rodrigo.serna@aalto.fi, Aalto University

**Additional Information/  
Publications**

Filianin K., Taavitsainen V-M., Reinikainen S-P., Sainio T. Spectral interaction Javor, Z., Aspiala, M., Schreithofer, N., Heiskanen, K., Serna, R., 2016. The development of a new attachment timer for predicting the change in ore floatability. Poster session presented at: XXVIII International Mineral Processing Congress, Quebec City, Canada.

## 6

## NEW SAMPLING PROBE FOR SMELTERS

## SHOWCASE 1



### Description of the tool

The online measurement of temperature and melt levels has been done manually for decades. This leads to safety risks and human error, decreasing the accuracy of the measurements. By automating this, more accurate online process data can be gathered, thus improving the efficiency of the process. The development of the new sampling probe is based on the automated platform, enabling frequent online measurement of other interesting and useful data, namely the liquidus temperature of the melt.

Typically, smelting processes are operated at a slag superheat, depending on the simulated process conditions and melt analysis, or even at a specific set point for slag temperature, leading to excess heat compared to what is necessary. Through the development of a liquidus probe and necessary algorithms, the true liquidus temperature of the bath can be measured, and the operation parameters can be adjusted to match a predetermined superheat instead of a predetermined slag temperature. This leads to a significant decrease in energy consumption in terms of additional fuel and oxygen consumption.

### Application

The tool has been pilot tested in industry. An example calculation based on the industrial testing showed a possible saving of 540 tons of oil per year in the specific furnace.

### Technologies

The technologies involved include an automated mechanism for sampling, the sampling probe modified from the steel industry to match the needs of non-ferrous metals production, and the algorithms for determining the liquidus point of the slag.

### Scope of application

The tool can be utilized in the non-ferrous and ferrous smelting processes.

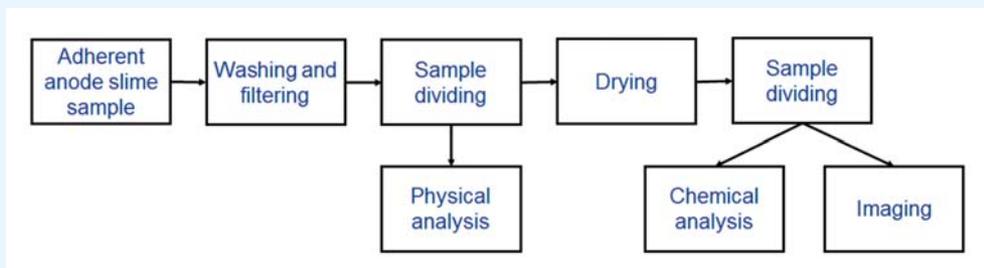
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#### Additional Information/ Publications

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## SHOWCASE 1

**Description of the tool**

High impurity levels in copper anodes can increase anode slime quantities in the copper electrorefining process. In copper electrorefining, the anode impurities deport to the electrolyte or to the anode slime, which can be divided into bottom, floating, and adherent anode slimes. Adherent anode slime can contribute to anode passivation, which lowers the efficiency of the electrorefining process, or cathode contamination, as the anode slime does not fall to the cell bottom. By characterizing the adherent anode slime, information on its properties and formation can be gathered. Information on anode slime properties enables prediction of whether anode impurity levels are so high that slime adherence becomes too high. In addition, a standardized characterization procedure makes it easier to handle and compare anode slime samples in the future.

**Application**

The collection and characterization procedure has been tested with real tankhouse slime.

**Technologies**

The characterization was conducted using particle size distribution measurements, settling rate tests, chemical analysis, XRD, and SEM.

**Scope of application**

The information on adherent anode slime can be used to improve the electrorefining process.

**Contact persons  
– Inventors**

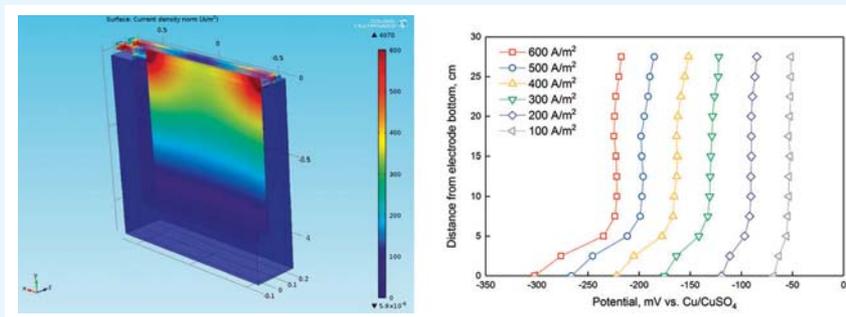
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Jari Aromaa, jari.aromaa@aalto.fi

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## MEASURING CURRENT DENSITY PROFILE IN A COPPER ELECTROREFINING CELL

### SHOWCASE 1



### Description of the tool

Current distribution is an important feature in a copper refining cell. The aim was to develop a solution to measure the current distribution profile in production-scale copper electrorefining electrodes. Uneven current distribution can cause excessive anode dissolution or rough cathodes. No commercial equipment to measure local current density was found. Therefore, a method of estimating local potential on the electrode surface was developed, based on cathodic polarization monitoring methods. The device is based on a sharp point contacting electrode surface and a pseudo Cu/CuSO<sub>4</sub> reference electrode. Simulation results of the electrorefining electrode pair showed that the highest current densities were expected on current connectors, meaning anode lugs and the cathode hanger bar. Tests in the laboratory and in the Boliden Harjavalta Pori tankhouse showed that, for anodes and cathodes, local potential changes on the electrode surface were not large, except for the high polarization of the electrode bottom.

### Application

The tool was tested in laboratory and field tests, but has not yet been applied further in industry.

### Technologies

Surface potential mapping with COMSOL field tests was used.

### Scope of application

The tool measures surface potential differences in surfaces of copper anodes and cathodes. With this information, a current distribution map can be built in order to investigate anode passivation and systematic uneven growth on cathodes.

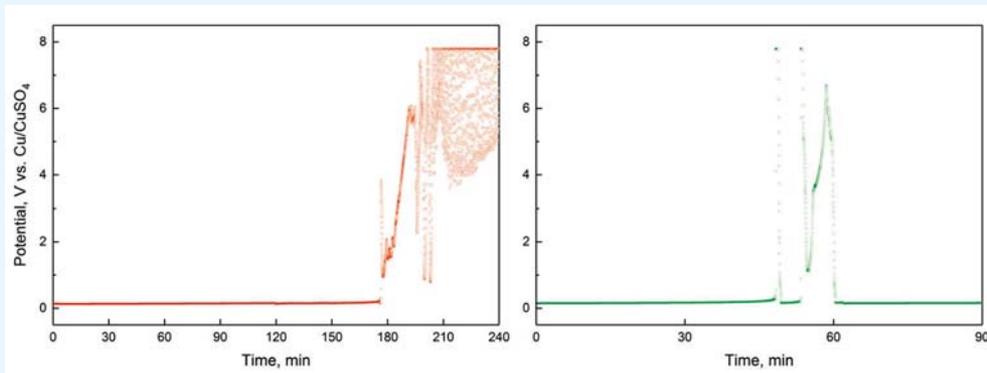
#### Contact persons – Inventors

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Taina Kalliomäki, taina.kalliomaki@aalto.fi, Jari Aromaa, jari.aromaa@aalto.fi

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Kalliomäki, T., Wilson, B. P., Aromaa, J., Lundström, M., Diffusion Coefficient of Cupric Ion in a Copper Electrorefining Electrolyte containing nickel and arsenic. Submitted.

## SHOWCASE 1

**Description of the tool**

Rising impurity contents of anodes can cause a stronger passivation tendency due to adherent anode slime. Passivation is a random event that results from the crystallization of copper sulfate under and within the adhering anode slime. A test method to estimate the anode passivation tendency was developed based on the theory of crystallization. Anodes are tested in galvanostatic tests using high current densities at the kA/m<sup>2</sup> level and by varying temperature. Anodes with a higher tendency for passivation show a more rapid potential increase as current density is increased or temperature decreased. Rapid successive potential increases followed by reactivation indicate that the anode slime is not adherent.

**Application**

The method has been tested on a laboratory scale for different anode treatments and high-nickel anodes. The method is to be used with the adherent anode slime characterization procedure.

**Technologies**

The tests have been done using standard electrochemical equipment.

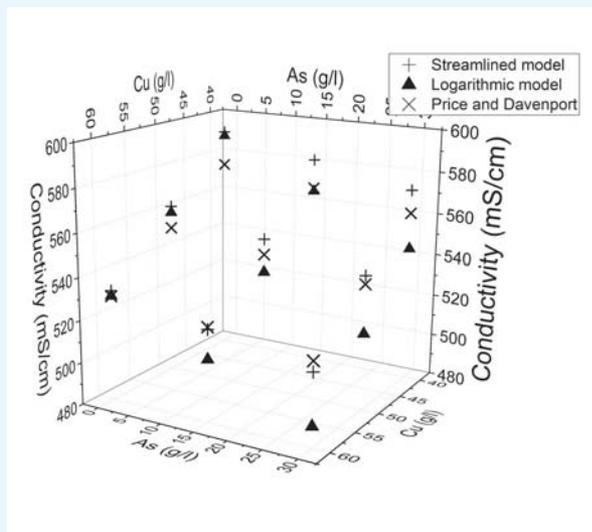
**Scope of application**

This method can be used to compare different anode batches to predict passivation tendency.

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Jari Aromaa, jari.aromaa@aalto.fi

**Additional Information/  
Publications**  
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B.Sc. Thesis, Aalto University 2016, 21 p.

## SHOWCASE 1



## Description of the tool

The electrical conductivity of copper electrorefining electrolytes affects the energy consumption of the electrorefining process. Energy consumption can be minimized by maximizing the conductivity within the applicable limits. That can be carried out, optimizing the composition and temperature, by keeping the metal concentrations low enough and the temperature and sulfuric acid concentration high enough. The conductivities were measured from synthetic electrolytes of varying compositions at different temperatures for the regression models of this tool. The models have been validated using field tests.

## Application

Field tests have been conducted at Boliden Harjavalta (Pori), Aurubis (Hamburg and Lünen), and Glencore Nikkelverk (Kristiansand).

## Technologies

The design of experiments and modeling work were carried out with MODDE 8.

## Scope of application

This tool can predict the conductivity of copper electrorefining electrolyte with good accuracy, as a function of temperature and Cu, Ni, As, and  $H_2SO_4$  concentration.

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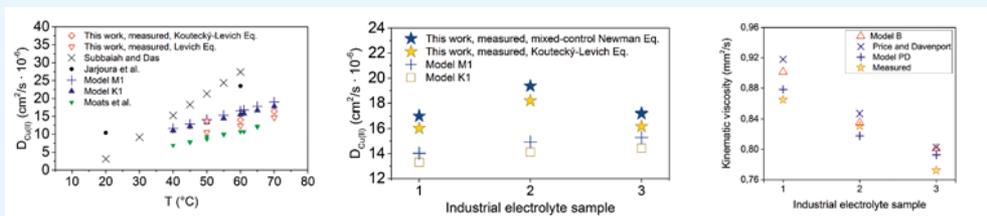
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## SHOWCASE1



## Description of the tool

In industrial copper electrorefining, the diffusion coefficient of cupric ion ( $D_{Cu(II)}$ ) significantly affects the energy consumption of the process.  $D_{Cu(II)}$  is affected by composition and temperature, as well as density and viscosity. To optimize energy consumption, it is favorable to maximize  $D_{Cu(II)}$  and minimize viscosity in the electrolyte. Likewise, to minimize the impurities in cathode copper, it is favorable to minimize the viscosity and density of the solution. Increasing viscosity and density in the electrolyte decreases  $D_{Cu(II)}$ .  $D_{Cu(II)}$ , density, and viscosity were measured from electrolytes with varying compositions at different temperatures for the development of this tool.

## Application

Field tests have been conducted at four European industrial copper refineries.

## Technologies

The design of experiments and modeling work were carried out with MODDE 8.

## Scope of application

This tool can predict  $D_{Cu(II)}$  of copper electrorefining electrolyte with suitable accuracy, as a function of temperature and Cu, Ni, As, and  $H_2SO_4$  concentration.

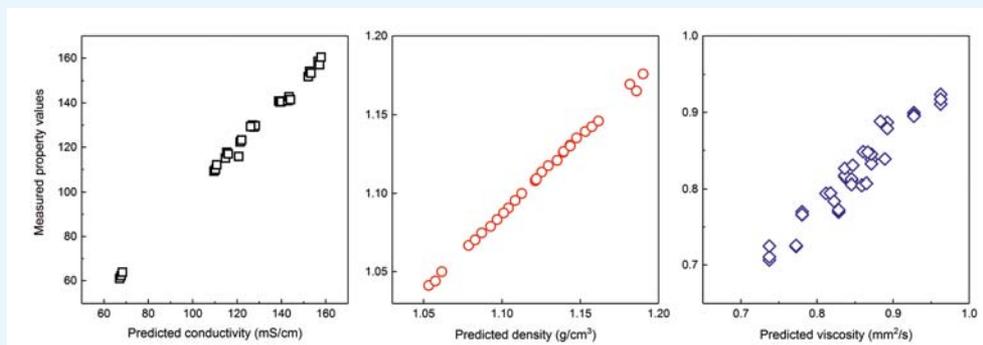
Contact persons  
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Additional Information/  
Publications

Filianin K., Taavitsainen V-M., Reinikainen S-P, Sainio T. Spectral interaction technique as data pre-treatment to eliminate matrix effect in industrial energy-dispersive X-ray fluorescence analysis. Submitted December 2016.

## SHOWCASE 1



### Description of the tool

Efficient recovery of noble metals from anode slime is essential for the economy of a copper electrorefinery. Three models for the conductivity, density, and viscosity of synthetic silver electrorefining electrolyte as a function of concentration and temperature were developed. The concentration factors were silver and free acid as the main components of silver electrolyte, with copper and lead as the major impurities that dissolve during the process. Understanding the physico-chemical properties of silver electrolyte, including conductivity, density, and viscosity, is considered to be economically important. The conductivity of electrolyte is related to the specific energy consumption of the silver electrorefining process, while density and viscosity affect the diffusion of silver and the purity of the final product deposited on the cathode. By using the models in this study, the silver electrorefining process can be optimized.

### Application

These models are under validation for real industrial conditions. The first two industrial sites that have been measured were Aurubis AG, Germany, and PT. Antam, Indonesia.

### Technologies

These models were developed using Modde, which is DOE software from Umetrics.

### Scope of application

Optimization of the silver electrorefining process.

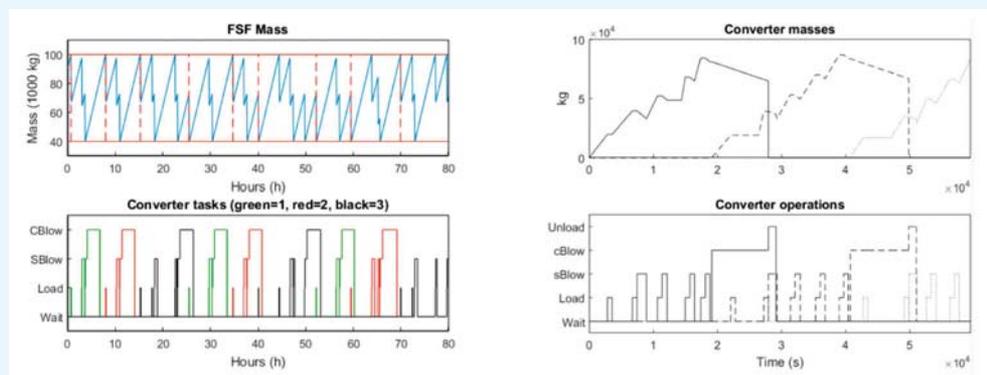
#### Contact persons – Inventors

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#### Additional Information/ Publications

Aji, A.T., Kalliomäki, T., Wilson, B.P., Aromaa, J., Lundström, M. Modelling the effect of temperature and free acid, silver, copper and lead concentrations on silver electrorefining electrolyte conductivity. *Hydrometallurgy* 166(2016), pp.154–159.

## SHOWCASE 1



### Description of the tool

Optimization methods were developed for scheduling copper production plant operation. The solutions consider the operation of the continuously operated flash smelting furnace (FSF), the three batch-operated Pierce-Smith converters (PSC), and the batch-operated anode furnaces, while taking into account the handling of off-gasses and the logistical constraints imposed by material transfer. Linear models can produce solutions quickly (<1s), even with long time horizons, while non-linear models can easily be used to simultaneously optimize material quality.

### Application

The scheduling solutions are to be presented to operators and engineers as an advisory tool, to enable improved production control.

### Technologies

The optimization problems were implemented in Matlab. In-built Matlab optimization algorithms were used to show the potential for production optimization.

### Scope of application

When the optimized schedules are presented to operators or engineers, the different effects of unit processes can be taken into account. Production rates can be further optimized and different abnormal operating conditions can be better managed.

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#### Additional Information/ Publications

Suominen, O., Mörsky, V., Ritala, R., & Vilkkö, M. (2016). Framework for optimization and scheduling of a copper production plant. In 26th European Symposium on Computer Aided Process Engineering, 2016. (Vol. 38, pp. 1243–1248).

SHOWCASE 1

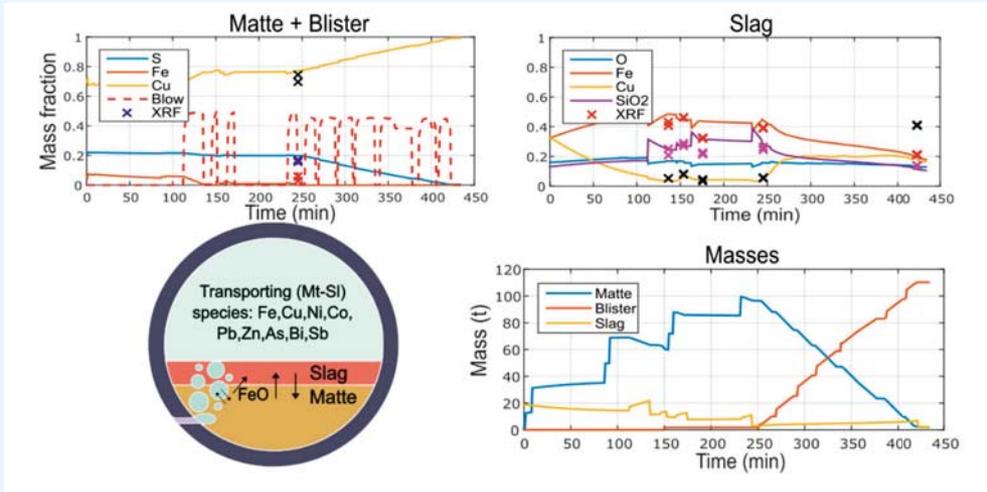


Figure 1. A simplified illustration of the process at the slag-making stage, and an example simulation run compared with plant data

Description of the tool

A dynamic non-equilibrium model concept of the P-S converter was developed for real-time operation optimization and scheduling purposes in copper production. The copper-converting operation involves minimizing copper loss to slag through gas feed end-point prediction, control of slag properties, and removal of minor elements that affect product quality. The model is based on the main reactions in the gas-liquid interactions, liquid-liquid mass transfer kinetics, and energy balance. An approximative model for the internal liquid phase conditions was implemented to avoid time-consuming thermodynamic equilibrium calculations. The resulting model enables faster computations while maintaining the capability to model interactions beyond the two main reactions of the process.

Application

After the simulation is integrated with the energy balance calculation, the method can be used to estimate the state of the converter batch.

**Technologies** Modeling and simulation were done in MATLAB and Simulink.

Scope of application

Efficient simulation of phase composition and temperature trajectories provides useful information for operators, but it also enables the potential use of robust predictive control strategies to optimize converter operation with uncertainties in input material composition.

**Contact person – Inventor** Matti Vilkkö, matti.vilkkö@tut.fi, +358 40 833 2830, Tampere University of Technology

## SHOWCASE 1

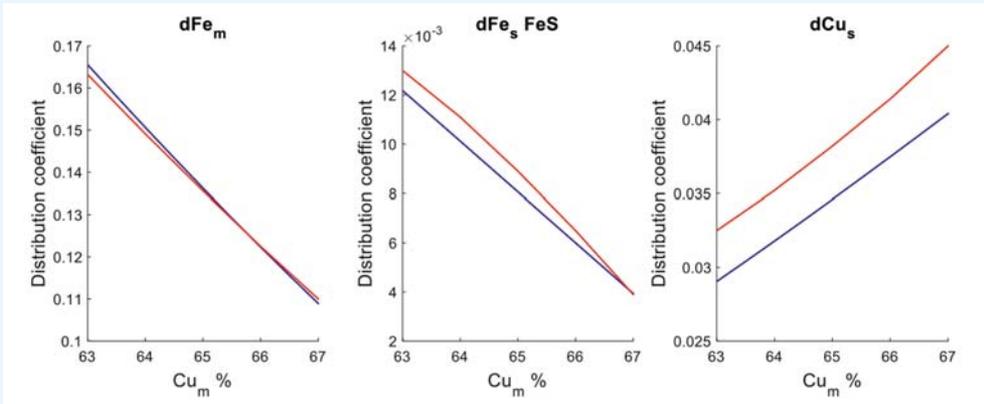


Figure 1. Flash smelting furnace model conversion: A comparison of analytical solution results in blue and iteratively calculated HSC Sim results in red as a function of copper matte percentage

### Description of the tool

HSC Sim pyro models are mathematical process models based on mass and energy balances, and empirical knowledge controlling the equilibrium state. The drawback of these models is the slow iterative calculation needed to reach the equilibrium state. The developed tool is a method of converting iterative output controlled balance models to direct calculating models for online process scheduling. The basic idea is to form a symbolic equation group based on the HSC Sim model and to solve this group analytically.

### Application

The tool enables the conversion of iterative output controlled balance models to direct calculating models for process scheduling.

### Technologies

This study uses the Symbolic Toolbox in the Matlab software.

### Scope of application

The developed method can be used to convert HSC Sim pyro models that need fast execution. Here, the converted model will be used in copper smelting-line scheduling to optimize the whole line operation.

**Contact person – Inventor** Matti Vilkkö, matti.vilkkö@tut.fi, +358 40 833 2830, Tampere University of Technology

**Additional Information/ Publications** Björkqvist, T., Suominen, O., Vilkkö, M., Korpi, M., From Iterative Balance Models to Directly Calculating Explicit Models for Real-time Process Optimization and Scheduling, 2016, 9<sup>th</sup> EUROSIM Congress on Modelling and Simulation, Oulu, Finland, September 12–16, 2016, IEEE Computer Society, p. 184–189.

SHOWCASE 1

**Cu-resepti** Siirrä **BOLIDEN**

V2.3b

Käyttöönottopäivä: 1.2.2017  
 Kokonaissyöttö DMT (t/h): 275,00  
 Kokonaissyöttötavoite (t/d): 6600,00

Vain harmaalla pohjalla olevat kentät ovat muutettavissa!

Raaka-aine	Osuus											Kaasu- määrä	
	Tonnit	pedistä	B-kerroin	O-kerroin	H-kerroin	Zn %	Pb %	Cu %	Cu/S	As %	Bi %		Yr %
Kylmäaine	1250	6 %	0,64683	58	890	0,27	0,56	25,00	2,45	1,41	1,36	10,85	3,25
Sakka1	750	4 %	0,3881	-121	-1370	0,06	0,05	6,30	31,50	10,70	0,96	14,54	5,13
Romu1	1000	5 %	0,51746										
Sakka2	50	0 %	0,02587	77	750	0,60	4,20	36,21	2,31	0,04	0,10	0,44	7,34
Seos1	25	0 %	0,01294	-77	-510	3,30	1,81	14,80	22,64	15,36	0,72	18,24	11,58
Puru	50	0 %	0,02587	431	18000	0,00	0,31	10,00	10,00	5,00	3,00	13,00	1,32
Rikaste1	800	4 %	0,41397	57	1430	1,00	0,25	42,58	3,00	2,40	0,81	5,64	2,09
Rikaste2	900	5 %	0,46572	297	3090	0,10	0,21	27,50	0,66	1,00	0,05	1,20	3,29
Rikaste3	1100	6 %	0,56921	253	3230	0,03	0,54	31,20	0,74	0,12	0,04	0,30	5,20
Rikaste4	1400	7 %	0,72445	270	3400	0,40	0,01	16,50	0,65	3,50	1,10	7,90	8,20
Rikaste5	3300	17 %	1,70763	241	3100	0,01	0,01	18,20	0,83	2,15	0,75	5,15	12,95
Rikaste6	2200	11 %	1,13842	215	2850	0,02	0,95	32,21	0,75	0,16	0,03	0,28	20,43
Sakko1	1500	8 %	0,7762	248	3090	0,07	0,02	15,20	1,25	0,60	0,20	1,40	32,24
Sakko2	3300	17 %	1,70763	202	2590	0,02	0,09	19,00	1,02	0,20	0,06	0,44	5,20
Sakko3	1700	9 %	0,87969	0	0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	5,79
<b>19925</b>	<b>100 %</b>	<b>10</b>					0,47	24,47	1,00	1,43	0,01		
<i>Edellinen peti:</i>								0,52	25,16	0,79	1,67	0,01	

Description of the tool

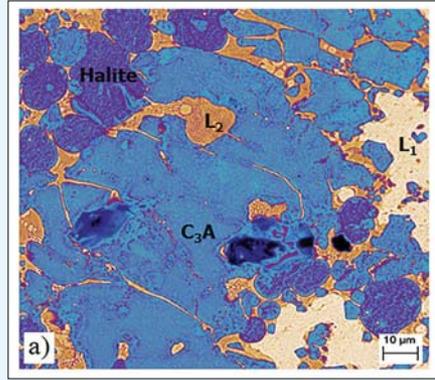
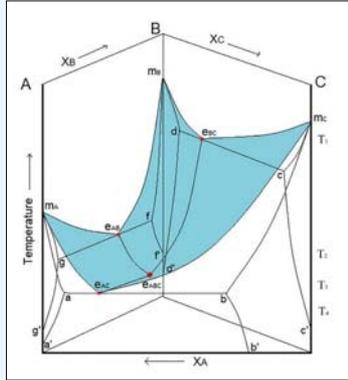
The copper smelter raw-material mix is made to ensure the stable and predictable composition of the copper anode for the copper refinery. Many disturbances, like multiple internal material loops, affect anode composition. With the new raw-material estimator model, greater confidence levels in anode composition estimations can be achieved. The model was made with Excel to reach as many users as possible.

Application

The improved anode composition estimation tool is in use at the smelter.

Contact person Petri Latostenmaa, petri.latostenmaa@boliden.com, Boliden Harjavalta

SHOWCASE 1



Description of the tool

Digitalization of sulfide smelting technology relies on a trust-worthy thermodynamic description of slag-making and fluxing chemistries. The approach enables, for example, calculation of phase boundaries of slag in the various conditions of primary smelting, as well as in auxiliary operations, such as converting, anode furnace refining, anode slime smelting, and slag cleaning. This gives flexibility in process control when the raw materials vary in composition and trace element content, and enables optimization of the production and operation of pyrometallurgical vessels.

The thermodynamic databases used for such purposes need good experimental data, and they are developed using the Calphad technique. This permits and ensures consistency in the computational data from small to large systems, and from one pure component to another.

Application

This is the key to advisory, simulation, and process control systems for industrial use, and for IoT.

Technologies

The several key sub-systems of the copper and nickel smelting slag have been studied experimentally, using a novel gas equilibration technique. There, true chemical compositions of the phases were directly measured in-situ, post-quenching, at a high temperature, without the need to separate them from each other for chemical analysis. The focus was on the liquidus surface data with well-defined constraints, and on selected trace element distributions.

Scope of application

The experimental results will be used in subsequent modeling and upgrading work on the Mtox database by NPL.

Contact persons – Inventors

Pekka Taskinen, Joseph Hamuyuni, Niko Hellstén, Rui Zhang, Longgong Xia\* and Imam Santoso; K. Avarmaa, D. Strengell, M. Valkama, P. Piskunen & S. Anttila, Aalto University, School of Chemical Technology, \*Central South University, Changsha (Hunan), PRC

Additional Information/ Publications

Altogether, 32 publications around this subject by the above persons.

# DYNAMIC MULTIPHYSICS MODELING FOR STEEL PRODUCTION

SHOWCASE  
2.1

**Agne Bogdanoff, Seppo Ollila/SSAB Europe Oy; Saku Kaukonen/Sapotech Oy; Jari Savolainen/Outokumpu Stainless Oy; Kari Välimaa/Ovako Imatra Oy Ab; Ari Kruskopf, Seppo Louhenkilpi/Aalto University; Tuomas Alatarvas, Matti Aula, Aki Kärnä, Toni Liedes, Esa Muurinen, Mika Pylvänäinen, Petri Sulasalmi, Satu Tamminen, Henri Tervo, Ville-Valtteri Visuri, Anna-Mari Warttinen/University of Oulu**

## Summary of the project's motivation and achievements

In order to shorten lead times, optimize yield, and improve product quality, new online measurements and sampling techniques are needed for improved process control and production planning. Moreover, requirements on steel quality and properties are increasing all the time and the mastery of inclusions is a key element for success with some steel grades. The main areas of research have been: 1) dynamic inclusion control in the primary steelmaking process up to the final product, focusing mainly on ladle treatment processes, and 2) multiphysics modeling of unit processes in primary and secondary metallurgy.

For dynamic inclusion control, a new online OES-PDA model has been developed and the results are very promising. It seems that the number of inclusions and their types can be predicted well using this new concept, and the concept seems to be fast enough for online purposes. With this new method, the industry can control much better the steel cleanliness and the state of inclusions than before. The rejection rate of one steel grade has been decreased significantly by using OEA-PDA in conjunction with conventional methods. Furthermore, there is clear potential to lower the rejection rate from 15% to 0% for two steel grades that make up 10% of annual production at Ovako Imatra Oy Ab.

The effects of inclusions on steel properties were also studied. Ductility and toughness are important properties in modern ultra-high-strength steels, to guarantee the manufacturability of products made of these steels and their service performance. In 500 MPa offshore steels, it is important to achieve good toughness at low temperatures even in weld heat-affected zones. Inclusions have been shown to play a significant role regarding this property. Thus the research into the effects of inclusions on mechanical properties will significantly help to improve the quality of these steels and to open new application possibilities.

Due to the project, knowledge of new online measurement techniques has increased. A vibration-based stirring intensity monitoring system has been implemented at the SSAB Europe Oy in Raahe. The advantages of the system in comparison to the subjective assessment of the operators are its fast response time and objectivity. A Ladle Condition Index (LCI) was developed for ladle condition monitoring. The LCI describes the cost-effectiveness of a stirring with the minimum amount of argon gas, and leads to cost savings in production.

In stainless steelmaking at the melt shop of Outokumpu Stainless Oy in Tornio, better online control of the EAF process was trialed with Luxmet's ArcSpec system, which deduces the state of raw material melting in the furnace based on electric arc light emissions. With the help of the ArcSpec system, the process time can be reduced by 7% and energy losses can also be reduced.

Sapotech Oy has studied laser direct illumination and made an evaluation of sensors. The feasibility of technologies for the measurement and monitoring of certain processes, as well as to gain understanding of customer needs in specific applications, is investigated. Ready-made tools for performing both online measurements and offline visualization and analysis have been developed and are now commercially offered.

During the project, a lot of modeling work was carried out. With the help of the developed CAS-OB model, it is possible to predict end compositions of the slag and steel accurately, as well as the temperature of the steel. The BOF model is promising, but needs some more work before online use. A mathematical model of the AOD process has been developed. This can be used for offline modeling, in order to study the dynamics of the AOD process, or for offline trialing of different operating practices, which can be tested in the actual process. Currently the knowledge obtained with the model has been used for improving the current AOD control model used at Outokumpu Stainless Oy in Tornio. Offline modeling has shown that the processing time of low carbon steel grades in the AOD process can be reduced by 10% with certain changes in operating practice, and will lead to savings on production costs.

## Carbon steelmaking

At the SSAB and Ovako melt shops, requirements on steel quality and properties are increasing all the time. Every process step in steelmaking is important and affects the quality of the end product. In many processes, direct measurements are impractical or even impossible due to harsh operating conditions. In order to fulfill increasing demand models, new online measurements and sampling techniques have been developed.

The key results can be listed as follows:

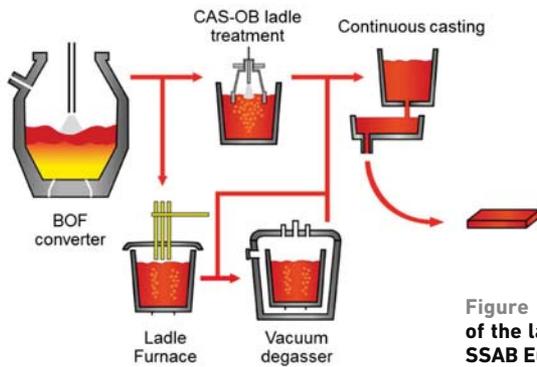
### HIGHLIGHTS OF SHOWCASE 2.1

- A mathematical model for the BOF process: a tool for optimizing production practice in terms of material and energy efficiency
- A vibration-based monitoring method for monitoring gas stirring at vacuum tank degassing station to decrease quality variance, ensure high cleanliness of special steels and decrease costs coming from incomplete treatments caused by poor ladle stirring
- A mathematical model for the CAS-OB process, a simulation tool for improving product quality and energy efficiency
- A liquid steelmaking quality monitoring tool, which helps to control product quality and fasten development work of new products
- An OES-PDA-based model for rapid analysis of steel cleanliness to control product quality and to get cost and energy savings by reducing rejections
- Online monitoring of inclusion composition in steel to improve product quality
- A method for finding clusters of inclusions in SEM specimens
- A mathematical model of the AOD process, which has been employed in combination with existing automation system to obtain a 10% reduction in processing time
- An electric arc furnace control system based optical emission spectroscopy
- Laser illumination and sensing techniques for measuring and imaging molten and solid metal, as well as refractory linings.

A more detailed description of the results is provided in the following.

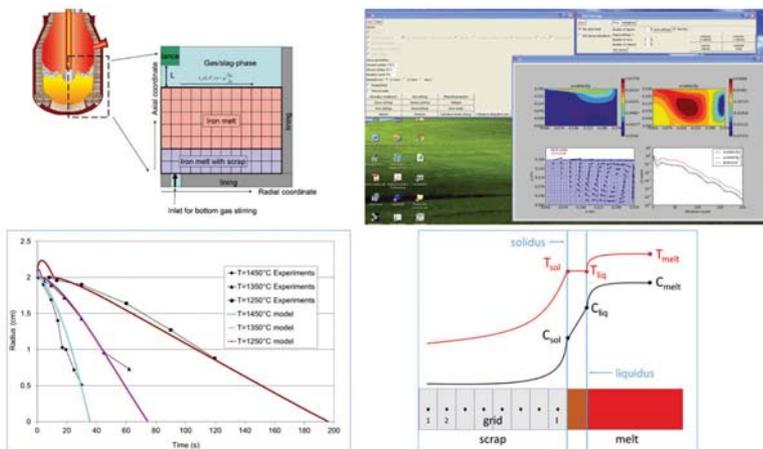
#### Mathematical model for the BOF process

The steelmaking melt shop follows a batch-type operating manner and the liquid steel is transferred in ladles between the unit processes (Figure 1). In blast furnace-based steelmaking, the first step after the blast furnace process is to refine the hot metal to steel in a steelmaking converter process, the most common of which is the basic oxygen furnace (BOF). During the process, the temperature of the metal bath varies in the range of 1300°C to 1700°C, but local temperatures in excess of 2000°C have been recorded. Owing to the high temperature, direct online measurements are very difficult to arrange. Modeling and simulation offer tools to improve BOF control and a possibility to decrease energy consumption without expensive experiments.



**Figure 1. Schematic illustration of the layout of the melt shop at SSAB Europe Oy**

Optical measurements are one possibility for realizing a reliable online measurement. Optically measured flame temperature can be used to control carbon content in the BOF process. Optical fiber-based measurement was tested in Raahе, and the method appears to be suitable for calculating the carbon content at the end of the BOF oxygen blow. The production of high-quality steel necessitates effective secondary metallurgy treatments, which are used for alloying and homogenization of the composition and temperature of the metal bath. A vacuum degassing process is used for the most demanding steel grades, when ultra-low levels of hydrogen, nitrogen, and carbon are required.



**Figure 2. Aalto University has developed a fast BOF simulation model for offline and online use**

At Aalto University (metallurgy), a preliminary converter simulation model has been developed (Figure 2). The model consists of three sub-models: 1) a scrap melting model, 2) a fluid flow solver for liquid metal, and 3) a gas mixture and a chemical reaction model. The scrap melting

model calculates how scrap pieces of different thickness melt. This model also takes into account the mass transfer of carbon, which lowers the melting point of the steel and thus affects the melting behavior considerably. The flow solver calculates the flow field of the steel melt when it is mixed with gas, stirring from the bottom of the furnace. This is important to the estimation of the mixing in the melt and the advancement of the chemical reactions taking place in the process. The chemical reaction model calculates an equilibrium for the chemical components at the phase interfaces and, combined with the fluid solver, can be used to calculate the rate of the chemical reactions. The model can be used to simulate and optimize the BOF process with different recipes and controls. Testing in real processes is always expensive and it must be done without risks. With a simulation model, it is possible to test ideas in a wide area. The details of the developed models have been published in scientific journals and conference proceedings.

### Vibration-based monitoring method for gas stirring at a vacuum degassing station

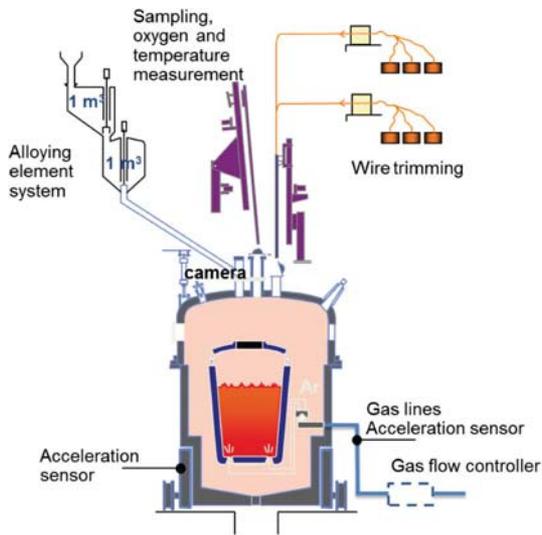
Liquid steel is stirred in a steel ladle in a vacuum tank using argon gas injection in order to achieve homogeneous composition and high-purity steel. A vibration-based stirring intensity monitoring system has been implemented at the SSAB Europe Oy in Raahe (Figure 3). The advantages of the system in comparison to the subjective assessment of the operators are its fast response time and objectivity.

A Ladle Condition Index (LCI) was developed for ladle condition monitoring. The LCI describes the cost-effectiveness of a stirring with the minimum amount of argon gas. The LCI values summarized for each steel ladle revealed significant differences between them. In combination with other indirect measurements, the vibration measurements can be employed for improved control of ladle stirring processes. Measurements are important in secondary metallurgy for exact process control when high cleanliness of special steels is needed. The vibration-based stirring intensity monitoring system ensures proper stirring intensity for different steel grades, regardless of operator experience. The Ladle Condition Index improves ladle maintenance and decreases the costs of incomplete treatments caused by poor ladle stirring.

#### Company impact

“The Ladle Condition Index describes the cost-effectiveness of a stirring with the minimum amount of argon gas, and leads to cost savings in production. Application of the vibration measurements for prediction of the efficiency of VD treatment will improve the productivity and stability of the steelmaking process.”

*Jarno Pirinen, Manager, Steel Production, SSAB Europe Oy*



**Figure 3. Vacuum tank degasser and a schematic figure of sensor locations**

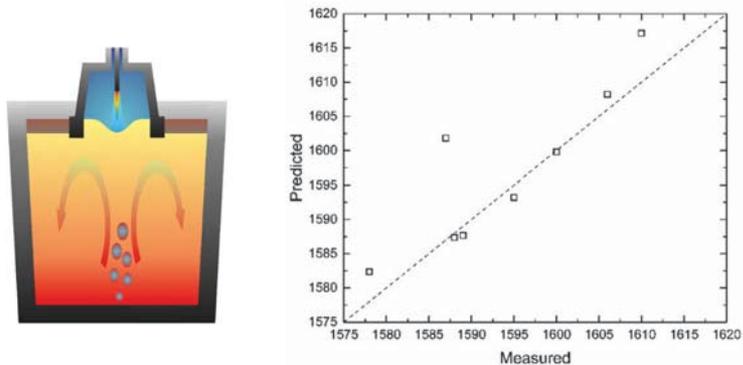
### Mathematical model for the CAS-OB process and related fluid flow studies

To support the development of a phenomena-based mathematical model for the CAS-OB process, computational fluid dynamics models were constructed for detailed studies of the process:

- A model for a supersonic oxygen lance blowing inside a CAS-OB bell was constructed using ANSYS Fluent. The main results are correlations for heat and mass transfer that can be used in fast mathematical models of unit processes. The results of the work have been published as a journal article.
- The fluid flow field in the metal bath was studied using an OpenFOAM®-2.3.0 CFD package. The flow model developed for CAS-OB was validated against the literature, where similar systems were studied. The calculated plume velocity profile and the slag-free open-eye area were compared against experimental data from the literature. A good agreement between calculated and experimental results was found. In the future, this model could be used to study the effect of the immersed bell and wall shear stresses to estimate the wearing of the refractory lining.
- The emulsification of slag during the reduction stage was studied using ANSYS Fluent. The results were found to be in good agreement with earlier studies on the subject. Furthermore, it was found that the size distribution of the slag droplets could be described well with the Rosin-Rammler Sperlting distribution function.

In the heating stage, solid aluminum is fed into the ladle and oxidized using supersonic oxygen blowing from a top lance under a ceramic bell. Simultaneously, argon is injected from the bottom. Making use of the detailed mass transfer study on top-blowing, a mathematical model was developed for the heat-up stage. The model has a reaction-solving system together with an energy conservation system. The rate expressions are formulated according to the modified Law of Mass Action-based kinetic approach. The main reactions and heat transfer mechanisms and the effect of the bottom stirring were taken into account in the model. With the model, the end composition of steel, slag, and gas phases can be predicted time-dependently. Furthermore, the steel temperature can be predicted in a transient manner. Although the calculation method is fast, stability needs to be improved in the future. This model will be part of a whole CAS-OB process model, intended for online use.

The main objective of modeling the slag reduction stage of the CAS-OB process was to develop a computational tool for predicting the chemical composition of steel and slag, and heat transfer dynamically during slag reduction, which takes place after the heating stage (Figure 4). The model takes into account the main steel-slag reactions and heat transfer mechanisms during slag reduction. Emulsification of slag plays an important role in the reduction of slag. Due to vigorous bottom stirring during the process stage, slag droplets are detached from the top slag layer. Droplet formation increases the interfacial area between the slag and steel considerably, enhancing the mass transfer between the phases



**Figure 4. Left: schematic illustration of the CAS-OB heating stage. Right: measured versus predicted steel temperatures at the end of the reduction stage**

Similar to the heat-up model, the reaction system is formulated according to the modified Law of Mass Action-based approach. The underlying assumption is that since the temperature in the process is very high, the reactions become controlled by the mass transfer, and by setting the

reaction rate constants sufficiently high in the model, the equilibrium at the reaction interface is reached. In addition to the emulsification sub-model, a number of other sub-models were needed in constructing the reduction stage model, including activity models of the species, models for the physical properties of the phases, and models for the mass and heat transfer coefficients. The validation of the model indicates that the model is able to predict end compositions of the slag and steel, as well as the temperature of the steel, accurately. Development of the reduction stage model also aimed to extend the heating stage model in order to form a comprehensive CAS-OB process model.

The heating stage model can be applied to predicting the heating rate and steel temperature. The model also enables the optimization of the material feed and the length of top lance blowing. The reduction stage model can be used for optimizing the length of the reduction stage and predicting the end temperature of the steel. Two journal articles and a doctoral thesis were published regarding modeling the CAS-OB process during Showcase 2.1.

### Liquid steelmaking quality monitoring tool

A new online quality control tool (SUMA) has been developed at the SSAB Raahе steel plant. SUMA is a quality monitoring tool for heats with a web-based graphical user interface (Figure 5). An online connection to a history database enables daily quality monitoring and immediate fixing of problems. With better process control and monitoring, it is possible to optimize process units (e.g. tapping, casting, slab grinding, and repairing), save energy and time, and receive and store more information about intermediate and final products. Benefits of the project are:

- Detection of process deviation from the normal state
- Quick analysis of how a melting succeeded
- Provision of an overall understanding of liquid steelmaking process quality
- Help and support for product development and operators in their work process quality deviations
- A monitoring tool that can be used as a learning tool, for example with new operators and engineers
- A tool to improve steel cleanliness for strengthened customer demands, for example in the automotive industry
- Faster development work

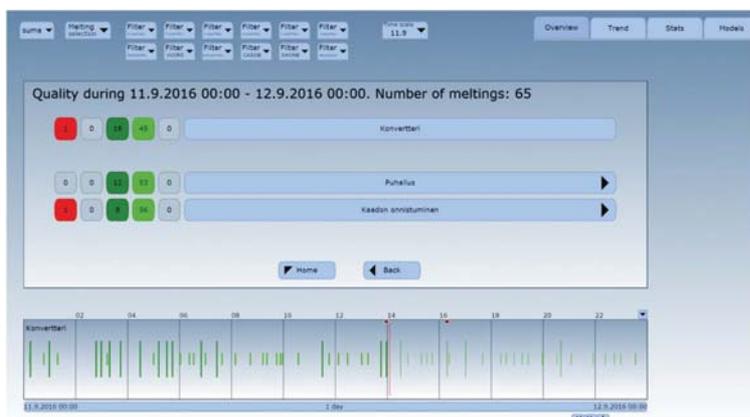


Figure 5. User interface of the SUMA tool



## Company impact

“The liquid steelmaking quality monitoring tool gives a quick analysis of how melting succeeded and shows development needs. It also saves working time.”

*Maija Kärkkäinen, Quality manager, Steel production, SSAB Europe Oy*

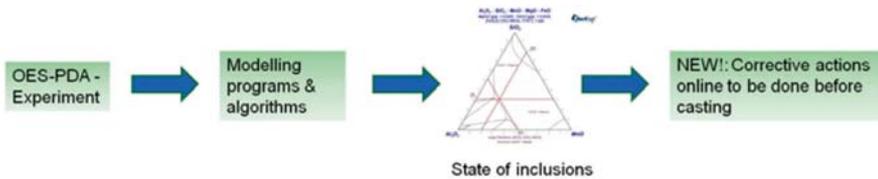
## OES-PDA-based model for rapid analysis of steel cleanliness

Online control of steel cleanliness is a very real theme in all steel plants, as problems in steel cleanliness may lead to severe quality problems, downgrading of the products, poor castability, and internal rejections. The general aim in the industry is to reduce the total amount of inclusions in liquid steel and to ensure that the remaining inclusion chemistry and size distribution is closely controlled. Traditional microanalysis methods generally take too much time for online control. An OES-PDA analyzer (Optical Emission Spectrometry with Pulse Discrimination Analysis) with advanced mathematical tools is a relatively fast method for determination of types and size distributions of inclusions in steel samples. The commercial tools coupled to OES-PDA are today mainly based on statistical or logistical concepts, and they do not predict the inclusion types accurately and robustly enough.

During the project, a new online OES-PDA model has been developed, together with Aalto University, SSAB Europe Oy, and Ovako Imatra Oy Ab, in cooperation with voestalpine Stahl GmbH, Linz, Austria. The principle of the method is illustrated in Figure 6. The results are very

promising. It seems that the number of inclusions and their types can be predicted well using this new concept, and the concept seems to be fast enough for online purposes. One planned next step is to couple the developed system with an in-house thermodynamic tool, such as IDS or ChemSheet, to predict forward in time to see how the inclusions will behave in the next operation steps, and this will also give guidance for possible revision operations at the present time. Some preliminary work has already been carried out.

It is difficult to estimate the importance and business value of the results, but it is clear that by improving the control of inclusions in steel plants, many kinds of quality and practical problems can be solved, and if it is possible to get fast feedback concerning inclusions, corrective actions can be taken when the steel is still in the processing phase. So the outcome of this new concept is that the industry can control steel cleanliness and the state of inclusions much better than before. The work is now on the level of “proof of concept”, meaning that the aim has been to show and verify its feasibility. The concept can be applied by all steel plants.



**Figure 6. Principle of the OES-PDA model in industrial use**

### Online monitoring of inclusion composition in steel

In the production of special steels, the importance of optimal inclusion composition is increasing due to increasing requirements for steel quality and properties. For Ovako’s M-steels, the key property is good machinability, which gives the customer significant savings in machining costs. The machinability of steel is traditionally determined by a machining test, and the results are received only after the steel has been cast and rolled into the final dimensions. Therefore, there is a clear need to find a way to estimate the machinability earlier in production and make it possible for the process to make corrections.

OES-PDA measurement is seen as a possible technique for estimating machinability during production, and there is interest in attempting to use it for process control. Other potential applications for OES-PDA are steel cleanliness measurement and control of calcium treatment of steels. During this project, the OES-PDA technique has already been used as a valuable tool for analyzing the production process of machinable

steels. The rejection rate of one steel grade has been decreased significantly by using OEA-PDA in conjunction with conventional methods.



## Company impact

“There is a clear potential for lowering the rejection rate from 15% to 0% for two steel grades that make up 10% of annual production at Ovako Imatra.”

*Kari Välimaa, Manager, Manufacturing process development,  
Ovako Imatra Oy Ab*

Fast measurement of inclusion composition is currently in use for research purposes, to study the effects of different process parameters during ladle metallurgy, with the main focus being on the machinability of the steel. It enables faster process development and, as a result, cost savings and a higher quality level in the production process.

### Computational thermodynamics of non-metallic inclusions in steel

Computational thermodynamics play a significant role in inclusion research. Especially for assessing the inclusion stabilities in the molten steel, FactSage calculations have been carried out. Sulfur may be present in steel as harmful sulfide inclusions or soluble within the steel matrix. The conventional analysis methods do not provide information on how sulfur is distributed between inclusions and the matrix. The influence of calcium, oxygen, and sulfur contents on the sulfur distribution was considered. Computational results were compared to inclusion analyses of the samples taken from the SSAB Europe Raahе steelworks, and it was concluded that sulfur is partly dissolved and partly present as CaS inclusions before the solidification of steel. The dissolved sulfur can form MnS inclusions during solidification and cooling. The occurrence of CaS inclusions is especially dominant when both oxygen and sulfur contents of the steel are low.

### A method for finding clusters of inclusions in SEM specimens

There are several methods for analyzing and identifying inclusions in steel specimens. Currently, there is a need for methods for steel purity analysis with low costs and high accuracy, and which enable the online analysis during production on a large scale. The goal of this research is to develop criteria that will characterize the purity of steel and enable the comparison of different specimens.

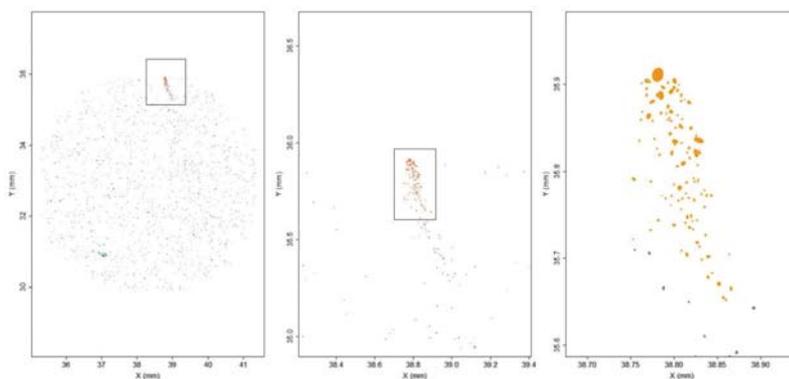
The first task in this research was to find clusters in SEM specimens. There were different types of specimens, and thus, the types and sizes of inclusions varied, as well as the shapes of the clusters. The analysis was not restricted to certain cluster shapes; chain-like inclusions, for example, were assumed to be only a special type of cluster. During the tool development, the functions have been built by using as much parameterization as possible. Thus, the user can try different parameters to define clusters and to monitor results.

The search for clusters was started from a simple method. A very simple and fast way to achieve a very rough picture of the distribution of the inclusions in a SEM specimen is to define a grid for the SEM specimen and calculate the number of centers of inclusions in each part of the grid. The search for clusters was continued by a method in which only the centers of the clusters were utilized for distance calculation. This is also a fast and easy way to get an overall picture of the distribution of the inclusions in a SEM specimen. In a more accurate cluster search, each inclusion is assumed to be an ellipse, with the length, width, and direction specified by the SEM analysis for the corresponding inclusion, and the clusters are identified based on the distances between the ellipses. For each cluster, the properties of the included inclusions can be monitored and summarized. For this type of cluster identification, the search time is significantly longer but still acceptable. If more realistic shapes were used, the search time could grow exponentially.

The data contained test samples from melting and after rolling. The test specimen type is not restricted, but the user can select appropriate parameters for each type. The specimen during melting has been visualized in Figure 7. The whole specimen can be seen on the left, a zoomed view in the middle, and one interesting cluster has been magnified on the right. The user can select different views of the specimen, which helps to find interesting details for closer inspection. Different clusters are visualized using colors, and the dimensions of the inclusion correspond to the dimensions of the ellipse. Inclusions that do not belong to existing clusters are gray. If one interesting cluster has been magnified, the colors illustrate the types of inclusions in the interesting cluster, and other inclusions are gray. For example, in Figure 7 on the right, most of the inclusions in the interesting cluster are AlO.

The current results can be utilized in two different ways. The user can visually check the existing clusters in test specimens. The tool can also help to verify the results from OES-PDA analysis: at the moment, the results from this and SEM differ significantly, especially in the number of inclusions, and with our cluster identification tool it is possible to check whether the number and location of clusters associate better with the OES-PDA data. When the OES-PDA analysis produces reliable results,

it can be used on a much larger scale during production than the SEM analysis. Thus, the next step of the research is to improve the OES-PDA analysis.



**Figure 7. Left: a whole test specimen with actual inclusion sizes; middle: a zoomed view; right: one cluster for a closer inspection**

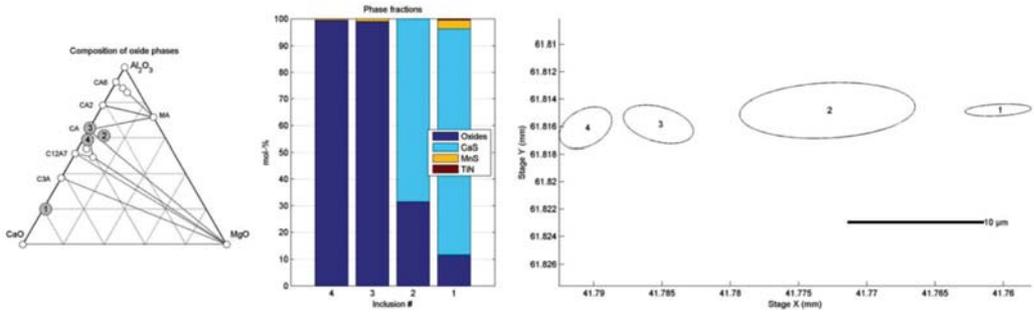
### Evolution of oxide inclusions during continuous casting and hot rolling

During the steelmaking processes, inclusions are allowed to float up into the top slag and to be removed from the steel melt. This can happen until the mold and continuous casting, where the steel starts to solidify. From that point on, practically no measures can be taken to remove or modify inclusions. Besides, new inclusions form during the solidification of steel. Samples were taken from the mold and from the hot-rolled final product to investigate the changes in inclusion characteristics. The evolution of oxide inclusions was examined during casting and rolling with the electrolytic extraction and cross-sectional methods. It was found that too low Ca additions resulted in unmodified spinel inclusions in both mold and product samples. The compositions of inclusions obtained with the electrolytic extraction and cross-sectional methods were fairly comparable.

### Locating and identifying oxide inclusion stringers in SEM samples

In the final product, chain-like oxide inclusion stringers are known to be detrimental to the mechanical properties of steel, similarly to elongated sulfides. The formation of elongated manganese sulfides can be effectively prevented, but the formation mechanism of oxide stringers is not clearly understood. Thus, the prevention of their occurrence is also problematic. A method to automatically locate the oxide-sulfide inclusion chains from the sample data of a hot-rolled product has been developed at the Process Metallurgy Research Unit of the University of Oulu, in close cooperation with SSAB Europe Oy. An estimate of the phases present is

also provided among the inclusion chain properties (Figure 8). The phases present have a marked effect on the deformation of inclusions during hot rolling, and consequently on the mechanical properties of the steel.



**Figure 8. Properties of an inclusion stringer discovered in a hot-rolled product**

### Effect of inclusions on steel properties

Inclusions such as oxides, sulfides, and nitrides are known to be deleterious to various properties of steels. However, it is not clear what the critical level is for each inclusion type, regarding the number, size, and distribution, in order to achieve the desired mechanical properties. Research efforts have been directed toward understanding the following: 1) the mechanisms by which inclusions affect various mechanical properties, 2) the combined effect of microstructure and inclusions on properties, 3) the kinds of inclusions that are typical in different types of steels, 4) the effect of steel strength on the critical inclusion level, 5) how to modify inclusion structure to be less harmful, and 5) the role of alloy element segregation during solidification on the formation of inclusions. In the Materials Engineering and Production Technology Research Unit of the University of Oulu, these things were studied in cooperation with SSAB Europe's Raabe plant. The studied materials were modern ultra-high-strength direct-quenched steels with a martensitic microstructure, as well as 500 MPa advanced offshore steels with a ferritic/bainitic microstructure.

Steels with different impurity contents were studied using scanning electron microscopy with energy dispersive spectrometry (SEM-EDS), to characterize the inclusion structure, and by tensile testing and Charpy V-notch impact toughness testing, to determine mechanical properties such as ultimate tensile strength, tensile ductility, and impact toughness at various temperatures. Typical inclusion distributions of the studied steels were evaluated and the most harmful inclusions regarding ductility and toughness were identified.

It was found that even with relatively low sulfur contents, elongated manganese sulfides deteriorate the transverse tensile ductility and transverse impact toughness remarkably at room temperature for ultra-high-strength levels. Similarly, coarse titanium nitrides were discovered to weaken the low temperature impact toughness in the studied steels.

The low temperature toughness of coarse-grained heat-affected zones in 500 MPa offshore steel appeared to have deteriorated due to the existence of coarse (Ti,Nb)N inclusions. Thus, by modifying the inclusion structure, it should be possible to improve the weldability of the studied steels. Good ductility and toughness are properties that can be linked to properties such as bendability and weldability. These are important properties in modern ultra-high-strength steels, to guarantee the manufacturability of products made of these steels and their service performance.

In 500 MPa offshore steels, it is important to achieve good toughness at low temperatures even in weld heat-affected zones. Inclusions have been shown to play a significant role regarding this property.



## Company impact

“The research into the effects of inclusions on mechanical properties will help to significantly improve the quality of 500 MPa offshore steels and open new application possibilities.”

*Pertti Mikkonen, Product development manager at SSAB Europe Oy*

## Stainless steelmaking

Quality and production volume requirements have increased at the melt shop of Outokumpu Tornio during the past few years. The current low price of stainless steel has created pressure to decrease overall production costs. Therefore, new methods for lower production costs, higher volume, and better product quality are constantly sought. Better control and understanding of every melt shop process step (Figure 9) is required in order to increase productivity and decrease costs. Steel melt shop processes are usually batch-type processes, and therefore slight deviations occur from batch to batch. The effect of these deviations can be reduced by better online control of process steps. Another aspect in increasing productivity is the development of process practices by better process models. With good models, alternative production practices can be studied offline in order to find the potential to shorten lead times, and to reduce costs and environmental effects. Subsequently, the new practices can be tested in the actual process and introduced into production.

At electric arc furnace (EAF), with better online process control, was trialed with the ArcSpec system developed by Luxmet Oy. The ArcSpec system deduces the state of raw material melting in the furnace from electric arc light emissions. The electric arc is used to melt solid raw materials to liquid form in the following process step. The ArcSpec system enables the use of higher electric power without decreasing operational reliability at one EAF of the Outokumpu Stainless Oy in Tornio.



### Company impact

"With the help of the ArcSpec system, the process time can be reduced by 7%. The ArcSpec system also reduces energy losses by €200k annually."

*Niko Hyttinen, Researcher at Outokumpu Stainless Oy*

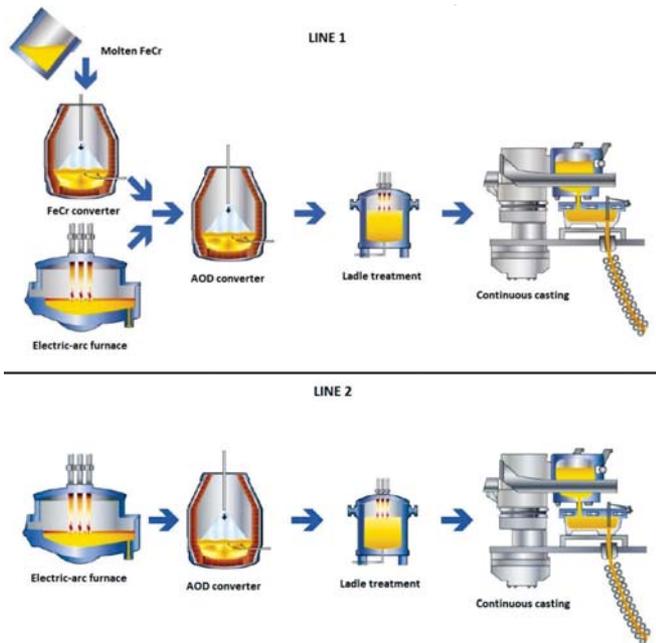
The next process step after the EAF is argon-oxygen decarburization (AOD), which is used to refine the molten steel coming from the EAF. Productivity of the AOD process has a significant effect on the total productivity of the steel melt shop. A mathematical model of the AOD process, named the converter process simulator (CPS), has been developed in cooperation with the University of Oulu and Aalto University. The model employs a novel Law of Mass Action-based approach for the treatment of mass transfer-controlled reaction equilibria. The structure of the model follows a modular principle and consists of phenomena-based reaction models for reactions during side-blowing, top-blowing, and reduction of slag. The CPS can be used for offline modeling in order to study the dynamics of the AOD process. The CPS can also be used for offline trialing of different operating practices, which can be tested in the actual process. The knowledge obtained with the CPS has been used to improve the current AOD control model used at Outokumpu Stainless Oy in Tornio.



### Company impact

"Offline modeling conducted with the CPS has shown that the processing time of low carbon steel grades in the AOD process can be reduced by 10% with certain changes in operating practice. In a full-capacity utilization situation, the potential annual savings at the Tornio melt shop are approximately €3M."

*Pentti Kupari, Senior researcher at Outokumpu Stainless Oy*



**Figure 9. Schematic illustration of production lines 1 and 2 at Outokumpu Stainless Oy (Modified from Metallinjalostajat ry 2009)**

After the AOD process, steel is poured into the casting ladle, which acts as a process step for additional refining and as temporary storage for steel before casting. During pouring, the steel is partly exposed to air, which is considered a quality-decreasing factor in the production of stainless steel, says Jari Savolainen, research engineer at Outokumpu Stainless Oy. Sapotech's Reveal-tap camera system was trialed to see how steel flow behaves during tapping from the converter to the casting ladle. The behavior of steel flow during tapping of different batches was compared to known factors affecting quality. As a result, better tapping practices were found to minimize the effect of tapping on quality.

During the project, Outokumpu Stainless Oy has collaborated with the University of Oulu, small and medium-sized enterprises from Finland (Luxmet Oy, Sapotech Oy), and carbon steel producer SSAB Europe Oy. Collaborative action inside the project created resources that Outokumpu required during trialing, and interpretation of the results gained from the new measurement techniques and process models. During the project, new measurement techniques and process models were identified, developed, and trialed. As a result, notable improvements in productivity can be achieved, which can be seen from the numerical results.

Inevitably, steels contain non-metallic inclusions, which are considered detrimental not only for the process, but also for the product. The composition of steel is adjusted during ladle treatments. Some alloying elements are only desirable when in soluble form within the steel matrix.

Even though their amount in the steel may be very low, they are necessary in order to achieve the required properties of the steel. The maximizing of the yield of these microalloying elements, such as titanium and niobium, in the steel matrix is one of the targets of the steel melt shop, to reduce costs. However, the routine elemental analysis of the steel only provides the total composition of the steel, including both inclusions and the steel matrix.

The electrolytic extraction method, utilized at the Process Metallurgy Research Unit of the University of Oulu, can be used to separate the steel matrix and the non-metallic inclusions from each other. When coupled with advanced analysis methods (ICP-OES, GF-AAS, FAAS), the distribution of certain elements between the steel matrix and the inclusions can be accurately assessed. In addition, the method can be used to measure various concentration levels, from ppm level (e.g. vanadium) to over 20 per cent (e.g. chromium). Electrolytic extraction is the only method that provides detailed information on the element distribution between the inclusions and the steel matrix. Alternative methods for fast characterization of inclusions were studied at Outokumpu Stainless Oy. The results of light optical microscopy, scanning electron microscopy, and the electrolytic extraction method were found to be roughly comparable when inclusions are characterized from the surface of the steel samples.

### **CASE: Commercialization of high-tech products – experiences from Sapotech Oy**

As a startup company, Sapotech's objective in the SIMP program has been to study and develop laser illumination and sensing techniques for measuring and imaging molten and solid metal, as well as refractory linings. A secondary objective has been to gain more knowledge about extreme and harsh conditions (high/low temperature, dust, humidity) and related protection techniques. New information can immediately be applied to product R&D. The SIMP program overall has had a significant positive impact on the startup development, by revealing new business opportunities and contributing to the R&D work.

#### **Study of laser direct illumination**

A powerful diode laser can be used as a primary illumination source for machine vision applications. High output power with a fast pulse rate facilitates taking sharp images of hot moving objects such as cast or rolled steel products. As part of this study, the optical arrangement for the illumination has been further developed, to simplify the device configuration and to improve the lighting efficiency and reliability, as well as to reduce costs. The main objective has been to develop a direct illumination system by replacing optical fiber in the current lighting configuration.

The direct illumination prototype was manufactured and its performance measured. The work has involved participation by Cavitar Oy in Tampere. Figure 10 (before) and Figure 11 (after) depict the impact of direct illumination on intensity. The next step is to productize and evolve the technique used in the prototype.

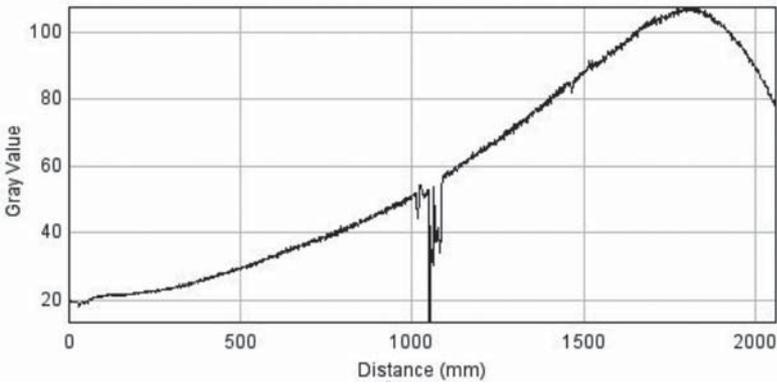


Figure 10. Light intensity vs. distance (fiber + lens + diffuser)

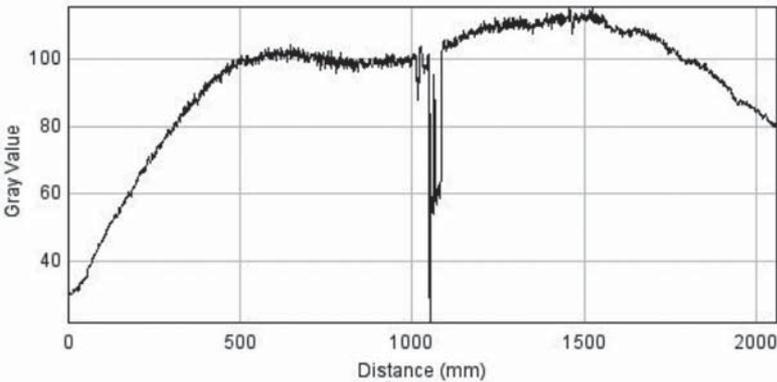


Figure 11. Light intensity vs. distance (lens + diffuser)

### Evaluation of sensors

In this task, we studied the performance and function of some commercial off-the-shelf (COTS) sensors, to assess suitability for hot process measurements. Target temperatures in these applications typically vary between 800°C – 1600°C. Studied COTS products include 2D laser scanners, laser distance measurement (LDM) sensors, and line projection lasers for machine vision applications. Testing has been performed in the lab and, for some, in real production conditions. Table 1 lists the evaluated products and a summary of the results. As a result, the Noptel LDM sensor was selected for Sapotech's Reveal 360 product.

**Table 1. Summary of sensor evaluation results**

Manufacturer	Sensor	Type	Applicability to hot surfaces	SDK	Protection feasibility	Remark
Micro-Epsilon	scanCONTROL Compact 2900	2D laser scanner	No	Yes	Poor	Short distance to target restricts applicability and protection
Triple-In	PS-100-90HT	2D laser scanner	Yes	Yes	Good	
Noptel	Several	LDM	Yes	Yes	Good	
Jenoptik	LDM 42.2	LDM	Yes	Yes	Good	
Z-laser	Z30M18S3-F-640-LP20	Line laser	Yes	Yes	Good	

### Tool deliveries

Besides acting as an industrial partner in the program, Sapotech has had the opportunity to provide products and services to the industry, acting as a subcontractor for other partners in the program. These deliveries have further helped to assess the feasibility of technologies for the measurement and monitoring of certain processes, as well as to gain understanding of customer needs in these specific applications. Sapotech Reveal products are ready-made tools for performing both online measurements and offline visualization and analysis.

A six-month proof of concept project was delivered to SSAB Europe Oy in Raahe, whereby Reveal CAST technology was applied to measuring and calculating shape profiles (contours) of hot-rolled plates. A secondary objective was to assess the feasibility of surface quality monitoring and automatic defect detection for roll marks and other repetitive surface defects on the plates. An outcome of the study was that shape profiles could be measured at resolutions better than 1 mm per pixel and at accuracies of 0.1%. Repetitive surface defects (e.g. roll marks) could also be automatically detected.



**Figure 12. A Reveal TAP system with IR and monochrome cameras**

Sapotech Oy has delivered two Reveal TAP systems to Outokumpu Stainless Oy in Tornio works: one for AOD-1 converter tapping monitoring at the steel melt shop and another for FeCr EAF furnace no.3 bottom tapping monitoring at the ferrochrome plant. As one of the main benefits, Reveal TAP data has helped to analyze and understand the impact of the tapping procedure on the liquid metal pick-up of gases like nitrogen and oxygen. Figure 12 depicts a typical Reveal TAP system installation and Figure 13 shows a related cloud service user interface.



Figure 13. Reveal TAP cloud UI showing tapping from an AOD converter

### CASE: Commercialization of high-tech products – experiences from Luxmet Oy

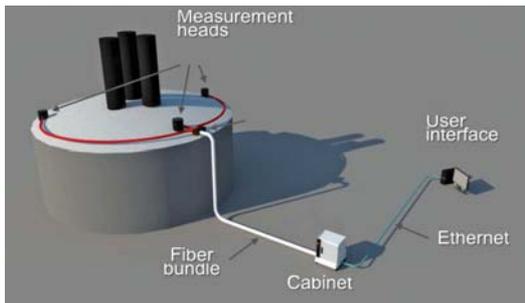
As a start-up company, Luxmet Oy executed three sub-contractor projects from Outokumpu Stainless Oy and SSAB Europe Oy during the DIMECC SIMP program. The main focus for Luxmet Oy in the project was the development of a measurement system for an electric arc furnace.

#### Electric arc furnace control system

An electric arc furnace is a process in which raw steel can be produced from recycled steel scrap. Steel scrap is molten with electricity, which is consumed in high amounts. Even though electric arc furnaces have been around for many years, accurate measurement of scrap melting is a challenge. When scrap melts, the energy of the arc is lost to the sides, which means that energy efficiency gets lower and refractory wear increases. Currently, scrap melting is measured from the cooling water temperature difference on the mantel, but the problem is that this is too slow, since it measures energy already lost.

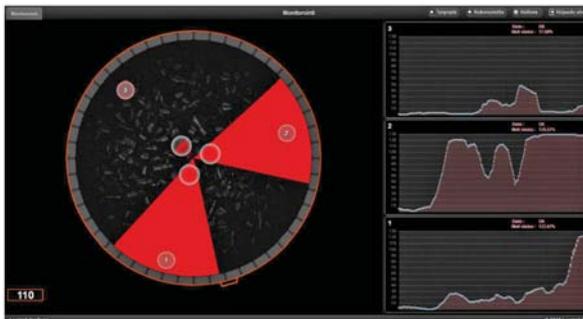
In order to measure scrap melting accurately, Luxmet Oy conducted two projects with Outokumpu Stainless Oy. In these projects, a measurement system was tested in both Outokumpu Stainless Oy, Tornio Works, electric arc furnaces. The approach of Luxmet Oy was to measure the

light emitted from the furnace sides, which indicates if the protective slag layer is molten. The approach was internationally novel; no previous measurements of light have been recorded from industrial AC furnaces. Measuring light enables the use of optical fibers, which in turn enables the delicate measurement equipment to be placed away from the hazardous environment of the furnace. Even though light could be measured remotely, getting the fibers intact in the electric arc furnace roof was a tough challenge. Continuous improvement of equipment design made it possible, by the end of the second project, to achieve a system requiring very little maintenance. The measurement system is presented in Figure 14.



**Figure 14. Luxmet measurement system**

The system developed for measuring scrap melting was tested in online control in Outokumpu Stainless electric arc furnace 1. An example of the user interface is presented in Figure 15. In these tests, higher than normal arc power was used, because the loss of energy to the sides could be controlled better. The tests resulted in approximately 7% faster furnace operations compared to conventional process practice. Reduced power-on time also gives many other benefits, which are harder to calculate accurately. There is still further potential for savings by integrating the system more into operational practice. The results could be obtained without increased furnace wear.



**Figure 15. ArcSpec user interface**

The DIMECC SIMP program was crucial in the development of this new technology. At the end of the program, the technology was ready for operational use. Luxmet is currently implementing a new control system based on this technology in Outokumpu Stainless Oy electric arc furnace 1. The project was very important to Luxmet Oy, since it showed that the system works in online control, which gives Outokumpu Stainless Oy new ways to control and optimize their process. The University of Oulu, Process Metallurgy Research unit, took part in reporting the findings of the measurements. The results were disseminated in scientific publications and conferences. In addition, a doctoral thesis describing the optical emissions from electric arc furnaces was published.



## Company impact

"The DIMECC SIMP program has played a major role in enabling Luxmet to test and further develop its technologies in new applications, together with industrial partners in the metal industry."

*Mikko Jokinen, managing director of Luxmet Oy*

## Future potential

It is clear that by improving the control of inclusions in steel plants, many kinds of quality and practical problems can be solved, and if it is possible to get fast feedback concerning inclusions, corrective actions can be made when the steel is still in the processing phase. Therefore, the outcome of the new online OES-PDA concept is that the industry can control the steel cleanliness and the state of inclusions much better than before. The work will continue in a further project on industrial online application. The concept can be applied by all steel plants.

Inclusion clusters have a high impact on the mechanical properties of a steel product, and the study of the effects have been started in this project. The variation in the size and shape of clusters can be large between products, and the effect of these parameters on mechanical properties is unknown. Additionally, the cleanliness of the steel is a quality property without an unambiguous variable that would enable the comparison and ranking of steel products. However, it is not clear what the critical level is for each inclusion type, regarding the number, size, and distribution, in order to achieve the desired mechanical properties. Tools for inclusion control and quality prediction of the product will help to improve the smelting process and to meet the requirements for quality. This study will be continued in a future project on the model for predicting the mechanical

properties of a product, depending on the inclusion cluster distribution and process parameters in large-scale quality prediction of a product.

Measurements are important in secondary metallurgy for exact process control when high cleanliness of special steels is needed. A vibration-based stirring intensity monitoring system ensures proper stirring intensity for different steel grades, regardless of operator experience. A Ladle Condition Index improves ladle maintenance and decreases the costs of incomplete treatments caused by poor ladle stirring. Application of the vibration measurements for prediction of the efficiency of treatment has been envisaged as a potential topic for further research. Future work on the mathematical modeling and simulations of vacuum ladle stirring and vibrations is already ongoing, and there is a plan to apply vibration measurement for the BOF process.

Productivity of the AOD process has a significant effect on the total productivity of the steel melt shop. A mathematical model of the AOD process, converter process simulator (CPS), has been developed in co-operation with the University of Oulu and Aalto University. The CPS can be used for offline modeling in order to study the dynamics of the AOD process. The CPS can also be used for offline trialing of different operating practices, which can be tested in the actual process. The knowledge obtained with the CPS has been used to improve the current AOD control model used at Outokumpu, Tornio. The work will be continued in a further project by improving the numerical routine for a side-blowing model of the AOD simulator, and the simulator will be validated for combined-blowing.

Sapotech Oy and Luxmet Oy will continue commercialization of the new technologies and products developed during the DIMECC SIMP program. The SIMP program was crucial for these companies in the development of these new technologies.

## Further information

### KEY PUBLICATIONS:

Aula, M. 2016. Optical emission from electric arc furnaces. Doctoral thesis, University of Oulu.

Järvinen, M., Kärnä, A., Visuri, V.-V., Sulasalmi, P., Heikkinen, E.-P., Pääskylä, K., De Blasio, C., Ollila, S. and Fabritius, T. 2014. A Novel Approach for Numerical Modeling of the CAS-OB Process: Process Model for the Heat-Up Stage. *ISIJ Int.*, 54(10): 2263–2272.

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**Publications** 49

**Doctoral theses** 2

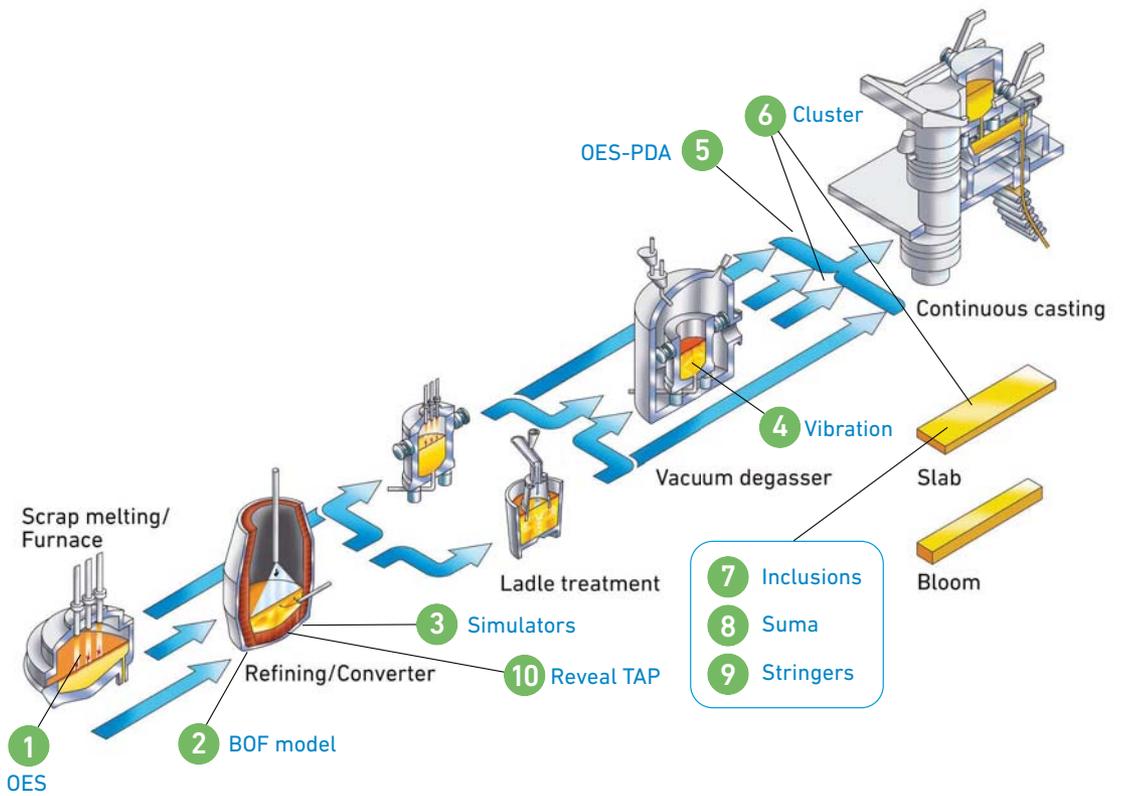
**Master's theses** 10

### CONTACT PERSONS:

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Ville-Valtteri Visuri, Project secretary, University of Oulu

### PARTICIPANTS:

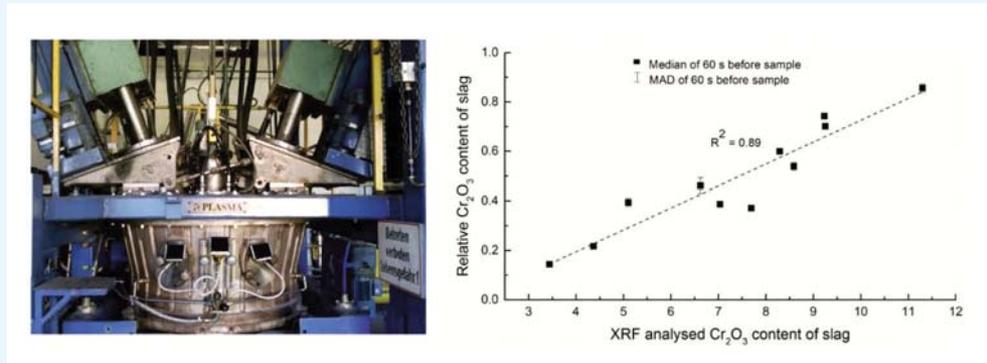
Aalto University, Luxmet Oy, SSAB Europe Oy, Outokumpu Stainless Oy,  
Ovako Imatra Oy Ab, Sapotech Oy, University of Oulu



**Figure 16.** The numbered bullets in the process scheme represent the tools developed in Showcase 2.1. The tools are described in the following pages

ONLINE SLAG COMPOSITION ANALYSIS FOR ELECTRIC ARC FURNACES BASED ON OPTICAL EMISSION SPECTROMETRY

SHOWCASE 2.1



Introduction

Slag composition is an important factor when producing stainless steel grades with EAF. Too high chromium content of the slag in the EAF causes high chromium content in the tapped slag. The objective of this work is to measure online slag chromium content in an electric arc furnace. The measurement is based on the optical emission spectrum (OES) of the electric arc plasma.

Measurements

The measurement concept was originally tested in the laboratory EAF at the University of Oulu. Further tests were conducted with a pilot scale AC EAF at RWTH Aachen University, Department of Industrial Furnaces and Heat Engineering. The comparison between the OES and XRF analysis shows that the slag chromium content can be measured with an average absolute error of 0.64 %-points and a standard deviation of 0.49 %-points.

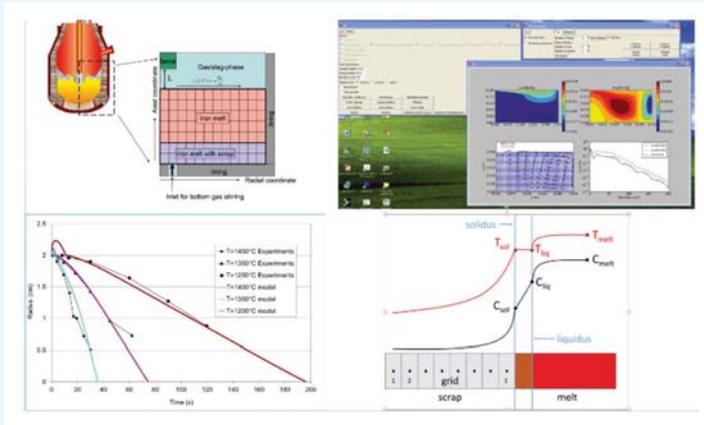
Conclusions

Online optical emission spectroscopy is a promising tool for online slag composition analysis. Currently, it is possible to analyze slag chromium content with sufficient accuracy on laboratory and pilot scale. The focus of future development is on broadening slag composition analysis to other slag components, and applying the methods on an industrial scale. The work will be continued in the project OSCANEAF, funded by the European Commission.

**Contact person** Matti Aula, University of Oulu, matti.aula@oulu.fi

**Additional Information/ Publications** Aula, M. 2016. Optical emission from electric arc furnaces. Doctoral thesis, University of Oulu.

## SHOWCASE 2.1



### Description of the tool

The steel converter process model consists of three submodels, which are: a scrap melting model, a fluid flow solver for liquid metal and gas mixture, and a chemical reaction model. The scrap melting model calculates how scrap pieces of different thickness melt. This model also takes into account the mass transfer of carbon from the liquid, which lowers the melting point of the steel and thus affects melting considerably. The flow solver calculates the flow field of the steel melt when it is mixed with gas stirring from the bottom of the furnace. This is important to the estimation of the mixing in the melt and the advancement of the chemical reactions taking place in the process. The chemical reaction model calculates an equilibrium for the chemical components at the phase interfaces, and can thus be combined with the flow solver to calculate the rate of the chemical reactions.

### Application

The aim of this model is to improve predictions when process parameters change. The improved control of the process can lead to faster batch process and increased yield.

### Scope of application

The modeling tools developed for this process can be applied to other processes which are characterized by similar phenomena.

**Contact person** Ari Kruskopf, Aalto University, ari.kruskopf@aalto.fi

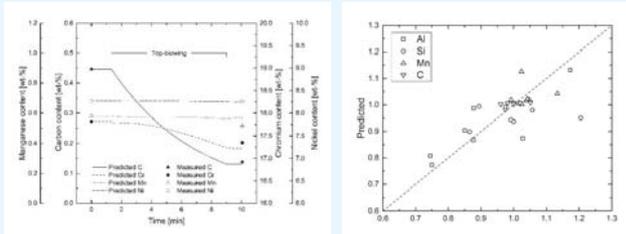
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SHOWCASE 2.1



C and Cr content prediction using the CPS (left). Steel composition prediction using the CAS-OB simulator (right)

Description of the tool

The objective of this work was to develop modular, thermodynamic-kinetic simulators for the Argon-Oxygen Decarburization (AOD) and Composition Adjustment by Sealed argon blowing – Oxygen Bubbling (CAS-OB) processes. Both simulators employ a Law of Mass Action-based kinetic approach. The Converter Process Simulator (CPS) consists of three main reaction models. The side-blowing model assumes that the reactions take place in the gas plume, which is treated as a three-phase plug flow reactor. In the top-blowing model, reactions take place simultaneously in the cavity and on the surface of the splashed metal droplets. The reduction model is based on the assumption that reactions take place between the steel bath and slag droplets. The CAS-OB process simulator consists of two main reaction models. The heat-up model considers chemical heating of the steel bath by oxidizing aluminum with a pure oxygen jet inside a bell structure. The heat and mass transfer coefficients of the jet were determined by computational fluid dynamics (CFD) simulations. The reduction stage model considers reactions and heat transfer during slag reduction, which is carried out after the heating stage.

Application

The simulators can predict the dynamic changes in the compositions and temperatures of the metal, slag, and gas phases. They can be employed for optimizing several process parameters, including composition and temperature of the material inputs, composition and injection rate of gas, and types of material additions and their feed rates. At Outokumpu Stainless Oy, the length of the AOD treatment of certain steel grades was reduced by 10% with the help of simulations with the CPS and automation system. The annual savings were valued at EUR 3 million in the case of full production.

Technologies

The simulators were executed in C++ and validated using measurement data obtained from Outokumpu Stainless Oy and SSAB Europe Oy.

Scope of application

The simulators can be extended or modified to simulate other process stages (e.g. secondary desulphurization) or processes (e.g. ferrochromium converter).

Contact persons – Inventors

Ville-Valtteri Visuri, Petri Sulasalmi, Aki Kärnä (University of Oulu), Mika Järvinen (Aalto University)

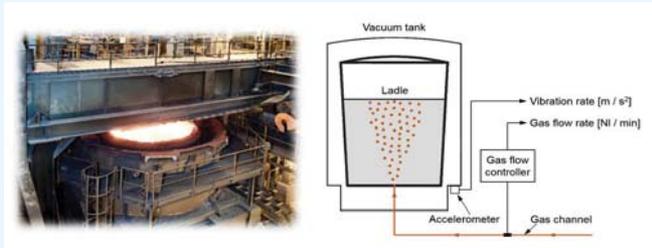
Additional Information/ Publications

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## 4

VIBRATION-BASED TOOL FOR GAS-STIRRING  
EFFICIENCY ASSESSMENT IN LADLE TREATMENTS

## SHOWCASE 2.1



Open vacuum tank with a ladle inside

Measurement system

**Description of the tool**

The objective of this work is to develop a mechanical vibration-based objective indicator, which can be used for monitoring stirring intensity, detection of gas leakage during the stirring process, and condition monitoring of ladles.

The measurement system depicted in the top-right figure consists of a gas flow controller and a one-axial accelerometer that is installed on the outer surface of the vacuum tank. The accelerometer measures the mechanical vibration of the vacuum tank in the vertical direction. The gas flow rate information is generated by the gas flow controller, and it is recorded as an average using intervals of one second.

A vibration indicator is created from the vibration signal by means of signal processing, using one second intervals. The most adequate vibration indicator with the closest relationship to the gas flow rate is searched by conducting statistical analysis.

**Application**

An adequate vibration indicator, together with the gas flow rate, can be used for monitoring purposes in order to detect stirring gas leakages during the stirring process. The vibration indicator and the gas flow rate can also be jointly used for the condition monitoring of ladles, meaning for monitoring their ability to generate the maximum amount of vibration with the minimum amount of gas.

**Technologies**

Vibration measurement data obtained from the SSAB Europe Oy steel plant in Raahé was treated by signal processing methods using Matlab. Statistical analysis of the vibration indicator together with gas flow rate was conducted with R.

**Scope of application**

The tool is applied to the vacuum tank degasser at SSAB Europe Oy in Raahé. Instead of subjective observation of the process stage, the process operator has an objective and numeric indicator for stirring intensity.

**Contact persons  
– Inventors**

Mika Pylvänäinen, Ville-Valtteri Visuri, Toni Liedes, Jouni Laurila, Konsta Karioja, Timo Fabritius (University of Oulu), Seppo Ollila (SSAB Europe Oy)

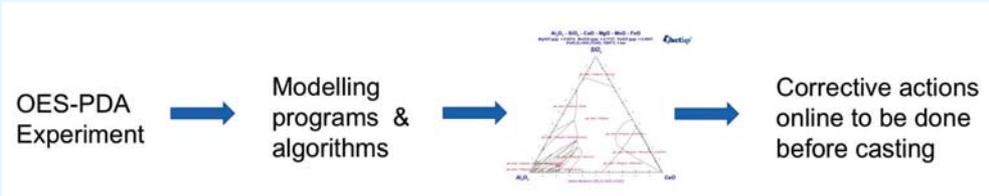
**Additional Information/  
Publications**

Pylvänäinen, M., Visuri, V.-V., Liedes, T., Laurila, J., Karioja, K., Pikkupeura, S., Ollila, S., and Fabritius, T. 2016. Vibration-based Assessment of Gas Stirring Intensity in Ladle Treatments. Proc. 5th International Conference on Process Development in Iron and Steelmaking, Swerea MEFOS, Luleå, Sweden.

5

NEW ONLINE MODEL FOR CALCULATION OF TOTAL OXYGEN OF LIQUID STEEL USING OES-PDA DATA

SHOWCASE 2.1



Description of the tool

Online control of steel cleanliness during steelmaking is a very real theme in all steel plants, as problems in steel cleanliness may lead to severe quality problems, downgrading of products, poor castability, and internal rejections. Cleanliness can be correlated with the total oxygen (O total) content of the liquid steel. It is, anyhow, very difficult to measure and define the total oxygen or steel cleanliness online. An OES-PDA analyzer (Optical Emission Spectrometry with Pulse Discrimination Analysis) with advanced mathematical tools is a relatively fast and efficient method for determination of steel cleanliness and total oxygen. However, commercial tools coupled to OES-PDA are mainly based on statistical or logistical concepts, and they do not predict the inclusion types or total oxygen accurately and robustly enough. In DIMECC SIMP, the new concept is to use thermodynamic and metallurgical knowledge together with statistical or logistical concepts. The concept can be applied by all steel plants.

Application

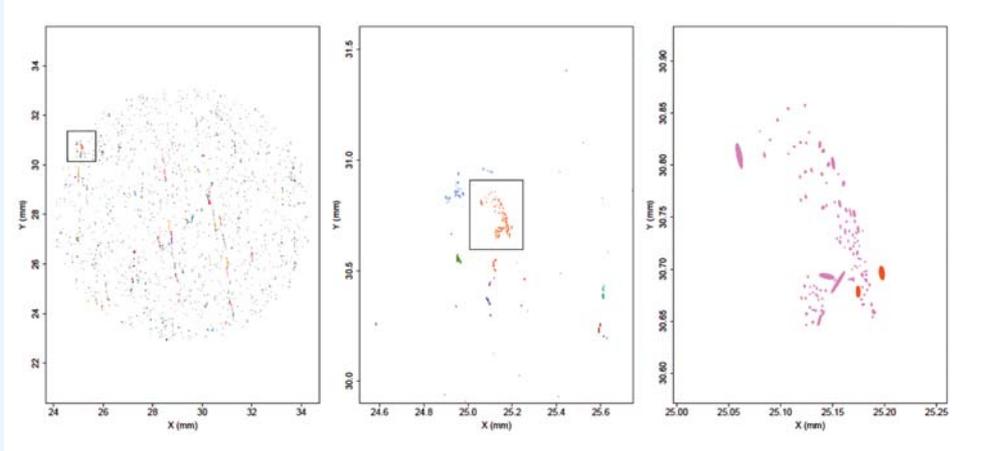
The results are very promising. It seems that the number of inclusions and their types can be predicted well using the new concept, and the concept seems to be fast enough for online purposes. This means that the necessary revision operations can be done if the values are not as desired. In addition, a fast quality check of the final product is one of the main advantages of this method. The outcome of this new concept is that the industry can control steel cleanliness and the state of inclusions much better than before. The results have been checked against Leco measurements.

Technologies

OES-PDA data coupled with in-house computer programs and algorithms.

**Contact persons – Inventors** Partners: Aalto University, SSAB Europe Oy/Raabe and Ovako/Imatra in cooperation with Voestalpine steel plant, Linz, Austria.  
 Contact person: Seppo.Louhenkilpi, Aalto University (seppo.louhenkilpi@aalto.fi)

SHOWCASE 2.1



Description of the tool

The tool finds inclusion clusters in SEM specimens and produces a summary for each cluster based on Inca Feature data. The tool has flexible parameterization for cluster definition. The results can be visualized in several ways, and the tool can be used for all kinds of SEM specimen types. The tool improves steel purity control. When the purity of steel products can be compared, it is possible to use this information for sales and marketing.

Application

Inclusion clusters have been studied for several different, both liquid and end-product, SEM specimens. The identified inclusion clusters have been validated visually. The R-based tool was delivered for test use at SSAB Europe Oy and the University of Oulu.

Technologies

The free statistical program R was used for inclusion clustering, output summaries, and visualization.

Scope of application

The tool can be used by anyone who wants to get a closer look at SEM specimens and is interested in steel purity. With this tool, it is easier to compare specimens from different products. The tool was built in cooperation with SSAB, but the method can be used in any factory that needs information about inclusions in SEM specimens.

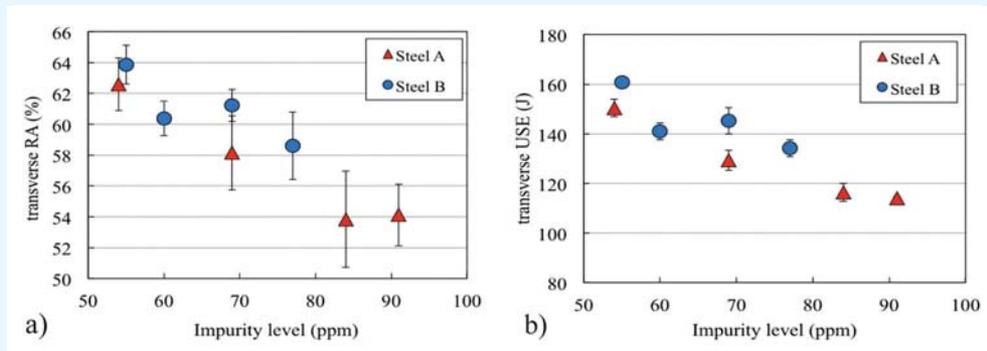
**Contact persons – Inventors** Anna-Mari Warttinen and Satu Tamminen, University of Oulu/BISG  
Leena Määttä, Tuomas Antola and Tuomo Saarinen, SSAB Europe Oy

**Additional Information/ Publications** Warttinen, A.-M. Steel purity and analysis of inclusion behaviour. Manuscript.

7

CRITICAL INCLUSION LEVELS REGARDING THE MECHANICAL PROPERTIES OF MODERN CARBON STEELS

SHOWCASE 2.1



Description of the tool

Inclusion data provided by scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS), as well as impurity content data provided by OES and combustion analysis, are compared to the mechanical properties provided by methods such as tensile testing and Charpy V-notch impact toughness testing. The provided data is compared quantitatively using statistical methods, as well as qualitatively by examining the fracture surfaces of the test specimens using laser scanning confocal microscopy (LSCM) and SEM.

Application

The aim of the method is to estimate the effect of inclusions on the mechanical properties of steels and to find the critical inclusion levels for each steel grade. This information can be utilized later as an input in online quality control systems, giving operators at the steelmaking plant an opportunity to modify the inclusion structure to match the desired properties.

Scope of application

The method can be used to estimate the effect of inclusions especially in carbon steels but possibly also in other materials.

Contact person – Inventor

Henri Tervo, University of Oulu, henri.tervo@oulu.fi

Additional Information/ Publications

Tervo, H., Kaijalainen, A., Porter, D., Pikkarainen, T., Kesti, V., Mehtonen S. and Leinonen, M. 2015. Effect of Impurity Level on the Mechanical Properties of an Ultra-High-Strength Steel. Proc. 9<sup>th</sup> International Conference on Clean Steel, Budapest, Hungary, 2015.

8

QUALITY MONITORING FOR THE LIQUID STEELMAKING PROCESS

SHOWCASE 2.1



Description of the tool

The tool is used for monitoring liquid steelmaking process quality. The tool gives an overall understanding of process quality. Deviations from the normal state are easy to detect. The tool provides a quick analysis of how a melting succeeded. It improves steel cleanliness for

strengthened customer demands, for example in the automotive industry. The tool helps and supports product development and operators in work process quality deviations. It makes development work faster and it can be used as a learning tool. The benefits can be summarized as follows:

- Detection of process deviation from the normal state
- Quick analysis of how a melting succeeded
- Provision of overall understanding of liquid steelmaking quality
- A tool to improve steel cleanliness for strengthened customer demands, for example in the automotive industry
- Help and support for product development and operators in work process quality deviations
- Faster development work
- The monitoring tool can be used as a learning tool

Application

The tool has been validated by testing carried out by SSAB process engineers. The tool is connected to SSAB online databases, so launching the tool gives a view of up-to-date process data and quality.

Technologies

- Operating system: Windows
- Web-based user interface: HTML5, PHP
- Server backbone: C++, Boost C++ library, ExprTk rule engine
- Models: Rules defined by SSAB process engineers
- Data source: Oracle

Scope of application

The tool is applied as a quality monitoring tool.

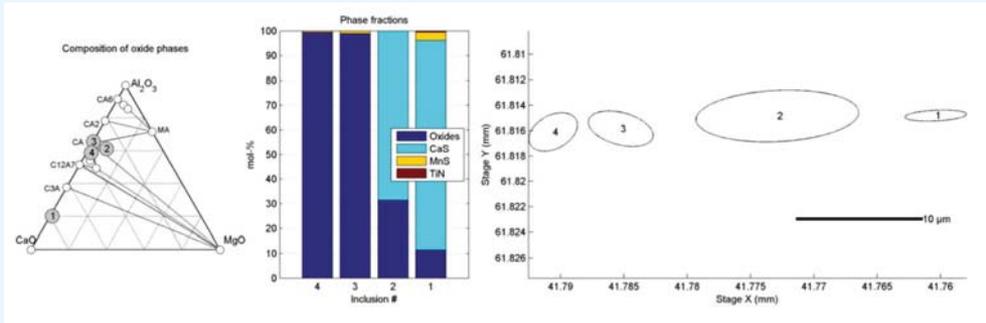
Contact persons  
- Inventors

Heli Helaakoski and Vesa Kyllönen, VTT Technical Research Centre of Finland Ltd  
Maija Kärkkäinen, Leena Määttä, Tuomas Antola and Seppo Ollila, SSAB Europe Oy

9

IDENTIFYING OXIDE STRINGERS IN HOT-ROLLED STEEL

SHOWCASE 2.1



Description of the tool

Matlab is utilized to identify and locate detrimental oxide–sulfide stringers in the hot-rolled product. A method to estimate inclusion phases of low carbon, aluminum-killed, and calcium-treated steels is proposed. The inclusions are taken as a mixture of CaS, MnS, TiN, and oxide ( $Al_2O_3$ -CaO-MgO) phases. The phase fraction and oxide phase compositions are calculated from the elemental analysis for each inclusion. The phases present have a marked effect on the deformation of inclusions during hot rolling, and consequently on mechanical properties.

Application

Inclusion analysis data gathered with a scanning electron microscope and exported from IncaFeature software is analyzed. In the procedure, the sample area is first divided into narrow horizontal strips to determine the number of inclusions within it. If multiple inclusions on a strip are close enough to each other, the inclusions are identified as a stringer.

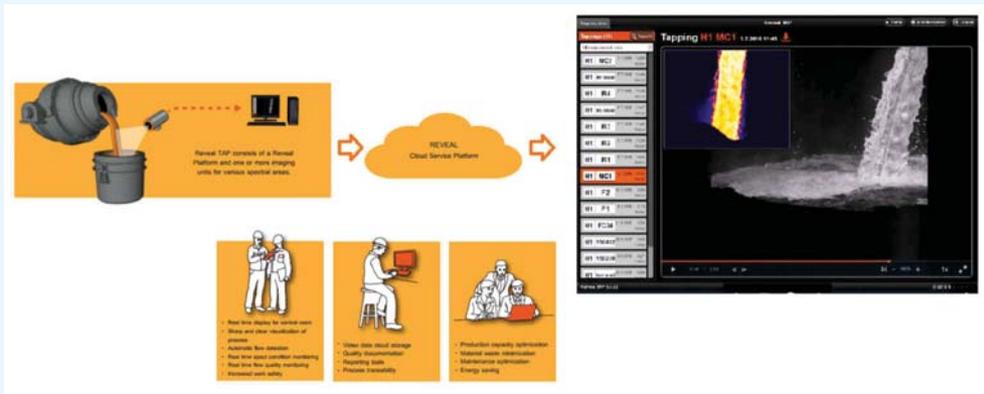
The following properties are presented for each stringer: the number of inclusions and the length of the stringer, phase fractions and compositions, and the composition of the unfragmented inclusion before hot rolling.

Scope of application

The tool can be applied to any rolled steel grade, to locate horizontally fragmented inclusions.

Contact person Tuomas Alatarvas, University of Oulu, tuomas.alarvas@oulu.fi

SHOWCASE 2.1



Description of the tool

Reveal TAP is a solution for monitoring hot metal flows based on visualization in unprecedented detail. Clear benefits are enhanced process control through data provided online, and process improvement through analysis offline. Significant cost savings are made through metal/slag detection. Work practice and safety are improved.

Application

Reveal TAP was applied as a SIMP pilot project in a real process environment for online monitoring of hot ferrochrome bottom tapping, and of steel tapping from an AOD converter. Offline visualization using a cloud service was also used. The project led to positive changes in tapping practice, contributing to better process efficiency and improved product quality.

Technologies

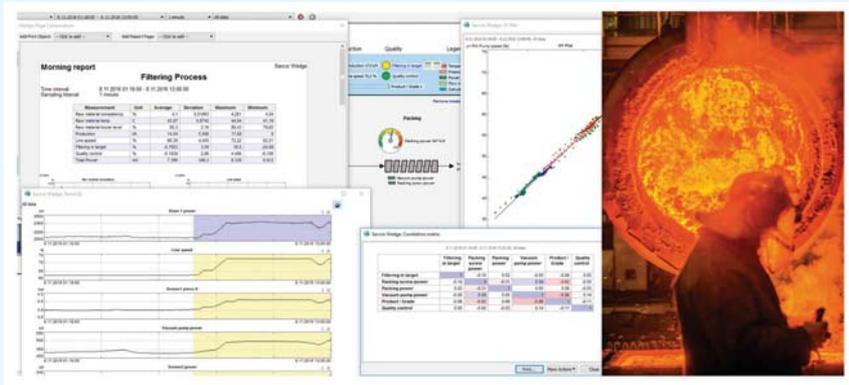
Reveal TAP is a web-based platform making full use of the Industrial Internet, enabling easy remote management and fluent distribution throughout organizations and locations. Additional measurement technologies and features can be further integrated into the platform according to users' specific needs.

Scope of application

Reveal TAP can be applied in many other metallurgic processes involving hot metal flows, such as monitoring steel foaming. New needs arise continuously. Reveal TAP solutions bring visualization of processes that have so far been difficult or even impossible to monitor with the human eye, with all the benefits involved, whether in process efficiency or work safety.

**Contact persons** Saku Kaukonen, Sapotech Oy  
**- Inventors** Juha Roininen, Sapotech Oy

SHOWCASE 2.1



Description of the tool

The tool is designed for finding root causes or consequences from process data, even over process delays. The tool can be used for trouble-shooting, process optimization, support for best operational practices, automation analysis, maintenance, and process development. The tool enables analysis of a vast amount of data.

Efficient process data utilization improves process material, time, and energy efficiency by reducing waste, internal material circulation, and nominal energy consumption.

Application

The system reads all time-stamped numerical process-related data, and is used by process management, process development, maintenance, and operators.

The tool is applied in the SIMP project in the Outokumpu smelting and casting departments, and in the SSAB hot rolling plant. The system was installed and integrated into the existing production plant environment and used online for real-case process efficiency improvements, trouble-shooting, and process and operational practices development.

Technologies

The Wedge system platform is integrated in existing process measurements, data retrieval, and storage systems and modeling tools.

Scope of application

The system background is in pulp and paper industry processes, and is also utilized in the chemical, dairy, and mineral industries. The tool can be utilized in any process industry that has a reasonable modern infrastructure and automation. The system is capable of finding root causes in seconds or minutes, rather than in the days and weeks required by traditional methods. It enables better process, material, and energy efficiency and quality optimization.

**Contact persons** Esa Puukko, Outokumpu; Matti Häkkinen, Savcor;  
**– Inventors** Mika Suojärvi, Savcor; Jarkko Vimpari, SSAB

# ADVANCED QUALITY MONITORING METHODS FOR STEEL PRODUCTION

## SHOWCASE 2.2

Seppo Louhenkilpi, Jyrki Miettinen/Aalto University; Jukka Laine/Casim Consulting  
Ilmari Juutilainen, Perttu Laurinen/Indalco; Matti Häkkinen/Savcor  
Olli Haapala, Juha-Matti Pesonen, Esa Puukko, Anna Uurtamo/Outokumpu Stainless Oy  
Agne Bogdanoff, Jussi Helkoma, Juha Jokisaari, Jari Nylander, Ari Pikkuaho,  
Elina Prokkola, Ismo Rentola, Tapio Salonpää, Maarit Sippala, Jarkko Vimpari/SSAB  
Timo Fabritius, Eija Ferreira, Joonas Ilmola, Harri Juttula, Esko Juuso, Konsta Karioja,  
Sami Koskenniska, Jari Larkiola, Aleksi Laukka, Olli Leinonen, Anssi Mäkynen, Aarne  
Pohjonen, Pekka Siirtola, Satu Tamminen/Henna Tiensuu, Lauri Tuovinen/University of Oulu  
Heli Helaakoski, Vesa Kyllönen/VTT Technical Research Centre of Finland Ltd

### Summary of the project's motivation and achievements

**A**fter liquid processing quality control of steel production includes several aspects from mechanical properties to slab and coil surface defects and plate shapes. In highly competitive and customer orientated market a quality is a key difference maker. In addition to that high quality material has to be delivered on time. Both companies SSAB and Outokumpu are also developing new steel grades requiring more precise process control for advanced product properties.

Work in Showcase 2.2 has focused on slab casting and hot coil and plate rolling in where volumes are high and thus, fast reaction to identify abnormal process condition is required. Detection in early stage of process enables also proactive adjustment to final processing steps.

Activities and achievements of the project could be divided under three main categories:

- Fundamental-based modelling and advanced statistical modelling
- Piloting of new platforms for overall quality monitoring in on-line environment
- Piloting of new measurement technology to provide new information for a quality prediction

Solidification phenomena during casting were further developed and new indexes for quality prediction were implemented for usage of SSAB and Outokumpu. Scaling mechanisms during slab heating were deeply studied and modelled to have better understanding their effect on Outokumpu's surface quality. New phase transformation model coupled to heat conduction model was developed to improve mechanical property

control of SSAB's special steels. FEM-modelling was introduced in several places of hot coil and plate rolling to understand how stresses affect on shape and pressure-related defects. Totally 10 different statistical analysis and models were done to predict quality risks and yield losses related to that.

On-line applications for phenomena-based casting monitoring were piloted in both SSAB and Outokumpu. For hot rolling a framework for overall quality monitoring was developed and implemented in on-line environment. Commercial process diagnostic system was successfully piloted in both companies while Outokumpu focused on casting area and SSAB focused on hot rolling. Impacts to quality improvements of all installed on-line applications will be seen after longer-term usage.

Three different novel measurements was developed and piloted to improve shape accuracy of slabs, plates and strips in both companies. New measurement technique for strip roughness was tested in Outokumpu.

### HIGHLIGHTS OF SHOWCASE 2.2

New simulation concept has been successfully used to estimate how to increase casting efficiency in Outokumpu and how to design the optimal cooling pattern to avoid corner cracks in SSAB.

By advanced statistical modelling and FEM-modelling major factors affecting Outokumpu's sticking defect risk was discovered as well as optimal combination between flatness and mechanical properties in temper mill processing of SSAB.

Mathematical modelling of combination parameters helped SSAB to minimize the waste in plate rolling process.

Several on-line quality monitoring systems were built-up for continuous usage both in SSAB and Outokumpu.

Piloting of position measurement lead to an industrial investment that will significantly stabilize critical hot rolling process in Outokumpu.

### Advanced models from continuous casting to a reheating furnace

Computational simulation and modeling of different phenomena in casting have greatly helped in solving practical problems in industrial casters and improving process practices and control. Advanced models are also needed for the subsequent processes after continuous casting. In the

DIMECC SIMP 2.2 subprojects, advanced simulation models have been developed for continuous casting (CastManager+IDS), for slab tracking after continuous casting (SlabManager+IDS), and for a reheating furnace (FurnaceManager+IDS). The aim has also been to make the developed models computationally fast, so that they can be used in online applications for process control and quality prediction. A steady state simulation tool, Tempsimu, has also been developed for continuous casting.

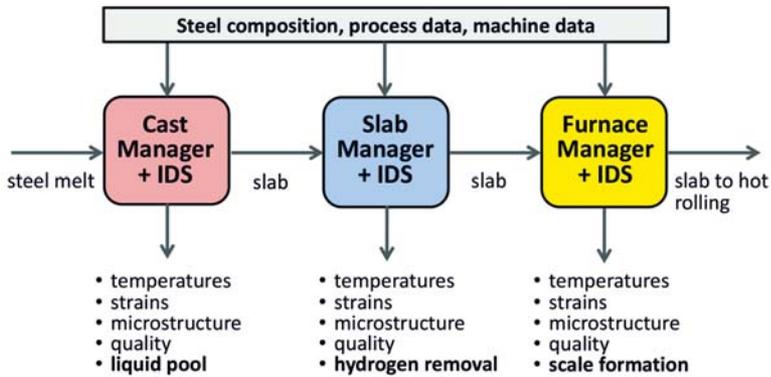


Figure 1. Online systems developed in DIMECC SIMP 2.2 for continuous casting, slab tracking after casting, and for a reheating furnace

## Improving the casting process with simulation and quality prediction system for continuous casting



### Industry impact

“IDS has reduced the time needed for preparations when new steel grades are produced. IDS is also easy-to-use, engineer-friendly software with an informational graphical user interface.”

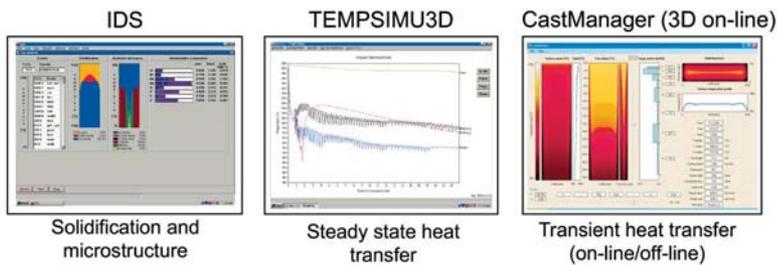
*Jari Savolainen, Outokumpu Oy*

“The main potential of CastManager is to get online calculation data on temperatures and defects for quality control and development.”

*Maija Kärkkäinen, quality manager, Steel Production, SSAB Europe Oy*

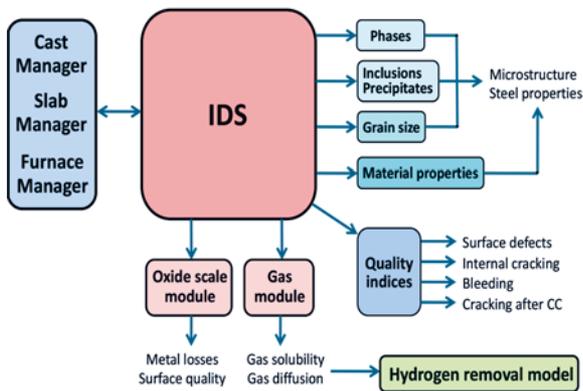
CastManager is a transient three-dimensional heat transfer model for continuous casting. It includes the mold and the strand model, and they are solved numerically using numerically fast implicit methods. IDS is a thermodynamic-kinetic-empirical tool for solidification and microstructure. IDS calculates phases, phase transformations, and several solidification, cooling, and reheating-related phenomena, including inclusions and precipitates from liquid state to room temperature and during reheating. The heart of the model is the large thermodynamic, diffusion, and microstructure databank made through our own assessment work. In particular, the thermodynamic database of IDS has been clearly extended. IDS also includes many special modules, such as the those of quality prediction (updated in SIMP), scale formation (developed in SIMP), stacking fault energy (developed in SIMP), material properties (updated in SIMP), and austenite decomposition (updated in SIMP). The previously developed material property and austenite decomposition modules were extended in SIMP by adding new sub-modules of creep rate and elastic modulus to the former, and new boron-related calculation algorithms to the latter. IDS has been validated by numerous solidification-related temperature, solute partition, and ferrite content measurements.

Tempsimu is a steady state version of the CastManager model. It can be used offline by research engineers, for instance, to design spray water nozzle arrangements for the casting machine or to calculate the length and shape of the solidifying steel shell. In steel manufacturing, when heating and cooling are repeated, the control of this is especially important for steel quality. In the casting machine, there are many spray nozzles causing temperature fluctuations in the strand, and especially for high-quality steel grades, it is important to design the spray nozzle system correctly so that quality problems can be avoided. A new option in Tempsimu is the stress module. This calculates mechanical stresses and strains during bending and unbending, as well as thermal stresses in the machine. The important creep effect is included.



**Figure 2. The following tools have been developed: IDS, Tempsimu3D, CastManager**

The IDS and CastManager models are integrated in one online concept. In real-time calculation, many practical requirements will be set for the system. The computing time must be short enough and the special process conditions, such as the start and the end of casting, as well as ladle change and steel grade change, must be included in the model. Now the numerical solution algorithms of CastManager and IDS are so fast that the system can easily be used for online applications. In addition, the start and the end of casting, as well as ladle change and steel grade change, are included in the model. The CastManager+IDS system is now installed in the automation system in SSAB Raahe and Outokumpu Tornio for testing purposes. The system simulates the important phenomena in continuous casting online and predicts the quality. Simulations with different cooling profiles and different amounts of impurities and gas components helped to understand the sensitivity of different steel grades with different types of defects. Using the desired cooling rates and compositions, IDS gives insight into the conditions in which the composition should be cast and handled to avoid, for example, crack formation.



**Figure 3. The CastManager+IDS package is developed for control of the continuous casting process**

The outcome of this new concept (CastManager+IDS) is that industry can now control much better than before the continuous casting process and steel quality. The models can be used online or offline to design the manufacturing concepts of new advanced steel grades and to solve their manufacturing problems, meaning a faster R&D cycle and minimization of costs.



## Industry impact

The new simulation concept has successfully been used to estimate how to increase casting efficiency.

Phenomena-based calculation has helped to understand how different elements in a composition affect slab quality.

The online concept has been used to monitor the casting process.

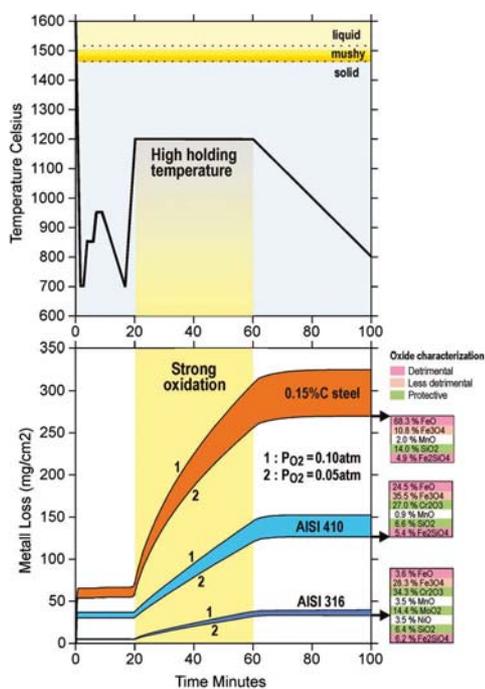
The models have been used to design secondary cooling and to define the optimal cooling pattern to avoid corner cracks.

### Avoiding metal loss at the reheating furnace by modeling

An online simulator package has also been developed for a reheating furnace. The aim is to improve the control of the states of the slabs (temperature, grain growth, dissolution of inclusions, scale formation...) when they are moving through the furnace. Another aim is to increase the hot charging ratio of the as-cast slabs in the reheating furnace and to save energy in the furnace by improved control and hot charging. The furnace model includes the heat transfer model (FurnaceManager) and the microstructure model, including the scale module (IDS). Each slab is tracked when it moves through the furnace. The heat transfer model is three-dimensional, as are the CastManager and SlabManager tools. The radiative heat transfer is a challenge in the reheating furnace, and special attention has been paid to correctly model this phenomenon, taking into account the gas radiation of the gaseous combustion products. The furnace model is validated by experimental temperature measurements in the steel plant, from the slabs moving through the furnace, and excellent agreement is obtained. SCALE is a sub-model of the IDS tool, which simulates oxide formation on the slab surface. SCALE applies a databank containing thermodynamic, diffusion, and material property data, and it has been validated with numerous measurements from the literature of oxide weight gain. The SCALE tool simulates the metal loss and the oxide weight gain on the slab surface, as a function of time, temperature, and oxygen pressure. It also gives an estimation of the fractions of different oxides formed, as well as their characterization (whether the oxide is protective or not). When used online, SCALE gets the slab temperature-time history and the oxygen pressure values from FurnaceManager, taking into account the specific conditions of each step (like changes in temperature and oxygen pressure in the reheating furnace).

The online version of the reheating furnace model, including the IDS and its scale module, will be implemented in one reheating furnace at Outokumpu Tornio steelworks. Now the offline version has been

developed for validating purposes. The scale model will be used, for instance, to find the optimal conditions (time, temperature, and oxygen pressure) to minimize scale formation and metal loss on the strand surface. As an example, Figure 4 shows how too high a holding temperature and oxygen pressure in the furnace clearly increase metal loss in a plain carbon steel (0.15%C), but not so much in stainless steels (AISI 410 and 316). The weaker oxidation in the latter steels is due to the formation of protective  $\text{Cr}_2\text{O}_3$  and  $\text{MoO}_2$  layers.



**Figure 4.** The simulated example shows how too high a holding temperature and oxygen pressure in the furnace clearly increase metal loss in a plain carbon steel (0.15%C), but not so much in stainless steels (AISI 410 and 316). The weaker oxidation in the latter steels is due to the formation of protective  $\text{Cr}_2\text{O}_3$  and  $\text{MoO}_2$  layers

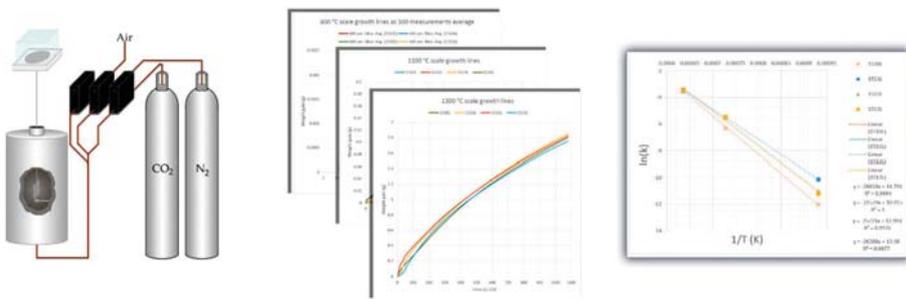
### Improving surface-quality flaws and yield at the reheating furnace by microalloying of boron and titanium

The main objective of this task was to find the effect that boron and titanium microalloying have on the scale formation of AISI 304 austenitic stainless steel in simulated walking beam furnace conditions. The industry-originated hypothesis was that boron and/or titanium microalloying

could reduce a slab's end scaling amount after reheating in a walking beam furnace. The effect of microalloying boron and molybdenum on the scaling of AISI 303 stainless steel was also investigated during the project. Clear differences were found, especially in the scale layer morphology. Activation energy results were directly applied as control parameters for furnace operation.

### Key results and impacts

Activation energy values were acquired by doing Arrhenius equation calculations based on the data acquired from thermogravimetric tests on AISI 304 stainless steel with different microalloying amounts of boron and titanium, and boron and molybdenum for AISI 303. These activation energy values were applied as control model parameters to an industrial walking beam furnace, resulting in a lower scaling amount for AISI 304 stainless steel slabs during reheating. Using steel grade and further alloy-specific operation parameters in the control of walking beam furnaces helps to reduce energy usage and scale formation. Doing experimental scale formation research helps in validating the IDS model. Reducing or targeting a specific amount of scale formation helps to reduce surface-quality flaws in subsequent processing.



**Figure 5. The process of calculating activation energy. Left: thermogravimetric measurements; center: the area normalized weight gain graphs; right: the Arrhenius plots from which activation energy can be acquired**

### Industry impact

- Advanced scale-growth models have helped in understanding how furnace conditions affect the quality of hot rolled material.
- Slab heating parameters were optimized to avoid excessive scale growth.
- Parameters for the quality prediction system were updated.

## Evaluation of different advanced (fundamental) methods to model microstructures for steels

An efficient multiscale, mesoscopic modeling approach capable of accurately predicting the formation of the solidification structure during the continuous casting (CC) process was developed. The modeling approach consists of integrating a macroscopic model (TEMPSIMU3D+IDS) with a stochastic mesoscopic solidification structure model (SolMicro). The integrated model can predict the evolution of the grain morphology and the columnar-to-equiaxed transition (CET), and is compared to experimental measurements for low-alloyed steel blooms and slabs. The validated model was then applied to determine the effects of superheat on the solidification structure of CC processed steel slabs. Future work will include additional model validation against experimental measurements, in terms of grain size and CET, for different steel alloys and for different sizes of blooms and slabs, and also the application of SolMicro with the online package CastManager.

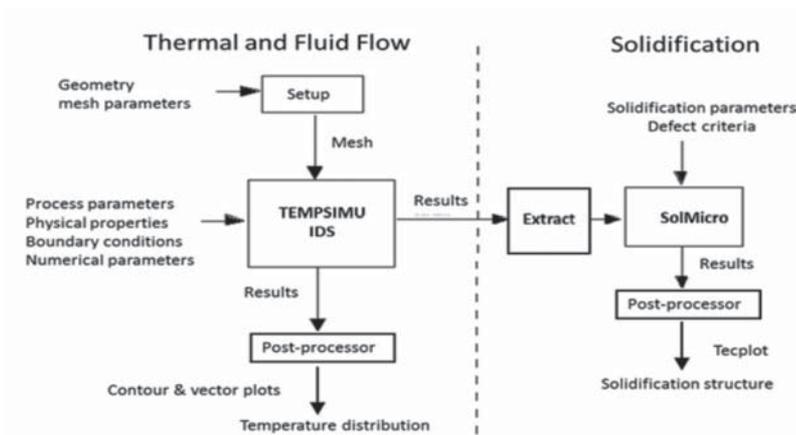


Figure 6. Coupling between TEMPSIMU3D+IDS simulation tools and the SolMicro Stochastic Solidification Structure Simulator

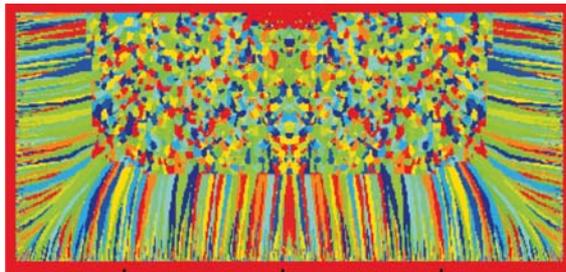


Figure 7. Model prediction for the bloom's grain morphology and CET

## Fully coupled model to simulate and optimize hot rolling and direct quenching

### FE model to simulate and optimize the Steckel hot rolling process

The knowledge and optimization of the steel strip thickness profile and contact stress distribution can be predicted accurately using the simulation FE model developed for the Steckel mill. The 3D simulation FE model enables illustration of the dynamic rolling process, considering elastic rolls and process parameters. The existing process data and models for roll wearing and thermal crowning are utilized as input data for the FE model. The simulation model is intended to control the steel strip material flow and study mechanical loadings, as well as to improve the rolling process.

#### Key results:

- The steel strip thickness profile and width spreading can be predicted considering the transfer strip thickness profile, thermal crown, and wearing of work rolls along with camber (Figure 9)
- Pressure and stress distributions on contact areas during a rolling pass (Figure 8)
- Study of transient process phenomena like strip threading and deviation from the center line
- Roll flattening and the shape of the roll gap can be predicted accurately (Figure 8)

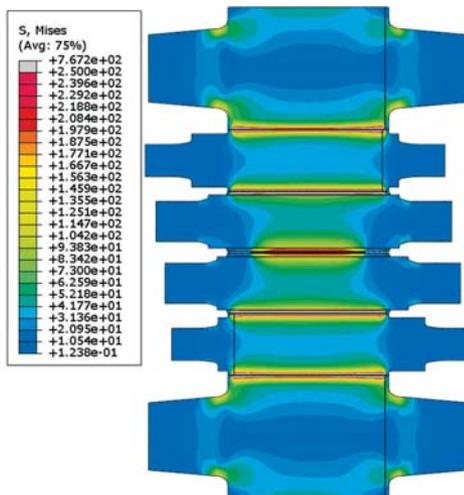


Figure 8. Cross-sectional von Mises stress

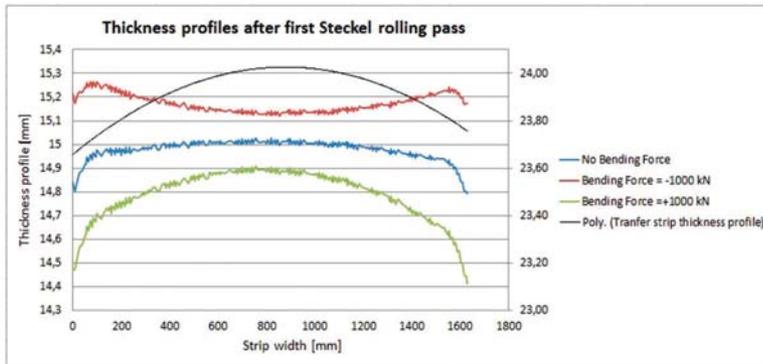


Figure 9. Strip thickness profiles after the first Steckel rolling pass



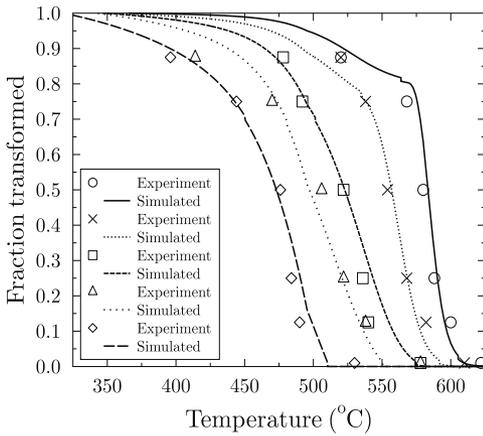
## Industry impact

- FEM simulation indicated that contact stress distribution in a roll gap does not expose it to quality defects
- By using the FEM model, local mechanical stresses in the hot rolling process could also be considered when tuning the set-up of process control

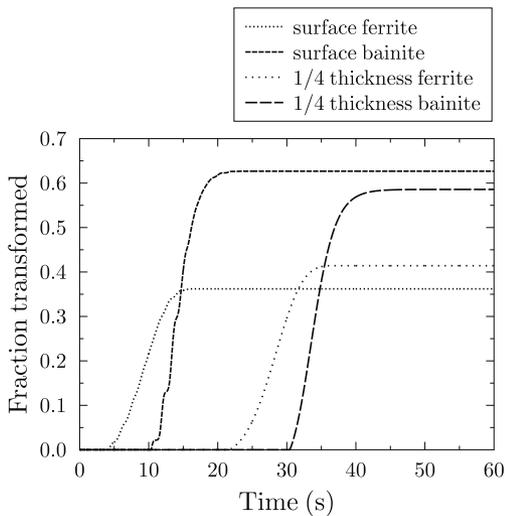
## New phase transformation model coupled to heat conduction model

Our new phase transformation model can be used to accurately describe the phase transformation onset and kinetics. The model is fitted using experimental CCT data obtained using a Gleeble physical thermo-mechanical simulator. The results obtained from the computer simulations are compared to an experimentally determined transformed microstructure. Results given by the model, fitted to commercially produced steel, are shown in Figure 10. The phase transformation simulations are coupled with finite element simulations of heat conduction and transfer, in order to simulate the phase transformations occurring on different parts of the water cooled strip/plate. An example of the simulation of phases formed at different depths during water cooling of steel is shown in Figure 11. The physical simulations of hot deformation and continuous cooling with the Gleeble thermo-mechanical simulator enable direct comparison of the experimental results against the results obtained with numerical codes. The simulations corresponding to the laboratory-scale

experiments can be used to understand microstructure evolution during plastic deformation, and its effect on the phase transformations occurring during subsequent cooling. The application possibilities of the model are described by Pohjonen et al. (2016).



**Figure 10. Fraction of austenite transformed as a function of temperature during cooling for different cooling rates; comparison of simulation versus experiment**



**Figure 11. Fraction of ferrite/bainite formed during cooling at different depths of steel strip, simulated with the coupled heat conduction/ phase transformation model**



## Industry impact

- The model helps industry to control phase transformations of ultra-high-strength-steels, leading to more uniform mechanical properties, higher quality, and lower risk of rejections.
- The model can be used in the future to predict the mechanical properties of new steel grades, and the number of expensive full-scale trials can be minimized while the speed of development is increased.

### Key results:

- The developed phase transformation model has been fitted to commercially produced steels (Figure 10)
- The phase transformation model has been coupled to the developed heat conduction simulation program (Figure 11)
- Physical deformation and cooling simulations have been applied to calibrate the phase transformation model for different hot rolling condition

### Improved calculation of residual curvature and internal stresses in roller leveling

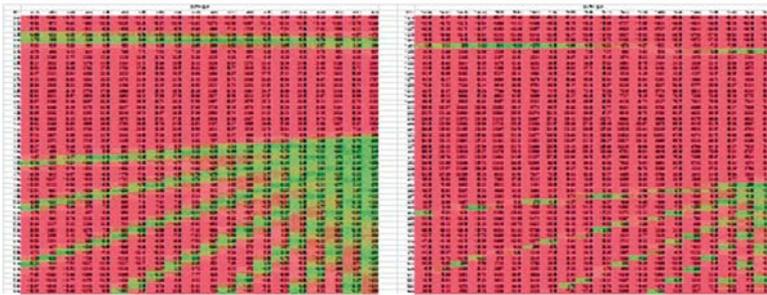
Previous calculations for roller leveling are simplified and inaccurate for predicting the residual flatness after leveling, and they do not take the incoming flatness and stresses into account. The target was to develop a tool to predict more accurately the residual flatness after leveling and the change in flatness when the machine is adjusted during leveling. The target was achieved by using a more accurate bending shape and by calculating the effect of every bend on the final leveling result.

In calculation, the strains of every bend are taken from the beam bending formula, and the residual stress, spring-back, and curvature are calculated using a FEM-like approach, with the elastic perfectly plastic material model. FEM is used only where the tightest bend occurs, to reduce the computing time. The calculation and user interface for the tool are made using an Excel spreadsheet for ease of sharing and usage of results and impacts.

The tool is able to predict the real-life observed non-linear behavior of residual curvature when the gaps in the roller leveling machine are adjusted. More accurate prediction of the outcome and behavior of the roller levelling process translates into cost and time savings, as less time is needed to find the values to produce sheets with good flatness. In addition, less material is scrapped, as the optimal process parameters are found faster. The roller leveling process is one of the last processes in

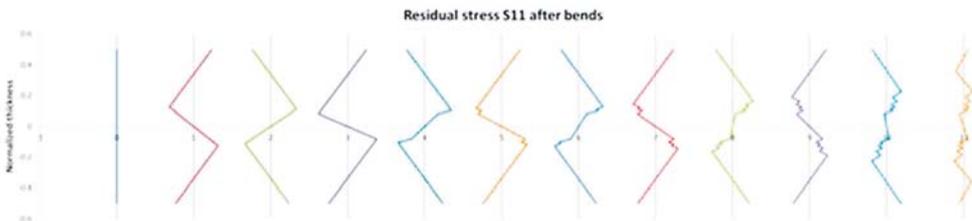
the steel factory, so in the long run this also creates the potential for more sustainable production, as fewer raw materials are needed in the first place to produce the desired amount of excellent end-product.

The tool can also provide a leveling map for any metallic material in roller leveling, where the optimal leveling values are expressed as green areas. One interesting finding from the use of this tool is that, if entry and exit gap values are expressed as plastification ratios, the optimal gap values form similarly shaped maps for different materials (Figure 12).



**Figure 12. Leveling maps for two 5mm-thick strips. Left: 400 MPa; right: 1600 MPa**

Another application of the tool is to study what kinds of residual stresses occur in the material during and after leveling. For that purpose, the tool produces a residual stress map, from which the residual stresses after every bend can be observed (Figure 13). It is also possible to input your own initial stress distribution and to see how the stresses are broken down during leveling.



**Figure 13. Longitudinal residual stresses over thickness after each bend**

For now, the tool is for offline use, but the calculation behind the tool can be applied to online use if suitable input values are available from the process control system.

Tool development was started in a Master's thesis work at SSAB, and continued at the University of Oulu in DIMECC SIMP program's Showcase 2.2. The tool would not have been possible without many leveling tests conducted at SSAB cut-to-length lines during and after the thesis work. The tool brought major improvements in understanding the non-linear behavior of longitudinal flatness observed in real-life levelling situations. The tool also provides more accurate initial setup values for new materials in leveling. The next step in development is to expand the scope of the tool to a 3D space, to tackle three-dimensional flatness defects.



### Industry impact

- More accurate modeling of residual stresses is strongly needed as there is no online measurement technique available, and the flatness measurement does not say enough about the actual flatness of the sheets.
- More precise estimation of optimal leveling parameters will help steel processing and will help the steel manufacturer to minimize rejected material and improve the quality of the sold steel.

### Improving flatness and mechanical properties at the temper mill by modeling processing

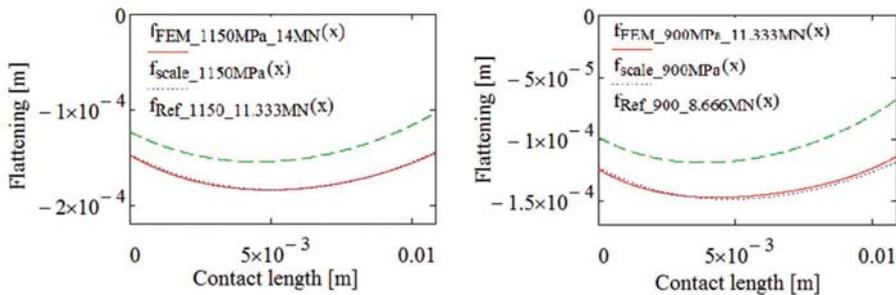
**Main targets** The original aim of this task was to develop an online fundamental temper mill process model to reveal stress and strain distributions during the process, together with an exploration of strip initial conditions and process parameters for material behavior, flatness defects, and residual stresses. Preliminary 2D and 3D finite element (FE) models of the 4-high temper rolling process were developed in the thesis "Finite element analysis of skin-pass rolling process" in 2014, and carried out as part of the DIMECC SIMP program. The model improvement was concentrated only on analytical models based on the 2D FE model of temper rolling.

**Key results and impacts** To develop a fundamental temper rolling process model, an FE model was required to describe the phenomena of elastic-plastic material flow, various friction conditions, roll deformation, initial strip conditions, roll camber, strip thickness profile, and so on. Although the FE model is able to consider a large amount of variables and parameters, it is not suitable for online use due to relatively slow calculation. Therefore, the FE model

is used to depict the process accurately and, on that basis, an analytical model is generated. Analytical online models can be integrated into the process. An analytical model without iteration loops enables very fast process control, as well as efficient and smooth rolling operation.

A new method predicting work roll flattening has been developed. The current trend in temper rolling is to make a small reduction to the steel strip in order to achieve higher strength with good formability and toughness. In addition, ultra-high-strength (UHS) steels can be cold rolled twice with very small reductions. This causes problems in setup values for cold rolling. Rolling models developed for lower-strength steels usually overestimate roll flattening in the case of small reductions. The developed model is based on 2D finite element analysis of fully elastic work and backup rolls, together with an elastic-perfectly plastic steel strip. Various FE analyses were made to understand the behavior of the contact between the work roll and strip. Variables used in the analyses were: rolling force, roll radius, and yield strength of the strip. Temper rolling mills are generally 4-high mills, so backup rolls were taken into account. The presence of the backup roll is essential to get reliable results for the phenomena in the roll bite for the 4-high temper rolling mill.

The analytical work roll flattening tool enables definition of work roll flattening and the contact length between the steel strip and work roll when the roll radius is between 200–300 mm and the yield strength of the strip is 350–1150 MPa. In addition, the FE model makes it possible to observe the plastic flow of the material in the roll bite and the formation of a residual stress state. Tentative verifications of the analytical model have been completed in collaboration with SSAB Europe. The results of work roll flattening of the scaled function (analytical tool) compared to FE results for a roll radius of 200 mm are depicted in Figure 14.



**Figure 14. Fourth-degree reference curve of FE result and scaled analytical function ( $Re=1150$  MPa,  $R=200$  mm,  $F_{Rolling}=14$  [MN/m] and  $Re=900$  MPa,  $R=200$  mm,  $F_{Rolling}=11.333$  [MN/m])**

Summary and further development Work roll flattening and contact length can now be predicted with a fast analytical model for two SSAB Europe temper rolling mills at Raahe and Hämeenlinna. The first comparison results between the developed model and the experimental results responded almost perfectly. More FE analyses are required in order to construct an even more accurate model and reduce assumptions. The analytical model needs to be verified closely by experimental tests to get it to run online.



## Industry impact

The temper mill is an essential part of the production chain for ultra-high-strength steels. The model describing the actual contact between steel sheets and work rolls will help industry to understand better how the machines should adjust for each steel grade and dimensional range in order to get the best possible combination of flatness and mechanical properties. The online model is crucial.

### Online prediction model of product properties, rejection risk, and delivery accuracy

The sub-project consists of several research projects that delivered models and tools for product property prediction and better process control. Models that have been implemented in the Quality Monitoring Tool, have been reported in the next chapter.

### Improving the dimensional accuracy of steel plate

The purpose of this study was to improve the dimensional accuracy of steel plate by updating the selection of combination parameters for slab design using statistical models. The aim of the combination is to ensure that there is enough material available to produce the ordered product with the desired dimensions. The successful combination process reduces material loss, energy consumption, and emissions, which in turn improves the cost-effectiveness of the steel mill.

The starting point for this research was that the combination was done currently based only on the thickness of the steel plate, which increases the risk of rejection and the amount of waste. The generalized boosted regression model (GBM) and the generalized additive model (GAM) were used to predict the dimensional properties of the combination parameters with process factors. The mean of each parameter was modeled with GBM and deviation with GAM. Modeling results helped to

discover the most important features with a strong influence on combination parameters. Furthermore, we found critical areas where the mean or the deviation of these parameters varies a lot. The modeling results significantly increased our knowledge of the combination process, and suggested that thickness alone does not always guarantee the desired dimensions for the steel plate.

During the research, it was found that in real-life applications, there are conditions that restrict the implementation of models in production. In this case, it was the guidance system in use at the steel mill. For real-life application, the modeling results were used to determine new combination parameter classes containing a larger number of process factors, instead of only one. The classification rules were updated based on the results from the GBM and GAM models. New combination parameter values were determined for each new class, and the results were compared to the thickness based classes currently in use at the production line. The comparison between the original classes and the suggested classes showed that, for a large number of products, the current combination variables possess a high risk of rejection caused by insufficient amounts of material. Similarly, there are products that are currently designed with unnecessarily large values, leading to an unnecessarily large amount of waste.

### Industry impact

The updated combination parameters have been introduced in everyday production, giving a competitive edge to hot rolled plate production. The number of plate ends that are too long has now been minimized, as has the risk of rejection due to insufficient material prior to hot rolling.

### Steel plate shape analysis

In the steel plate production process, it is important to minimize the waste piece produced when cutting a mother steel plate to the size ordered by a customer. The uneven shapes at the plate end sides and lateral sides cause yield loss, amounting to about 5% to 6% of the total tonnage of slab used. To minimize this loss, the shape of the rolled mother plates needs to be optimized. The aim is to produce plates with concave side edges, because wastage from concave side edges is smaller than from convex.

Our study is made for SSAB Europe, Raahe plate mill, Finland, where monitoring of the plate shape is currently done visually at the cooling banks. The measurements were made using a thickness measurement system from IMS Systems Inc. The data were collected from 399 plates, and therefore from 798 sides. It was noted that there are three

types of shapes of side edges: concave, convex, and other. We used classification and linear regression methods to define the direction and the amount of curvature of the side edges. This sub-project was divided into two parts: (1) classifying instances into two classes: a side is either a curve (convex or concave) or other, and (2) using data from convex and concave sides, train a regression model using an estimation of the amount and direction of curvature as a response. The research showed that the side edges can be classified as curved or not with 95% accuracy. A linear regression model was trained, using the same feature set, to estimate the direction and amount of curvature of the plate's side. The model worked very accurately. Using the developed methods, steel plates can be analyzed at a glance, and the methods also enable long-term statistical monitoring. Based on these statistics, it is possible to define new parameter values for the rolling process, to minimize the number of convex plates and to minimize cutting wastage.

## Industry impact

The calculation model created here is shown to be an effective tool for minimizing the material yield losses in hot rolled plate production. A new plate shape measurement unit is needed before the full potential can be realized.

## DQ process optimization

The tempering process of a steel plate improves the mechanical properties of the product. Well-selected time and temperature ensure that both strength and toughness properties hit the target. As many production variables have the opposite effect on these properties, the optimal selection should be found to achieve a balance. In this research, we have developed a tool that utilizes statistical quality prediction models for tempering time optimization.

Both mechanical properties and their variances were modeled with the generalized boosted regression model (GBM) and the generalized additive model (GAM) accordingly, and the predicted values were used in rejection probability calculation. In the proposed tool, optimization was based on a simple equation that found the recommended value for tempering time. Because the actual costs for different selections were not available, we studied the rejection surfaces that were built using multi-objective optimization methods. This way, the user can consider several possibilities for tempering parameters with equal quality rejection risk, and find the optimal solution for the current process state. The statistical modeling of the rejection risks enables intelligent production design and the optimization of the tempering process. With the tool, it is possible to

check how the rejection risk changes if more cost-effective tempering parameters are tried, instead of the current ones. As a result, there are potential savings in both rejection costs and production costs.

## Industry impact

The models created here will help industry to get higher yield and more uniform mechanical properties in tempered steel plates. This kind of steering method still needs to be implemented for all tempered steel grades.

### The effect of casting parameters on the as-cast structure and mechanical properties of the ultra-high-strength steel wear plate

The main aim of this work was to establish connections between the as-cast structure, segregation patterns, secondary cooling parameters, and the microstructure and mechanical properties of hot rolled wear plate. Improving the homogeneity of steel enhances usability and reduces the risks of internal rejection and complaints. In addition, information on effects of casting parameters on mechanical properties can be used to improve the performance of online casting applications. The key results of this project are given as follows:

- High superheat decreased the homogeneity of the steel, causing positive segregation at the CET and center line and negative segregation next to those lines.
- The composition differences due to segregation were the main factor in the variations in mechanical properties.
- The level of secondary cooling had a major effect on the as-cast structure, but there was no visible effect on the hardness values.

### Statistical mechanical property models with integrated metallurgical theory

The estimation of a non-linear regression model that fully integrates with metallurgical theory is statistically very challenging. Estimation of such models, containing hundreds of non-linear parameters, cannot be solved using any available optimization techniques. An adequate computational solution to solve the problem does not currently exist. The aim of the research was to develop mechanical property prediction models that fully integrate with metallurgical theory. When the underlying metallurgy is precisely described in the model, such models are expected to have superior predictive performance.

The research on non-linear regression models that fully integrate with metallurgical theory has produced new understanding on how to describe complex metallurgical phenomena as a set of metallurgical terms and estimable parameters. The result of the research and technology evaluation of optimization algorithms suitable for solving non-linear metallurgical models is an idea/prototype for a stage-wise optimization algorithm capable of solving the metallurgical parameters in the non-linear models. These results have improved the accuracy with which steel product metallurgical properties can be predicted based on alloy composition and thermomechanical treatments.

## Online quality monitoring system for hot rolling

### SIMP Quality Monitoring Tool (QMT)

This sub-project had two main goals: firstly, to develop an online tool for quality monitoring based on predictive models in a real industrial setting; and secondly, to test the Wedge tool by Savcor in different steel processes.

The quality monitoring tool is a framework for analyzing process quality status. Process measurement data can be read from various data sources, and calculation models turn raw data into quality information. Models can be implemented in R or as rules. R is a free, open-source language for statistical computing. Rules are handled with the C++ Mathematical Expression Toolkit Library (ExprTk), mathematical expression parsing, and evaluation engine. Some special models have been implemented in Python and C++. Process layout can be configured to QMT, and calculation models are set for defined process phases.

QMT has a web-based user interface that presents an overview of process quality as a starting point. The quality overview shows, using colors, the quality status for different process phases. Red indicates process defects or malfunctions, yellow indicates a warning of a process failure or deviation, and green indicates a normal operation state. White indicates that quality information could not be calculated, for example due to missing inputs. Process deviation from a normal state is easy to detect, and the user interface enables navigation to the process phase where a defect or deviation occurred. The quality overview hides mathematical models and numerous process variables from which quality information is composed. QMT also provides the possibility to view raw data and filter data. QMT has the possibility to show specific views for different user groups. System administrators can add new models to QMT and rule models can be created and updated directly from the user interface.

The quality monitoring tool is applied for hot strip rolling. The tool runs at SSAB Raahe and Outokumpu Tornio plants and is connected to

online databases. Different kinds of calculation models can be executed, and the tool can also be applied to other application areas. During the project, QMT was piloted with the following models:

- Roughness model and roughness model for ferritic strips in Outokumpu plant
- Stripe model (developed by Indalco) in Outokumpu plant
- Hardness model in Outokumpu plant
- Simple one variable models: rule-based, filtered derivative algorithm and SPC adopted model in SSAB and Outokumpu plant
- Absolute profile, profile deviation, and negative profile models in SSAB plant
- Chebyshev polynomials for transversal profile in SSAB plant
- Hold code model in SSAB plant

## Industry impact

The need for an online quality monitoring tool is essential. The tool created in DIMECC SIMP program is a first step in this area, but further development work is needed prior to actual online usage. If the tool is actually used as quality-gate system, it will help to minimize rejections and extra work tied to possible quality defects.

## Predictive models

### Profile models in QMT

The steel strip profile is a quality property for which product development and the customer set the target. This information is also essential for the following process steps; in particular, a negative profile can be very harmful to cold rolling. With prediction models, it is possible to design products that are more likely to fulfil the requirements, as well as to find root causes for failures. In our QMT, the user can select between the profile and the deviation from target profile models, depending on need.

For quality monitoring purposes, the profile of a steel strip, as well as the deviation from the target profile, was modeled in three process steps at SSAB, Raahé: after furnace, after roughing mill, and after finishing mill. The accuracy of profile modeling improves at the end of the process, but with these models, it is possible to give an early warning based on the preceding process steps. The model provides the user with better insight into the effect of process parameters, and it can also be used to test the user's prior assumptions or understanding of the process. For online use, only the design parameters were included in the models. The

output of the models, as well as the visual presentation of the results, was selected together with the end-users to ensure the effective output of the information.

### Temperature models in QMT

An accurate steel strip temperature is essential information for a rolling process. Predicted information is used to determine process settings, and the causes of deviation from the target are also important for process improvement and quality variability reduction. The temperature of the steel strips was modeled after the roughing mill at SSAB, Raabe. Different models were needed for oscillated and hot slabs, and the location of the transfer bar was also modeled individually (head, body, and tail). The root causes of deviation from the target temperature were sought visually using different tools. For example, the location of the slab in the furnace seemed to be critical for thicker and heavier slabs.

### Roughness models in QMT

One type of surface roughness in a stainless steel strip can be detected only after the strip has been polished. Before the finishing process, these products have to be shipped to another plant in a different country, after manufacturing. It would save time and effort if the risk of roughness was predicted and the user was able to reallocate the high risk coils for other end-users with lower surface quality requirements. It is equally important to detect the process settings that increase the risk and to re-adjust the process if systematic quality failures occur.

The roughness of the steel strip was measured visually on a scale from 0 to 9. Products with a roughness of 4 or higher were considered to be defective. The classification models for roughness worked better, but the models for the severity of roughness did not perform well. The quality was modeled at Outokumpu, Tornio for the whole production, but the research showed that ferritic products need an individual model, because the metallurgy behind the product differs significantly from that of austenitic products. Only the hot rolling parameters were used in modeling.

During the project, the center-line surface roughness after the RAP line was measured using a device developed by Focalspec. In this task, the goal was to find the most important production parameters that affect center-line roughness, and how strong the impact of the RAP line parameters is on the quality property. In addition, the usefulness of different roughness measurements was considered. The descriptive statistics, the association location, and simple predictive modeling were performed for the small data set.

## Industry impact

- An online framework for overall quality monitoring of the hot rolling process was implemented.
- Potential models for quality prediction were developed and connected to online process data.
- Modeling revealed many key variables to follow by methods of quality control.

### Savcor Wedge testing

In Savcor Wedge testing, a data retrieval infrastructure was designed that can handle thousands of process measurements at 10-millisecond time intervals. The infrastructure enables management of large data sets in a reliable manner. Wedge can also combine event and time-based data with the developed analysis method. This is needed to find the root causes of process delays, which is modeled for the hot rolling and casting machine. Wedge has been tested with good results in the SSAB hot rolling area and the Outokumpu smelting and casting areas.



## Industry impact

“The amount of data collected in the hot strip rolling process is huge, and the powerful use of all that data is a key for fast and precise decision-making. Wedge is definitely helping us by decreasing the time spent on data mining and finding a root cause.”

*Ari Pikkuaho, Process development engineer, SSAB Europe*

### Novel measurement systems

Several novel measurements have been tested and developed for slabs, plates, and strips for online quality monitoring purposes.



## Industry impact

“The new measurement not only improves engineer-level evaluation of the process, but it can be utilized as an online information system for operators, or even for automation-level process control. Machine vision is a cost-efficient technique to create accurate dimensional measurements for a difficult environment.”

*Olli Haapala, R&D engineer, Outokumpu Oy*

### **The lengthwise curvature measurement of a steel plate**

The lengthwise curvature of a steel plate is commonly specified by customers, while it has no standardized online measurement method. A laser distance sensor below a roller conveyor was used to measure the magnitude and direction of the lengthwise curvature of moving plates at SSAB steel mill. Curvatures of 10 mm and 3 mm thick steel plates with corrected curvatures were measured and compared with manual reference measurements. The laser distance sensor was able to measure lengthwise curvature and its direction in the 10 mm thick plates with good accuracy.

### **Video-based position measurement of a moving strip**

In a multi-stand hot rolling mill, crosswise position tracking is crucial for the rolling process. An offline machine vision application was developed for existing surveillance video cameras at Outokumpu's hot rolling mill in Tornio, in order to measure the position of a moving strip. Surveillance cameras at the site were able to track the position of the strips with 1–3 mm accuracy. Camera-based position data was in good agreement with the current mechanical force difference data of the corresponding tandem mill rolls.

### **Data-driven models in stress and condition monitoring**

Cumulative mechanical stress inflicted on a steel leveler at the SSAB steel mill was studied by the identification of correlations between steel strip properties and vibration features. Linear regression modeling proved to be a suitable approach to the estimation of relative magnitude of cumulative stress. The model predictions could be used to support maintenance planning. Condition monitoring of a slowly rotating machine was studied in laboratory tests, in cooperation with RWTH Aachen. Real order derivatives, enveloping, and cyclostationarity were applied in fault detection. According to the study, the methods have proven to be applicable in this field.

### **Online roughness measurement**

An online roughness measurement system was tested on the RAP line at the Outokumpu Stainless Tornio site. One target was to find the applicability of the novel measurement technique in continuous high-speed processing of stainless steel. Another target was to get a big data set to create a predictive model for strip roughness. For hot rolled strips, the measuring instrument gave correct roughness values and generally the system worked reliably. Thus, the data was applicable for modeling hot strip roughness. Changes in the processing parameters on the RAP line, such as in process speed in pickling, were clearly seen in roughness values.

## Vision systems for slab dimension measurements

Accurate dimension measurement is essential for effective production planning at the SSAB Europe Raahe works. The yield of steel production is better, and the work of production planners is easier, if the accurate length of the mother slabs is known before cutting them into daughter slabs. Identification of slabs is also essential. In this task, the verification of the usability of the camera in length measurement of the slab, and automatic recognition of slab identification numbers are done. According to the tests, the measurement error compared to the result of a measuring wheel was mainly between  $-0.3\%$  and  $+0.3\%$  and the method has potential. The results of automatic slab identification showed that identification of clear numbers was good, but unsharp pictures complicated identification.

### Industry impact

- Piloting of position measurement led to an industrial investment that will significantly stabilize the critical hot rolling process.
- Information on piloted measurement was used as accurate input into quality prediction models.
- The predictive calculation will help industry to improve maintenance actions and focus them in the most urgent areas. Further research is needed, however, before such a model can be implemented in everyday production.

## Next steps in developing advanced quality monitoring methods for steel production

Important collaboration between SSAB and Outokumpu and academia will be continued by initiating new R&D programs at national and European level. The developed quality monitoring tools that are now online and connected to processes will be introduced into full operational usage. With the aid of an open framework, new features and models will be implemented in the quality monitoring system, from casting to hot rolling.

### Future actions:

- The latest features of CastManager will be verified in production.
- Scale growth in the walking beam furnace will be studied in more detail with the aid of the IDS module.
- The FEM modeling approach will be used to tune up the whole hot rolling process.
- New prediction models and features will be implemented in the quality monitoring tool.

- New controls will be developed based on camera vision systems.
- The models and tools will be developed to be easy enough to use in everyday production, in process monitoring and control.
- Several independent tools will be combined and made to interact with each other, in order to get even smarter systems. The optimization should not focus on every process step, but the whole chain should be taken into account.
- An even more detailed level of process monitoring and models will be implemented.
- Models will be used to predict possible problems instead of to react to them.

Finnish companies and their suppliers will definitely benefit from using digitalization, modeling, and predictive tools, which all increase productivity and give a competitive edge. Advantages are undeniable for large companies, SMEs, academia, and finally for the whole Finnish national economy. The research done in the DIMECC SIMP program helps society only to catch up on the edge competitors have in certain areas, but in other fields we have been forerunners, breaking new ground.

We have a long tradition combining the needs of industry with academic research. This cooperation benefits both parties, and such symbiosis can be a seed for common success. The critical mass of researchers can grow big enough to create new ideas and to have enough resources for long-lasting tasks. The parties do not compete against each other, but their know-how supplements the others. It is admirable that we can still form such clusters without internal competition. This model of operation should be maintained in all economic situations. A good example is the Quality Monitoring Tool, which brought together major companies SSAB and Outokumpu, the University of Oulu, and VTT to build a totally new kind of combination of deep mathematical modeling, physical phenomena, and user interface.

During the DIMECC SIMP program, lots of models and tools have been created to help industry to increase productivity and to provide a competitive edge. The path is clear: digitalization continues, but meanwhile we also have to take care of basic research. Only when you can fluently handle physical phenomena can you try to control the complexity of, for example, steelmaking processes. However, you do not have to take care of everything by yourself: build a winning team with several competencies and share the knowledge! There are plenty of research subjects still to cover. Some subjects not finished during the DIMECC SIMP program will continue in companies' own work, but others and new ones require close cooperation between industry and academic society also in the future.

It was a pleasure and privilege to have a chance to be a member of this kind of research activity. Thank you all for your effort.



## Industry impact

“One of the most important things during SIMP was the active transfer of knowledge. The academic results benefit industry and the boundary conditions of the industrial environment help academic researchers to focus on the right subjects.”

*Jarmo Lilja, Process development manager, SSAB Europe*

## Further information

### KEY PUBLICATIONS:

Krajewski P., Krobath R., Bernhard C., Miettinen J., Louhenkilpi S., Ilie S. & Schaden T. 2015. A novel approach for the simulation of surface crack formation in continuous casting, Berg- und hüttenmännische Monatshefte, 160 (2015) 109–116.

Louhenkilpi S., Laine J., Miettinen J. & Vesanen R. 2013. New Continuous Casting and Slab Tracking Simulators for Steel Industry', Materials Science Forum Vol. 762 (2013).

Hietanen, P., Louhenkilpi, S. & Shan Y. 2016. Investigation of Solidification, Heat Transfer and Fluid Flow in Continuous Casting of Steel Using an Advanced Modeling Approach, Steel research int. 87 (2016).

Laukka, A., Heikkinen, E-P., Puukko, E. & Fabritius, T., 2017. The effect of boron and titanium microalloying on the scale formation of AISI 304 austenitic stainless steel in simulated walking beam furnace conditions. Steel Research International 88. Pre-published, DOI 10.1002/srin.201600365.

Nastac, L., Kärkkäinen, M., Hietanen, P. & Louhenkilpi S. 2016. Multiscale Modelling of the Solidification Structure Evaluation of Continuously Cast Steel Bloom and Slabs, TMS 2016 Annual Meeting & Exhibition.

Pohjonen, A., Kaijalainen, A., Somani, M. & Larkiola, J., 2017. Analysis of Bainite onset During Cooling Following Prior Deformation at Different Temperatures, Computer Methods in Materials Science, Vol. 17, No 1. pp. 30–35, ISSN 1641-8581.

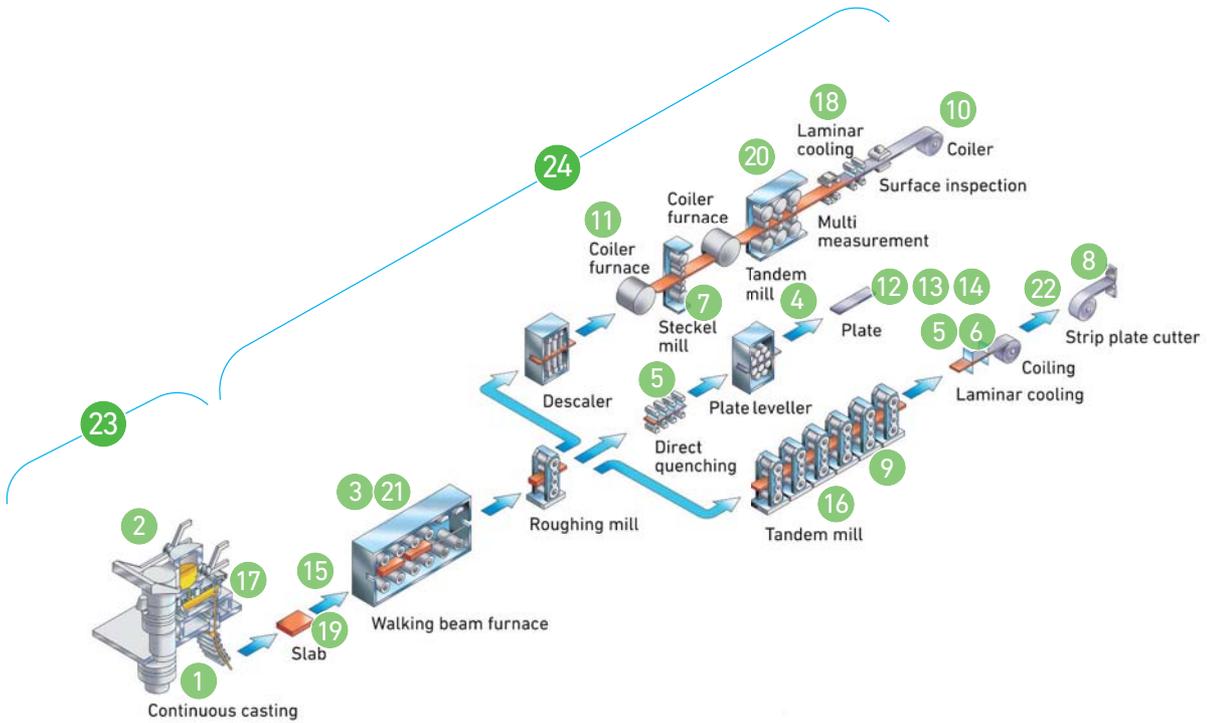
Pohjonen, A., Kyllönen, V. & Paananen, J., 2016a. Analytical Approximations and Simulation Tools for Water Cooling of Hot Rolled Steel Strip, 9<sup>th</sup> EURO-SIM Congress on Modelling and Simulation, pp. 731–736, DOI 10.1109/EUROSIM.2016.42.

Ilmola, J., Pohjonen, A., Larkiola, J. & Nylander, J., 2016. A New Method Predicting Contact Length and Flattening In Temper Rolling. Key Engineering Materials, Vol 716, pp. 605–613.

P. Siirtola, S. Tamminen, E. Ferreira, H. Tiensuu, E. Prokkola & J. Röning, 2016. Automatic Recognition of Steel Plate Side Edge Shape Using Classification and Regression Models, EUROSIM, 2016.

S. Tamminen, E. Ferreira, H. Tiensuu, H. Helaakoski, V. Kyllönen, J. Jokisaari, E. Puukko, J. Röning, "An Online Quality Monitoring Tool for Information Acquisition and Sharing in Manufacturing: Requirements and Solutions for the Steel Industry", Submitted 2017.

Nikula, R.-P., Karioja, K., The effect of steel leveler parameters on vibration features, Proceedings of the 9<sup>th</sup> EUROSIM Congress on Modelling and Simulation, IEEE Conference Proceedings, (2016) 392–397.

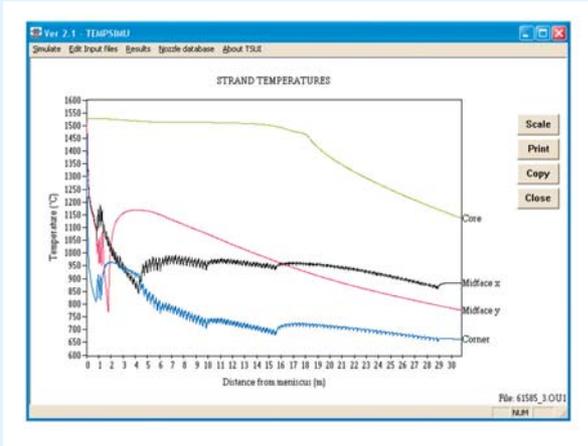


**Figure 15. The numbered bullets in the process scheme represent the tools developed in Showcase 2.2. The tools are described in the following pages**

1

TEMPSIMU – STEADY STATE PROCESS MODEL FOR CONTINUOUS CASTING OF STEEL

SHOWCASE 2.2



Description of the tool

Computational models have greatly helped to solve practical problems in industrial casters and to improve process practices and control. PROBLEM: Commercial tools are normally black box tools, and it is very difficult to know their details. Industry needs more in-house, open tools, which are easy to use and can be modified according to the specific needs of steel plants. In SIMP, online and offline tools have been developed for continuous casting, in order to meet the increasing requirements. The TEMPSIMU3D

tool is an offline simulation tool for continuous casting. Benefits: Industry is more capable of developing new advanced steel grades and solving their production problems. A faster R&D cycle and minimization of costs are also important benefits.

Application

Tempsimu calculates strand temperatures and shell thickness profiles. The new option is the stress module. Steel material data, including creep, elastic module, and thermal expansion data, is calculated using the IDS tool. Tempsimu is used during SIMP, especially in designing secondary cooling and calculating pool length. The model is validated using industrial measurements. Tempsimu is now in use in many steel plants.

Technologies

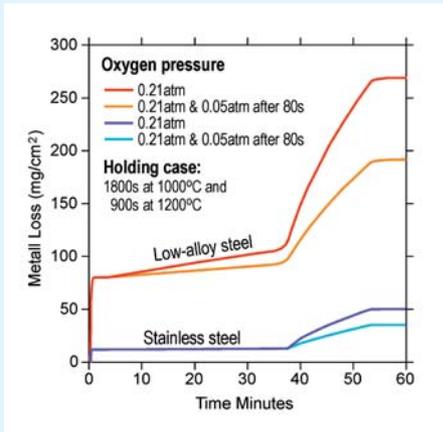
Tempsimu is in-house software for Windows PC, coded using the Visual Studio system. Partial differential equations are solved using the finite difference algorithm.

**Participants** Aalto University, Casim Consulting Oy, SSAB Europe Oy, Raahe, Outokumpu Stainless Oy, Tornio. Contact: Seppo Louhenkilpi, Aalto University (seppo.louhenkilpi@aalto.fi)



# 3 SCALE – TOOL FOR MODELING SCALE FORMATION IN DIFFERENT STEELS FROM CONTINUOUS CASTING TO HOT ROLLING

SHOWCASE 2.2



### Description of the tool

SCALE is a sub-model of IDS (another tool in SIMP) that simulates oxide formation on the steel strand surface. The tool output helps to find optimal process conditions (time, temperature, and oxygen pressure) to minimize scale formation and metal loss on the strand surface. This is a benefit in cost, quality, and sustainability.

### Application

SCALE can be used as a separate researcher’s tool or as a sub-model of the online continuous casting simulator, CastManager (another tool in SIMP). In the latter case, the simulation can be extended from the

start of continuous casting to the end of the possible reheating or rolling processes. Offline SCALE has been validated with numerous measurements in the literature of oxide weight gain, and online SCALE will be validated by the scaling intensity observed on the cast strand surfaces.

### Technologies

SCALE is programmed with VisualBasic, and it applies thermodynamic and kinetic theories coupled with empirical equations, based on its own optimizations.

### Scope of application

The online version of SCALE, running as a sub-model of CastManager (another tool in SIMP), will be implemented in the SSAB Raabe and Outokumpu Tornio steelworks.

**Contact persons  
– Inventors**

Jyrki Miettinen, Seppo Louhenkilpi, Aalto University  
Jukka Laine, Casim Consulting Oy

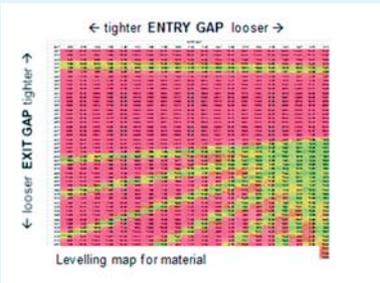
**Additional Information/  
Publications**

J. Miettinen: “A semi-empirical model for the estimation of oxide scale formation of steels in a furnace”, Aalto University, Espoo, 2015, 18 pp.  
J. Miettinen: “Simulation of oxide scale formation by the IDS model, Casim Consulting Oy, Espoo, 2015, 4 pp.

4

TOOL FOR PREDICTING RESIDUAL CURVATURE AND INTERNAL STRESSES IN ROLLER LEVELLING

SHOWCASE 2.2



Description of the tool

This tool was developed to predict the outcome and behavior of the roller leveling process more accurately than previous tools/calculations. More accurate prediction of initial process setup values translates into cost and time savings, as less time is needed to find the values to produce sheets with good flatness. In addition, less material is scrapped as the optimal process parameters are found faster. The roller leveling process is one of the last processes in the steel factory, so in the long run, this also creates the potential for more

sustainable production, as fewer raw materials are needed in the first place to produce the desired amount of excellent end-product.

Application

The tool is able to predict the non-linear behavior of the residual curvature when the gaps in the roller leveling machine are adjusted, and it can provide a leveling map for any metallic material in roller leveling. For now, the tool is in offline use, but the calculation behind the tool can be applied to online use if suitable input values are available from the process control system.

Technologies

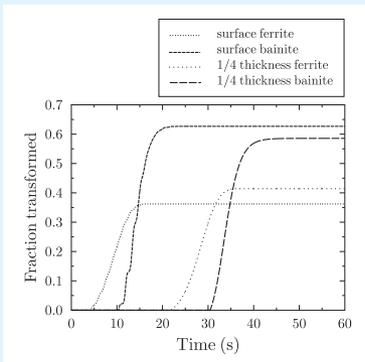
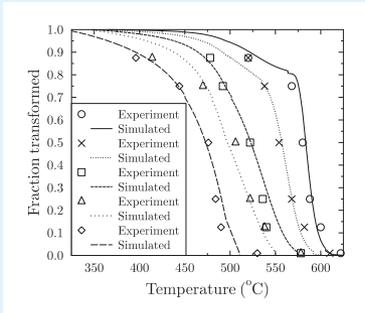
The improved calculation is based on a more accurate bending shape of the strip/sheet. The bending shape is estimated using basic beam bending formulas in every bend of the roller leveler. Material behavior is assumed to be *elastic perfectly plastic*. For ease of sharing and usage, the tool is coded in an Excel spreadsheet.

Scope of application

The tool and calculation can be implemented in every roller leveling process with parameter changes. With some tweaking, it can also be used in processes where solid material is flowing and experiencing plastic bending at the same time.

**Contact persons – Inventors** Contact person(s): Olli Leinonen, Jari Larkiola  
**Participants** University of Oulu, SSAB Europe Oy

SHOWCASE 2.2



Description of the tool

A new phase transformation computer model, which is coupled with our finite element heat conduction/transfer simulation program, has been developed. In spite of the funding cut-off, which significantly shortened the available development time, we were able to develop an accurate phase transformation simulation code, which has been accurately fitted to different commercially produced steels that have been thermomechanically treated in a laboratory setting corresponding to different rolling conditions. The model has been able to capture the effect of deformation on the kinetics, as well as on the onset of the transformation (Pohjonen et al. 2016 a, b; Pohjonen et al. 2017 a, b). The model can calculate the phases formed (see figure), as well as the hardness of the final product after cooling, along any user-defined cooling path. Since the model includes heat conduction and transfer, it can be used to calculate the phases formed at different depths of the cooled steel strip/plate (see figure).

Application

The tool is intended to be used in computer simulations of phase transformations occurring during water cooling of a hot rolled steel strip (see Pohjonen 2016b). The tool has been calibrated for different commercial steels using laboratory data from physical thermomechanical experiments.

Technologies

The Fortran programming language and MATLAB were used to develop the model and the optimization, respectively.

**Contact person** Aarne Pohjonen, University of Oulu

**Participants** University of Oulu, SSAB

**Additional Information/Publications**

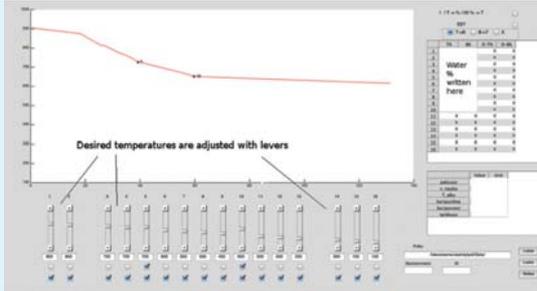
Pohjonen, A., Kaijalainen, A., Somani, M. & Larkiola, J., 2017a. Analysis of Bainite onset During Cooling Following Prior Deformation at Different Temperatures, *Computer Methods in Materials Science*, Vol. 17, No 1. pp. 30-35, ISSN 1641–8581.

Pohjonen, A. et al., 2017b draft manuscript.

Pohjonen, A., Somani, M., Pyykkönen, J., Paananen, J. & Porter, D. 2016a. The Onset of the Austenite to Bainite Phase Transformation for Different Cooling Paths and Steel Compositions. *Key Engineering Materials*. Vol. 716, pp. 368–375, ISSN 1662–9809.

Pohjonen, A., Kyllönen, V. & Paananen, J., 2016b. Analytical Approximations and Simulation Tools for Water Cooling of Hot Rolled Steel Strip, 9<sup>th</sup> EUROSIM Congress on Modelling and Simulation, pp. 731–736, DOI 10.1109/EUROSIM.2016.42.

## SHOWCASE 2.2



## Description of the tool

We have constructed a simplified model to estimate the required water usage to cool a steel strip/plate to a desired temperature along the cooling line. This work was part of a Bachelor's thesis (Paananen 2015). A detailed model that can calculate the temperature distribution in the thickness direction for the steel strip during water cooling was constructed earlier (Pyykkönen et al.

2012). However, for a quick estimation of the required quantity of cooling water, the detailed model is cumbersome, since the required water quantities would be calculated by trial and error (the amounts of water are used as an input, and the calculation of temperature distribution during the cooling takes a few minutes). For this reason, we developed an approximate method (Paananen 2015; Pohjonen et al. 2016a) to obtain the required water usage at different positions on the water cooling line, when the desired temperature in the mid-thickness of the strip at those positions is given as an input. After the approximate calculation has been first done in a few seconds, the more detailed model can be used to calculate the accurate temperature distribution during water cooling. The details of the fitting of the model and its application arena are described further in Pohjonen et al. (2016a) and Pohjonen et al. (2016b).

## Application

The tool is intended to be used as an aid when planning cooling water usage for a hot strip mill (Pohjonen et al. 2016 a, b). The tool gives a rough estimate quickly (in a few seconds). The more detailed (but slower) model can then be used to obtain more accurate results for fine-tuning.

## Technologies MATLAB

**Contact person** Aarne Pohjonen, University of Oulu

**Participants** University of Oulu

**Additional  
Information/  
Publications**

Pohjonen, A., Somani, M., Pyykkönen, J., Paananen, J. & Porter, D. 2016a. The Onset of the Austenite to Bainite Phase Transformation for Different Cooling Paths and Steel Compositions. *Key Engineering Materials*. Vol. 716, pp. 368–375, ISSN 1662-9809.

Pohjonen, A., Kyllönen, V. & Paananen, J., 2016b. Analytical Approximations and Simulation Tools for Water Cooling of Hot Rolled Steel Strip, 9<sup>th</sup> EUROSIM Congress on Modelling and Simulation, pp. 731–736, DOI 10.1109/EUROSIM.2016.42.

Paananen, J., 2015. Laskennallinen työkalu kuumavalssatun teräsnauhan jäähdyttämisen suunnitteluun, Bachelor's thesis, University of Oulu, Materials and Production Technology.

Pyykkönen, J., Somani, M., Porter, D., Holappa, M., Tarkka, T. 2012. Modeling of Thermal History and Microstructural Evolution on the Run-out Table of a Hot Strip Mill. *Proceedings from the 6<sup>th</sup> International Quenching and Control of Distortion Conference* pp. 817–828.

SHOWCASE 2.2

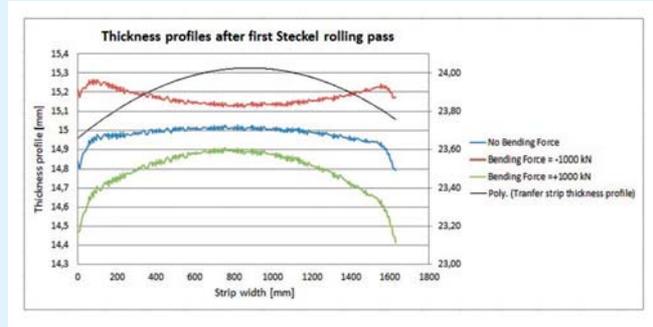
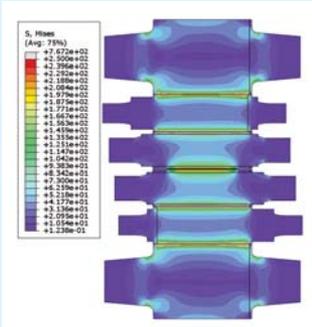


Figure 1. Cross-sectional von Mises stress      Figure 2. Strip thickness profiles after first Steckel rolling pass

Description of the tool

The knowledge and optimization of the steel strip thickness profile and contact stress distributions can be predicted accurately using the simulation FE model developed for Steckel mill. The model is easily redefinable for any kind of transient process analysis. Material models and rolling parameters can be specified by the user.

Technologies

The 3D simulation FE model enables illustration of the dynamic rolling process, considering elastic rolls and process parameters. The existing process data and models for roll wearing and thermal crowning are utilized as input data for the FE model. The simulation model is intended to control the steel strip material flow and study the mechanical loadings, as well as to improve the rolling process.

Scope of application

- The steel strip thickness profile and width spreading can be predicted, considering the transfer strip thickness profile, thermal crown, and wearing of work rolls, along with the camber (Figure 1)
- Pressure and stress distributions on contact areas during a rolling pass
- Study of transient process phenomena like strip threading and deviation from the center line
- Roll flattening and the shape of the roll gap can be predicted accurately (Figure 2)

**Contact persons**      Joonas Ilmola, University of Oulu; Jari Larkiola, University of Oulu,  
**– Inventors**              Olli Haapala, Outokumpu Stainless Oy

## SHOWCASE 2.2

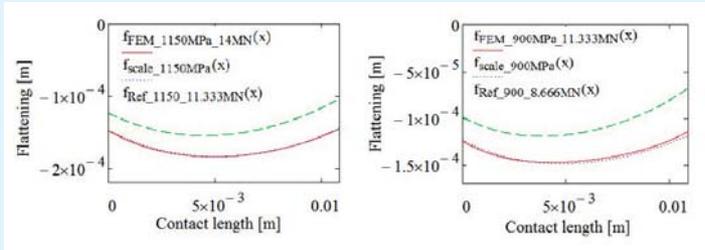


Figure 1. Fourth-degree reference curve of the FE result and scaled analytical function ( $R_e=1150$  MPa,  $R=200$ mm,  $F_{\text{Rolling}}=14$  [MN/m] and  $R_e=900$  MPa,  $R=200$ mm,  $F_{\text{Rolling}}=11.333$  [MN/m])

### Description of the tool

The original aim of this task was to develop an online fundamental temper mill process model to reveal stress and strain distributions during the process, together with exploration of strip initial conditions and process parameters on material

behavior, flatness defects, and residual stresses. Preliminary 2D and 3D finite element (FE) models for a 4-high temper rolling process were developed in the thesis “*Finite element analysis of skin-pass rolling process*” in 2014, and carried out as part of the DIMECC SIMP program. The model improvement concentrated only on analytical models based on the 2D FE model of temper rolling.

### Application

To develop a fundamental temper rolling process model, an FE model was required to describe phenomena of elastic-plastic material flow, various friction conditions, roll deformation, initial strip conditions, roll camber, strip thickness profile, and so on. Although the FE model is able to consider a large number of variables and parameters, it is not suitable for online use due to expensive calculation. Therefore, the FE model is used to depict the process accurately and, on that basis, an analytical model is generated. An analytical model without iteration loops enables very fast process control, as well as efficient and smooth rolling operation.

### Scope of application

An analytical work roll flattening tool enables the definition of work roll flattening and the contact length between the steel strip and work roll when the roll radius is between 200–300 mm and the yield strength of the strip is 350–1150 MPa. In addition, the FE model makes it possible to observe the plastic flow of the material in roll bite and the formation of a residual stress state. Tentative verifications of the analytical model are completed in collaboration with SSAB Europe. The results of work roll flattening of the scaled function (analytical tool) compared to the FE results for a roll radius of 200 mm are depicted in Figure 1.

#### Contact persons – Inventors

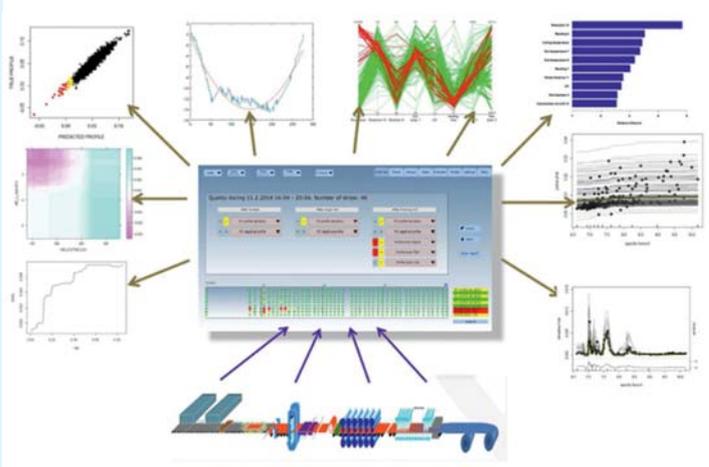
Joonas Ilmola, University of Oulu, Jari Larkiola, University of Oulu, Jari Nylander, SSAB Europe

#### Additional Information/ Publications

Ilmola, J., Pohjonen, A., Larkiola, J., Nylander, J., A New Method Predicting Contact Length and Flattening In Temper Rolling. Key Engineering Materials, Vol 716 (2016) 605–613.

# 9 STRIP PROFILE AND TEMPERATURE PREDICTION

SHOWCASE 2.2



**Description of the tool**

Steel strip profile and temperature information is essential for the following process steps. Our models predict the quality property and the deviation from the target quality. The profile is predicted after the furnace, after the roughing mill, and after the finishing mill. Temperature is predicted after the roughing

mill at three different locations on the strip (head, body, and tail). Using prediction models, it is possible to design products that are more likely to meet the requirements, as well as to find root causes of the failure.

**Application**

The data for both applications was collected at SSAB, Raahé. For online use, only the design parameters were included in the models. The output of the models, as well as the visual presentation of the results, was selected together with the end-users to ensure the effective output of the information. The model provides the user with better insight into the effect of the process parameters, and it can also be used to test the user’s prior assumptions or understanding of the process. In addition, the causes of deviation from the target are important for process improvement and quality variability reduction.

**Technologies**

The free statistical program R was used for prediction models and visualization of the results. The models have been implemented in the Quality Monitoring Tool (QMT) in Toolbox 2.

**Scope of application**

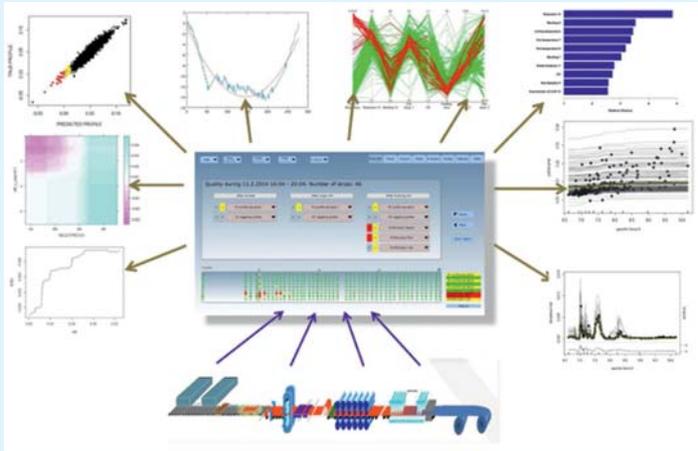
Similar modeling and visualization methods have been used for roughness modeling in SIMP.

**Contact persons – Inventors** Satu Tamminen, University of Oulu/BISG  
Juha Jokisaari, SSAB

**Additional Information/ Publications** S. Tamminen, E. Ferreira, H. Tiensuu, H. Helaakoski, V. Kyllönen, J. Jokisaari, E. Puukko, J. Rönning, “An Online Quality Monitoring Tool for Information Acquisition and Sharing in Manufacturing: Requirements and Solutions for the Steel Industry”, 2016, Draft manuscript.

# 10 MODEL FOR SURFACE ROUGHNESS PREDICTION

SHOWCASE 2.2



**Description of the tool**

One type of surface roughness of a stainless steel strip can be detected after the strip has been polished. Before the finishing process, these products have to be shipped to another plant in a different country, after manufacturing. Our model predicts the surface quality after hot rolling. During the project, the center-line surface

roughness after the RAP line was measured using a device developed by Focalspec. Our other goal was to find the most important production parameters that affect center-line roughness, and how strong the impact of the RAP line parameters is on the quality property.

**Application**

It would save time and effort if the risk of roughness was predicted and the user was able to reallocate the high-risk coils to other end-users with lower surface-quality requirements. It is equally important to detect the process settings that increase the risk, and to re-adjust the process if systematic quality failures occur.

**Technologies**

The free statistical program R was used for prediction models and visualization of the results. The models have been implemented in the Quality Monitoring Tool (QMT) in Toolbox 2.

**Scope of application**

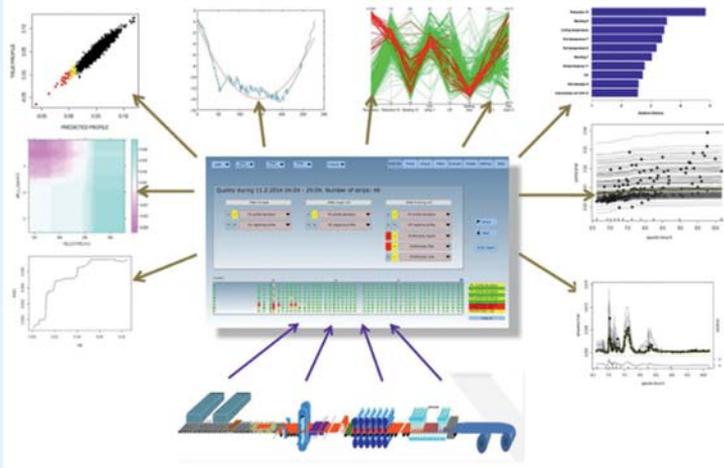
Similar modeling and visualization methods have been used for profile and temperature modeling in SIMP.

**Contact persons – Inventors** Eija Ferreira, Satu Tamminen, Henna Tiensuu, University of Oulu /BISG  
Esa Puukko, Anna Uurtamo, Outokumpu

**Additional Information/ Publications** S. Tamminen, E. Ferreira, H. Tiensuu, H. Helaakoski, V. Kyllönen, J. Jokisaari, E. Puukko, J. Röning, “An Online Quality Monitoring Tool for Information Acquisition and Sharing in Manufacturing: Requirements and Solutions for the Steel Industry”, 2016, Draft manuscript.

11 MODEL FOR AN UNEVEN ROUGHNESS SURFACE DEFECT

SHOWCASE 2.2



Description of the tool

Uneven roughness is a surface defect that can be detected only after the strip has been polished, although the original root cause of the defect may occur early in the production process. The developed model predicts the risk of an uneven roughness surface defect, based on:

- process conditions at the melting plant
- slab properties
- process conditions in temper rolling
- process conditions in finishing rolling
- strip dimensions

Application

The aim of the tool is to:

1. identify the coils for which the surface defect risk is increased
2. find the root causes of the defects.

Using the tool, the predicted risk of the defect can be monitored early in the process, before shipping the coil to a different plant for cold rolling and polishing. In addition, the model provides understanding and ideas for process developers to eliminate the root causes of the defect from the process.

Technologies

The free statistical program R was used for developing prediction models and performing root-cause analysis. The employed modeling method combined gradient boosting and cumulative link linear regression. The models have been implemented in the Quality Monitoring Tool (QMT) in Toolbox 2.

Scope of application

The actual implementation of the model is applicable for predicting the risk of occurrence of a specific surface defect (uneven roughness). However, a similar approach could also be employed to predict the risk and root causes of other surface defect types.

**Contact persons** Ilmari Juutilainen, Indalگو  
**– Inventors** Esa Puukko, Juha-Matti Pesonen, Outokumpu

# 12 IMPROVING THE YIELD OF STEEL PLATES BY UPDATING THE SLAB DESIGN WITH STATISTICAL MODELS

SHOWCASE 2.2

Class	Dev.	thick.1	thick.2	thick.3	thick.4	thick.5	thick.6	thick.7	thick.8	thick.9	thick.10	Total
		0.76	0.76	0.76	0.71	0.76	0.76	0.53	0.53	0.53	0.76	
1	0.74	894	744	145	340	1 413	5 590	135				9261
2	0.67							2 906	1 287	446	613	5 252
3	0.99	1 461	3 180	378	985	1 278	2 057	11				9 350
4	0.71		2	20	134	260	383					799
5	0.05							33				33
6	0.90							18				18
7	0.29	107	236	369	112	2	1					827
8	NA											0
9	0.51	22	481	2 335	2 922	1 764	1 080					8 604
10	NA											0
11	0.36	563	559	121	41							1284
12	NA											0
<b>Total</b>		<b>3 047</b>	<b>5 202</b>	<b>3 368</b>	<b>4 534</b>	<b>4 717</b>	<b>9 111</b>	<b>3 103</b>	<b>1 287</b>	<b>446</b>	<b>613</b>	<b>35 428</b>

### Description of the tool

The tool improves the dimensional accuracy of steel plate by updating the selection of combination parameters for slab design using statistical models. The aim of the combination is to ensure that there is enough material available to produce the ordered product with the desired dimensions. The successful combination process reduces material loss, energy consumption, and emissions, which in turn improves the cost-effectiveness of the steel mill. The new selection procedure is expected to increase yield and reduce the risk of rejection.

### Application

The tool was implemented in co-operation with SSAB. The tool highlighted vital problems in the production line, and there is also a lot of development work done in SSAB due to this study. Currently, the tool is used only with offline data, but it is possible to implement it for online use, as well.

### Technologies

The free statistical program R was used for modeling the mean and deviation of the combination parameters, classification, and visualization. R enables easy implementation on the devices used by product design engineers.

### Scope of application

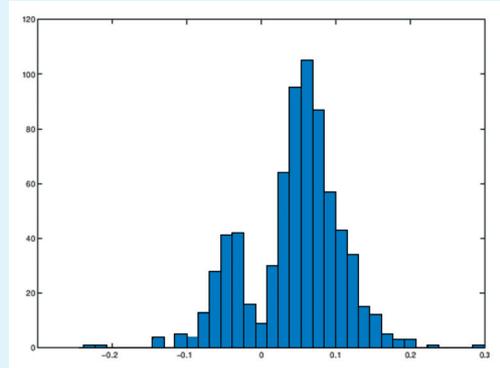
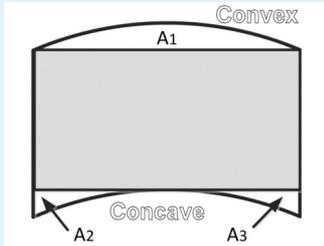
The developed tool is specially designed for plate manufacturing purposes, but the modeling methods can also be applied to other problems with distribution-based working allowances.

**Contact persons – Inventors** Henna Tiensuu, Satu Tamminen, University of Oulu/BISG  
Ari Pikkuaho, SSAB

**Additional Information/ Publications** H. Tiensuu, S. Tamminen, A. Pikkuaho, J. Röning, "Improving the Yield of Steel Plates by Updating the Slab Design with Statistical Models", Ironmak. Steelmak., 2016.

## AUTOMATIC RECOGNITION OF STEEL PLATE EDGE SHAPE USING CLASSIFICATION AND REGRESSION MODELS

### SHOWCASE 2.2



### Description of the tool

In the steel plate production process, it is important to minimize the waste piece produced when cutting a mother steel plate to the size ordered by the customer. The uneven shapes on the plate end sides and lateral sides cause yield loss, amounting to about 5% to 6% of the total tonnage of the slab used. To minimize the loss, the aim is to produce plates with concave side edges, because wastage from concave side edges is smaller than from convex (see Figure).

### Application

We defined the curvature of a time series describing the steel plate side edge, and used this information to build a statistical distribution model to visualize what kinds of curve shapes the studied data set includes, and how the amount of curvature is distributed in the manufacturing process (see Figure for current distribution). This information can then be used to optimize the manufacturing parameters to manufacture more plates with the desired shape. Data for the study is collected from the SSAB Europe, Raahe plate mill. The data were collected from 399 plates, and therefore from 798 sides.

### Technologies

The tool consists of classification and regression models trained using data extracted from time-series describing side edges. Models were trained using MATLAB, but this can also be done with any other mathematical or statistical program.

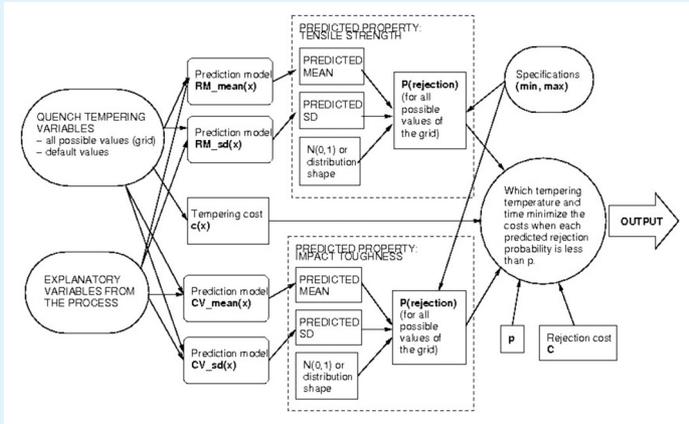
### Scope of application

The developed tool is specially designed for plate manufacturing purposes. Therefore, it is difficult to apply to other industrial processes. However, it is not limited to steel plates, as the material of the plate can also be another metal.

**Contact persons**  
– **Inventors** Pekka Siirtola, Satu Tamminen, University of Oulu / BISG  
Elina Prokkola, SSAB

**Additional Information/  
Publications** P. Siirtola, S. Tamminen, E. Ferreira, H. Tiensuu, E. Prokkola, J. Röning,  
"Automatic Recognition of Steel Plate Side Edge Shape Using Classification  
and Regression Models", EUROSIM, 2016.

SHOWCASE 2.2



Description of the tool

The tool is used for optimizing the steel plate tempering process. A statistical model predicts the rejection probability of the plate’s mechanical properties (tensile strength and toughness), and the predictions are used to find the most cost-effective parameters for the tempering, with an acceptable level of rejection risk. The tool will help to reduce the variation in the mechanical quality of the steel plates. In addition, excessive holding times can be reduced by planning tempering with the tool.

Application

The tool was modeled using process data from two different product groups from SSAB, Raahe, and an R-based tool was delivered for test use. Currently, the tool can be used only with offline data, but it is also possible to implement it for online use. The tool can be used by process development personnel and product development personnel.

Technologies

The tool consists of models and an optimization system made with the free statistical program R.

Scope of application

A similar method has been used previously for process optimization at Ovako, Imatra. The tool was based on different mechanical properties. The method is applicable to any industrial process optimization problem, if there are a couple of steering variables that have a strong impact on the selected quality properties.

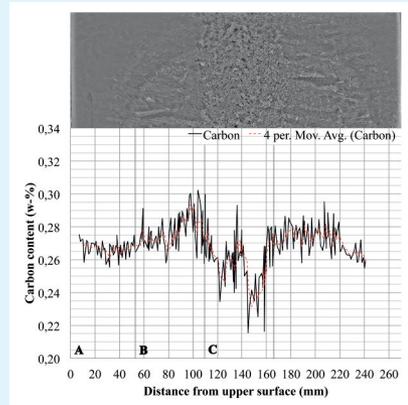
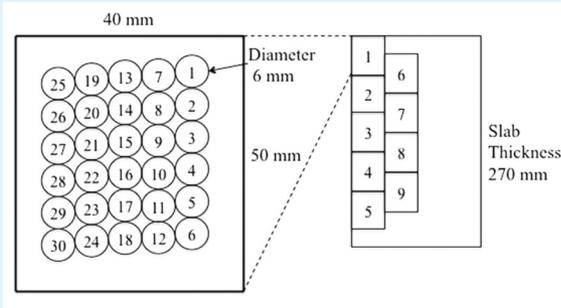
Contact persons – Inventors

Tapani Sipola, University of Oulu/BISG  
 Satu Tamminen, University of Oulu/BISG  
 Olli Leinonen, SSAB (previously)/University of Oulu/MEPT  
 Jussi Helkoma/SSAB

Additional Information/ Publications

T. Sipola, "Data-lähtöinen monitavoiteoptimointi teollisuudessa", Master’s thesis, 2016, Draft manuscript.

SHOWCASE 2.2



Description of the tool

The tool is used for getting a high-frequency composition profile with OES bulk analyzing equipment. This tool is necessary when the sample size is too big for micro analyzers. A total of 270 OES analyses were done from nine 40 x 50 mm<sup>2</sup> samples, so that the whole height of the slab was measured at 1 mm intervals. The resulting composition profiles were compared to macro-etched slab profile pictures, in order to see the effect of as-cast structures and the CET zone on the segregation of the alloying elements.

Application

This tool is used at SSAB Raabe when information about slab composition profiles is needed.

Technologies

An optical emission spectrometer (OES, OBLF QSG 750, OBLF, Witten, Germany) was used for the analyses.

Scope of application

The method is applicable to any large-scale composition profile analysis in the steel industry.

**Contact persons – Inventors** Teppo Pikkarainen, SSAB Raabe  
 Sami Koskenniska, University of Oulu/MEPT  
 Saara Mehtonen, SSAB Raabe



## SHOWCASE 2.2



### Description of the tool

Raman spectrometers in general are used to monitor the chemical composition of solid and liquid materials. Due to the low probability of Raman scattering, conventional Raman technology suffers badly from background radiation like that of photoluminescence of organic materials or thermal radiation of hot materials. Time-resolved Raman is able to suppress background radiation very effectively, and is thus suitable as a process analytical technology (PAT) in processes handling high-temperature materials.

### Application

The analyzer is commercialized by TimeGate Instruments Oy and has been field-tested at several industrial sites using direct or sampled input from processes.

### Technologies

Background suppression is achieved by using a pulsed laser for excitation, and time-gating the spectrometer correspondingly. Gating is implemented using single-photon detection and picosecond-accurate timing technology developed at the University of Oulu (CAS/ITEE).

### Scope of application

The time-resolved Raman spectrometer can be used in all those applications where conventional Raman spectroscopy has been found useful, but it is especially suitable for applications containing high-level background radiation. Note, too, that together with molecular structure-specific Raman spectra, the recorded time-resolved photoluminescence data (removed from Raman as background) can give valuable additional information on the analyzed material. Possible future applications include 3D chemical and temperature analysis of industrial gas volumes.

**Contact person– Inventor** Jyrki Savela, TimeGate Instruments Oy

## SHOWCASE 2.2



### Description of the tool

The SIBS (Spark Induced Breakdown Spectroscopy) analyzer is used to monitor the elemental (e.g. metal) composition of process liquids. Laboratory analyses can be replaced by continuous, real-time, online/at-line monitoring.

### Application

The analyzer has been field-tested at several industrial sites using direct input from processes.

### Technologies

A spark is generated in the liquid using a high voltage that dissolves the chemical compounds of the liquid into free excited atoms emitting characteristic radiation. The intensity of this radiation is proportional to the concentration of the particular element.

### Scope of application

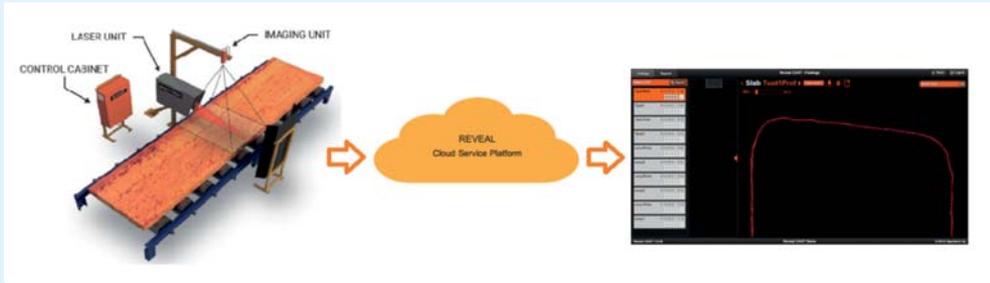
Besides the elemental content of process liquids in steel and other metal industries, the analyzer has been tested in applications like effluent and water monitoring in municipal and industrial water works and treatment plants.

### Contact persons – Inventors

Kalle Blomberg, OPEM/ITEE/University of Oulu  
Ari Mäkinen, OPEM/ITEE/University of Oulu  
Anssi Mäkynen, OPEM/ITEE/University of Oulu

19 SAPOTECH REVEAL CAST

SHOWCASE 2.2



Description of the tool

Reveal CAST is a complete solution for monitoring hot metal surface quality and the dimensions of cast and rolled products. High-definition imaging units, in synchronization with laser illumination, provide visualization of targets in unprecedented detail. Algorithms ensure defect detection. Tangible benefits are enhanced process control through data provided online and process improvement through analysis offline. Significant savings in resources, energy, process time, and materials are made through systematic detection of defects at the earliest possible stage.

Application

Reveal CAST was applied as a SIMP program in a real process environment for online monitoring of steel plate profile and surface quality at the exit of the hot rolling mill leveler. Results were extremely positive: the dimension profile of the plate was accurately calculated and specified surface defects were automatically detected.

Technologies

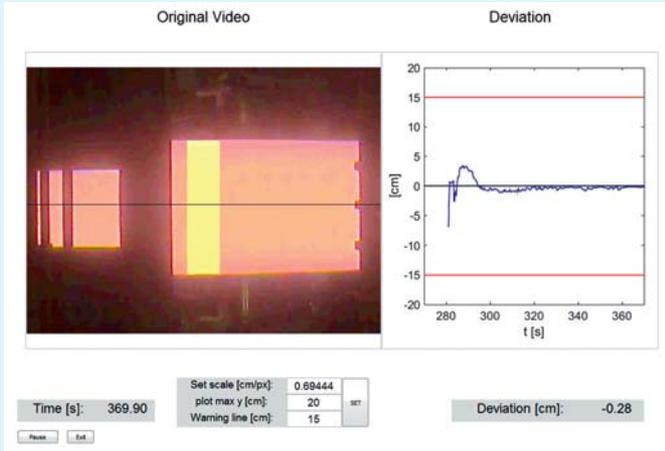
Reveal CAST is a web-based platform making full use of the Industrial Internet, enabling easy remote management and fluent distribution throughout organizations and locations. Additional measurement technologies and features can be further integrated into the platform according to users' specific needs.

Scope of application

Reveal CAST can be applied in surface quality and dimension monitoring of cast and rolled, long and flat

Contact persons – Inventors Saku Kaukonen, Sapotech Oy  
 Juha Roininen, Sapotech Oy

## SHOWCASE 2.2



### Description of the tool

A machine vision system measures the sideways position of a hot moving strip in real time using a video feed from an overhead surveillance camera.

### Application

The current offline tool uses a video feed from an ordinary surveillance camera positioned directly above the hot rolling line between two milling stands. The tool provides a video playback, real-time visualization of edge detection, and the center-line position of the strip as a function of time. The first online implementation is under way at the Outokumpu steel works in Tornio.

### Technologies

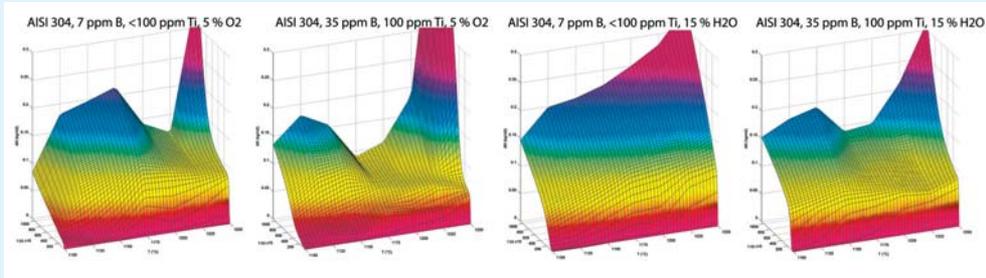
The offline tool uses MATLAB-based video analysis. The position of the strip is measured from a video feed using frame-by-frame image analysis and gradient-based edge detection. The system has built-in self-calibration and vibration compensation. The first online version uses machine vision cameras and a Windows server with multicore CPUs programmed using LabView.

### Scope of application

The tool can be used to measure the position of a hot strip or slab using an overhead video feed. The developed algorithms are applicable for online implementation of strip steering control, as well as various kinds of monitoring needs. The tool, as such, is applicable only in cases that include hot (incandescent) objects.

**Contact persons** Harri Juttula, OPEM/ITEE/University of Oulu  
**– Inventors** Anssi Mäkynen, OPEM/ITEE/University of Oulu

## SHOWCASE 2.2



### Description of the tool

Boron and titanium microalloying affects the scale formation of austenitic stainless steels in slab reheat furnace conditions. Arrhenius-type scale growth models are created for different boron and titanium alloying amounts of AISI 304 stainless steel. Tuning the parameters for slab reheat furnace operation allows for lower amounts of formed scale, resulting in decreased material loss, as well as understanding of formed scale layer morphology.

### Application

The tool was validated through multiple boron and titanium alloying amounts at different temperatures, as well as oxygen and water vapor content in the atmosphere. Calculated activation energies were used directly in an industrial walking beam furnace for slab reheating control. The results showed lower scaling amounts for AISI 304 stainless steel.

### Technologies

Thermogravimetric measurements are required for activation energy calculations. FESEM/EDS analysis is used in scale layer morphology characterization.

### Scope of application

Activation energies can be used in industrial walking beam/reheat furnaces as operation parameters, to run slab reheating furnaces optimally for a desired steel type. Thermogravimetric results can be used in IDS for validation purposes.

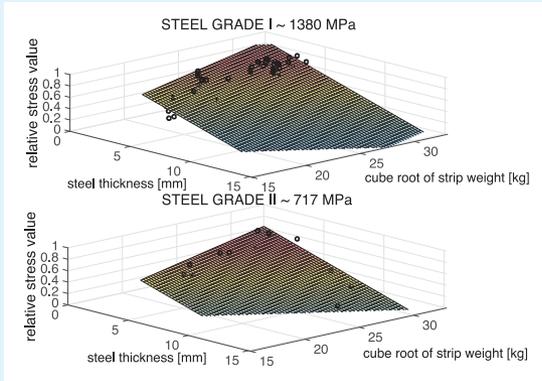
#### Contact persons – Inventors

Aleksi Laukka, University of Oulu; Timo Fabritius, University of Oulu;  
Esa Puukko, Outokumpu Stainless Ltd.

#### Additional Information/ Publications

Laukka, A., Heikkinen, E-P., Puukko, E., Fabritius, T. 2017. The effect of boron and titanium microalloying on the scale formation of AISI 304 austenitic stainless steel in simulated walking beam furnace conditions. Steel Research International 88. Pre-published. DOI 10.1002/srin.201600365.

SHOWCASE 2.2



Description of the tool

The tool provides a model of relative stress prediction in a roller leveler. The tool provides advanced evaluation of the relative stress level to improve failure prevention by maintenance planning.

Application

Tool was validated using measurement and process data from a roller leveler that is in continuous operation at a steel mill. The primary application of the tool is main-

tenance planning, and it could be used to support production planning. Currently, the model is an offline engineering tool and it can be potentially developed for online applications.

Technologies

Vibration measurements, process data, MATLAB-based signal processing, feature extraction, and regression modelling.

Scope of application

This technology is widely applicable in steel mill machinery stress monitoring. Similar signal processing techniques have been applied to steel cutter stress-level evaluation.

**Contact persons – Inventors** Riku-Pekka Nikula, Konsta Karioja, Esko Juuso, University of Oulu

**Additional Information/ Publications**

Karioja, K., Nikula, R.-P., Liedes, T., Vibration Measurements and Signal Processing in Stress Monitoring of a Steel Leveller, Maintenance, Condition Monitoring and Diagnostics & Maintenance Performance Measurement and Management, MCMD 2015 and MPMM 2015 (2015).

Karioja, K., Nikula, R.-P., Niedringhaus, C., Küch, C., Baltés R., Roller bearing fault detection using real order derivatives and cyclostationarity, 13th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies, CM2016/MFPT2016 (2016).

Nikula, R.-P., Karioja, K., The effect of steel leveler parameters on vibration features, Proceedings of the 9<sup>th</sup> EUROSIM Congress on Modelling and Simulation, IEEE Conference Proceedings, (2016) 392–397.

Nikula, R.-P., Karioja, K., Leiviskä, K., Juuso, E., Prediction of mechanical stress in roller leveler based on vibration measurements and steel strip properties. Journal of Intelligent Manufacturing (Submitted 2017).

Nikula, R.-P., Karioja, K., Steel grade specific stress predictions to support roller leveller maintenance. First World Congress on Condition Monitoring, London, 13–16 June, 2017 (Submitted).

## SHOWCASE 2.2

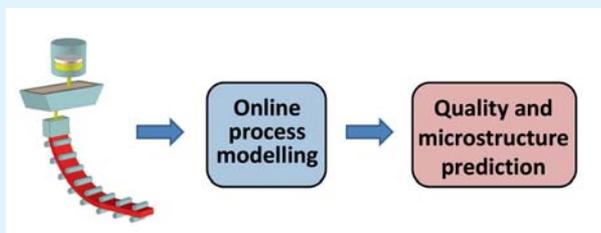


Figure 1. CastManager + IDS system for continuous casting

### Description of the tool

CastManager is an online continuous a 3D strand model, a 3D mold model, and a solidification and microstructure model, IDS. CastManager is capable of calculating temperature distribution, quality-related indices, and stresses in the strand in real time. The simulator is implemented in the SSAB Raahe and Outokumpu Tornio steelworks and is running online.

### Application

Main features: Fast real-time 3D temperature distribution calculation, liquid pool determination from temperatures, strand width change-handling during casting, steel grade change-handling with correct material data, stress calculation at critical locations. The online version of IDS, with a quality prediction module, is implemented in CastManager. IDS calculates material data, as well as a microstructure evaluation of the steel, including inclusions and precipitates.

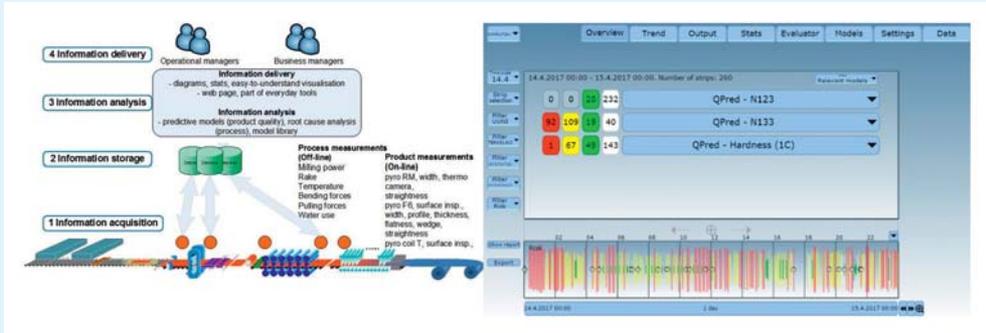
#### Contact persons – Inventors

Jukka Laine, Casim Consulting (casim.consulting@gmail.com)  
Seppo Louhenkilpi, Aalto University (seppo.louhenkilpi@aalto.fi)

#### Participants

Aalto University, Casim Consulting Oy, SSAB Europe Oy, Raahe, Outokumpu Stainless Oy, Tornio.

## SHOWCASE 2.2



### Description of the tool

The tool is a framework for integrating online data and calculation models, and it is used for analyzing and monitoring process quality. The tool gives overall understanding of process quality. Deviations from the normal state are easy to detect.

### Application

The tool has been validated by tests carried out by process engineers, and data correctness has been validated separately in the Outokumpu case. The tool is connected to SSAB and Outokumpu online databases, so launching the tool gives a view of up-to-date process data and quality.

### Technologies

- Operating system: Windows, Linux
- Web-based user interface: HTML5, PHP
- Server backbone: C++, Boost C++ library, RServe, ExprTk rule engine
- Models: R, rules, Python, C++
- Data sources: Oracle, MySQL

### Scope of application

The tool is configurable for data, process layout, models, user interface, and settings, so it can be applied to other industrial processes. It has been applied to liquid steelmaking in SC1 and to the cooling model in SC2.

#### Contact persons – Inventors

Heli Helaakoski and Vesa Kyllönen, VTT  
 Satu Tamminen, Henna Tiensuu and Eija Ferreira, University of Oulu/BISG  
 Juha Jokisaari and Tapio Salonpää, SSAB  
 Esa Puukko and Juha-Matti Pesonen, Outokumpu

#### Additional Information/ Publications

S. Tamminen, E. Ferreira, H. Tiensuu, H. Helaakoski, V. Kyllönen, J. Jokisaari, E. Puukko, J. Röning, "An Online Quality Monitoring Tool for Information Acquisition and Sharing in Manufacturing: Requirements and Solutions for the Steel Industry", Submitted in 2017.

# DECISION SUPPORT OF METALLURGICAL PROCESSES

## SHOWCASE 3

Jarmo Lilja, Olli Mattila, Jukka Pelttari/SSAB Europe Oy  
Lauri Halonen, Juho Kunelius, Esa Puukko/Outokumpu Stainless Oy  
Suvi Rannantie/Outotec (Finland) Oy  
Mikko Iljana, Antti Kempainen, Jari Ruuska, Ville-Valtteri Visuri, Ari Vuokila/University of Oulu  
Henrik Saxén, Mikko Helle/Åbo Akademi University  
Karri Penttilä/VTT Technical Research Centre of Finland

### Summary of the project's motivation and achievements

Work on SIMP Showcase 3 has covered primary production of iron and ferroalloys, mainly ferrochromium. The aim has been to support sustainable and cost-efficient production of metals by developing tools and methods to improve process control and process stability. An offline model has been developed to optimize material and energy flows at the SSAB Raahe Steel Works. At the Outokumpu Tornio Works, a dynamic simulation tool to calculate temperature and phase compositions at different layers of a submerged arc furnace has been developed. Knowledge of metallurgical phenomena is integrated into the models, which can be used to support decision-making on raw material selection and operating practices.

A number of models and measurements have been developed, especially for tuyère and raceway areas at the SSAB Raahe blast furnaces (BF). These include computational fluid dynamics (CFD) modeling of coal combustion inside the raceway, a method for controlling the carbon/oxygen ratio at individual tuyères, and a method for controlling combustion using information from tuyère cameras. This work has contributed to a smooth transition from oil to pulverized coal injection at the SSAB Raahe blast furnaces (BF). At the Outokumpu Tornio Works, after validation the dynamic simulator of a submerged arc furnace will be used to evaluate when and how raw materials affect process efficiency and product quality.

At the SSAB Raahe Works, a method to measure the burden level inside the blast furnace shaft has been developed and piloted on an industrial scale. At the SSAB Raahe coking plant, a coke blend optimization model and coke oven monitoring systems have been developed and applied to production with the aim of supporting smooth production and the extension of the coke battery lifetime. The first trials for a coke oven leakage detection system have been successfully conducted. At the

Outokumpu Tornio Works, a tapping monitoring system was successfully piloted for liquid ferrochrome and the application is in fully operational usage.

Outotec's new Pellet Size camera system has been installed at the Outokumpu Tornio Steel Works to monitor the green pellet size before the sintering furnace. The impact for the industry is valuable. Operators get quicker feedback from the process and they can focus on optimizing the process instead of doing manual measurements. Additionally, pre-reduced ilmenite was smelted in the pilot DC furnace located at the Outotec Research Center in Pori for first time in the world. Good quality slag and pig iron were produced during the test campaign, and the technical viability of the energy-optimized smelting process developed by Outotec was demonstrated.

### HIGHLIGHTS OF SHOWCASE 3

A decrease in elemental carbon consumption has been achieved at the SSAB Raahe blast furnaces.

The injection practice for pulverized coal has been improved at the SSAB Raahe blast furnaces with the aid of tools developed in this project.

An optical method to detect coke oven leakages has been successfully implemented at the SSAB Raahe coking plant.

New knowledge, control principles, and models have produced valuable information to support decision-making and process optimization.

An optical method for tapping monitoring was implemented at the Outokumpu Tornio FeCr plant.

A new dynamic model for a submerged arc furnace was developed and will produce valuable information to support decision-making and process optimization at the Outokumpu Tornio Works.

Pre-reduced ilmenite was smelted in the pilot DC furnace for the first time in the world.

### Company impact

"The DIMECC SIMP program has shown its strength by integrating novel measurements, modeling, and simulation into world-class control of metals processes. This is possible only when competent people in industry and academia are striving together toward a common target."

*Juhani Asunmaa, Head of process development, SSAB Europe Oy*

## Plant-wide operation control system for hot metal production

An optimizing model has been developed not only for hot metal but for the whole steelmaking process at SSAB Raahe Steel Works (Tool 1, page 166). The main target is cost optimization of the production system, including material and energy costs. In addition to optimizing material selection regarding costs, the model can be used for calculating a number of key parameters in the process (recycling rates, energy consumption, behavior of impurities, CO<sub>2</sub> emissions, etc.). All the main production processes, including the power plant and processes for side streams, are included in the model.

The model is unique and developed for a steelmaking process using an existing APS platform by SW-Development Oy. No such model is available on the market. The model is used offline and is installed in one of SSAB's production servers. Figure 1 shows the user interface, indicating the modular structure of the model. Material flows with all inputs and outputs for each sub-process are described here. For each sub-process, the distribution of elements between different phases is described as a table of coefficients. At this stage, the coefficients are fixed, but in the future it is planned to utilize specific process models to estimate the distribution of elements in more detail. This has been done for the BOF process using multivariate linear regression in the Matlab environment at the Control Engineering Research Unit at the University of Oulu (Tool 2, page 167).

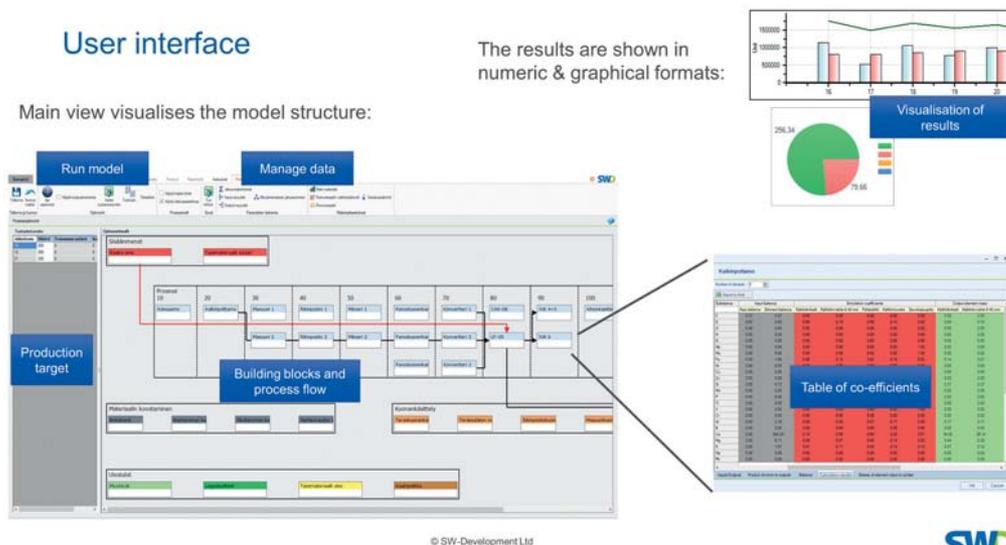


Figure 1. User interface of the optimizing model for the steelmaking process at SSAB Raahe Steel Works

The model has been validated with respect to mass balance. A specification of how to include energy balance in the model has been made but the implementation needs additional work, as well as visualization of the results. There are a number of ways to utilize the model. It has been shown that significant savings in raw material costs can be achieved when taking into account all impacts of changes in a particular raw material. A true value-in-use of a raw material or a change in the way of operation in the process can be calculated. The tool can be used by experts in different positions to compare scenarios in investments, raw material prices, production quantities, and new ways of processing. It is a powerful tool for decision-making and avoiding sub-optimization. The model fills a need for a transparent and standardized way of calculating the optimum usage of raw materials.

### **Improved blast furnace control**

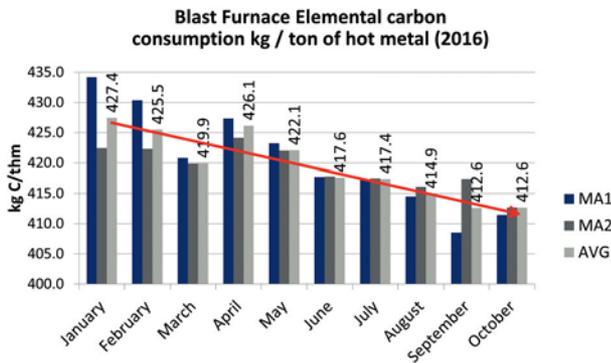
The target was to gain a deeper understanding of the BF process by means of a combination of mathematical models, laboratory experiments, and novel measuring technologies, and to apply this in the practical operation to take a considerable step toward lower consumption of fossil reductants and reduced emissions.

To understand the material flow and distribution on the BF burden surface, discrete element method (DEM) modeling has given an extremely valuable insight into the phenomena occurring in otherwise unobservable locations in the BF process. The sliding of material layers and the pushing impact of pellet on coke layers are the most valuable pieces of knowledge that can be used in the process control. The results of DEM modeling have been successfully transferred to the layer model used in the process, to design burden charging philosophies. Measurement technology to tolerate high dust and moisture loads for burden surface online scanning was tested to further improve the ability to react to process fluctuations. As a result of the actions, a central coke chimney was successfully achieved in the BF operation.

Information from the CFD modeling, as well as from tuyère image analysis, was used to control the injection lance length, as carbon deposits were blocking the air flow path into the BF. These actions made it possible to take full advantage of the developed injection control circuit, which resulted in a dramatic stabilization of the injection carbon-oxygen ratio, which is a key factor in successful reductant injection.

The development of new models and control principles, in addition to fine-tuning existing ones, has enabled a successful transition to the use of a new auxiliary reductant in the blast furnaces during the project. This work was done in close cooperation with Showcase 4. New knowledge, control principles, and models have produced valuable information supporting the decision-making process and process optimization.

Through understanding of material behavior in the process, the development of material properties, and the right selection of materials for the process, the blast furnace operational efficiency – measured by the amount of elemental carbon used to produce a ton of hot metal – has improved significantly. In 2016, the use of elemental carbon has decreased by nearly 15 kg/ton of hot metal (see Figure 2). The annual CO<sub>2</sub> saving due to improved process efficiency is approximately 120 kt.

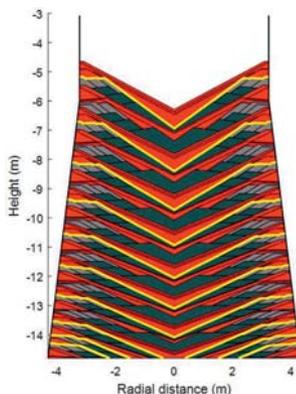


**Figure 2. A significant decrease in specific elemental carbon consumption at the SSAB Raahe blast furnaces (“MA1” and “MA2”) was achieved during 2016**

In the following sub-sections, the major achievements relating to the blast furnace operation are described more thoroughly.

### Burden distribution model (Tool 4, page 169 and Tool 5, page 170)

Burden distribution plays a key role in controlling the gas flow conditions inside a blast furnace. The distribution of ore and coke influences the gas permeability distribution in the lumpy zone and also in the cohesive zone, where the gas flows mainly through the coke slits. In this project, a Mat-lab-based burden distribution model, described in Tool 4, was further developed to be able to simulate a realistic burden layer structure in blast furnace operation. An example of a calculated burden layer structure is seen in Figure 3.



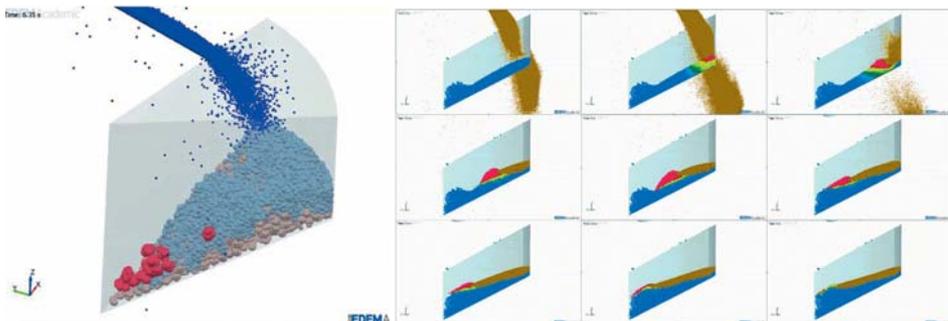
An example of a calculated burden layer structure is seen in Figure 3.

**Figure 3. Example of a calculated burden layer structure. The yellow lines indicate coke layers prone to collapse. Red colour indicates ore and grey coke**

Charging an ore dump with coke can sometimes cause the coke layer to collapse under the force of the heavier ore particles. This is known as 'coke collapse' or 'coke push', which results in a higher coke fraction than expected near the center of the furnace. A study of the coke push effect was carried out extensively, to be able to include this information in the burden layer model. Experiments in a small-scale charging rig (see Figure 4) together with DEM (see Figure 5 and [Tool 5](#)) were applied to tackle this issue.



**Figure 4. Small-scale test rig in operation, showing the coke push effect (by observing the motion of yellow coke particles)**



**Figure 5. Pellets pushing the coke layer to the center, estimated by DEM. Left: Pilot model simulation. Right: Full-scale blast furnace simulation where red indicates coke particles with high velocity, and blue indicates stationary particles**

The burden layer model is currently used in production on a routine basis to simulate different possibilities to adjust charging patterns in the automation system.

### **Burden surface measurements ([Tool 6, page 171](#))**

Blast furnace burden surface measurement is crucial for optimal BF burden distribution control. Current microwave radar systems suffer from the dusty environment and produce lagged and noisy single point signals

that cannot be used for proper burden control. To overcome the measurement problem in the dusty environment, frequency-modulated continuous-wave (FMCW) signals were tested in a material silo environment. The FMCW radar system was selected for blast furnace testing through the inspection hatch on the BF top. This signal is able to detect the burden material surface at long distances in a very dusty environment.

Measurements were made in real process conditions during the BF process start-up phase, which is characterized by a high material feed rate leading to the highest possible dust liberation rate in the gas phase. The ability of the FMCW radar system to produce the necessary signal was tested. It is possible to aggregate the FMCW radar measurement signals to produce an online 3D image of the BF burden surface. To protect the measurement head from the harsh environment prevailing inside the BF, the scanning radar system with a limited number of measurement heads seems to be the only viable option for further development.

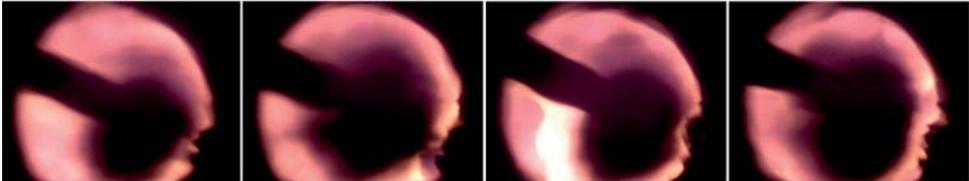
Online 3D burden surface information could be used to validate and fine-tune burden models to accurately estimate the burden layer structure (Tool 4). By designing the burden layer structure in advance when charged materials change, and to monitor changes in the layer structure online, allows for smooth and energy-efficient blast furnace operation. The online control of the burden layer structure also makes it possible to control heat losses, which improves the predictability of the BF campaign life.

#### **Tuyère camera system (Tool 7, page 172)**

Tuyère cameras were installed to monitor primarily the flow of pulverized coal (PC) into the process, the location of the PC flow in relation to tuyère, scaffold formation on the tuyère surfaces, and tuyère erosion caused by PC flow. The improvement compared to the previous practice is obvious, as process workers' personal opinions on the tuyère condition during the check round could be replaced by online image information collected and stored simultaneously from every tuyère. Problematic tuyères and special phenomena in the tuyère area can now be monitored in real time.

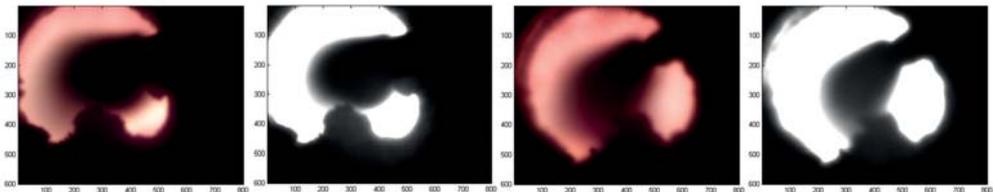
Each PCI lance is located individually inside the tuyère. The location of the lance depends on how the thermal insulation inside the blow-pipe is manufactured. When the PCI was started at Raahe Steel Works, the PC flow was directed – more or less – onto the center of the tuyère or onto the wall of the tuyère. When the PC flow was directed toward the tuyère wall, significant scaffold formation was observed. By adjusting the lance length, the location of the PC flow can be changed to minimize tuyère scaffolding problems. Scaffolding problems lead to uneven air flow into the blast furnace, disturbing the furnace circumferential material balance.

The tuyère camera system stores one image every two seconds from every tuyère in the database. Subsequent images have significant thermal distortion, which prevents straightforward pixel-wise image comparison and automated computation. In addition, the PC flow itself shows remarkable variation in subsequent images. An example of the differences can be seen in Figure 6.



**Figure 6. Subsequent images in the database. The time interval between the images is 2 seconds**

Tuyère camera images were manipulated in Matlab to be able to tackle the thermal distortion and the uneven PC flow-based problem basically by averaging 120 images (roughly 5 minutes) with necessary histogram non-symmetric threshold functions. An example of manipulation with lance length adjustment is shown in Figure 7. As a result of tuyère image analysis, the scaffold formation on the tuyère surfaces could be reduced remarkably by lance length adjustments.



**Figure 7. Manipulation of tuyère image with lance length adjustment. Left-side images: before lance length adjustment. Right-side images: after lance length (+2cm) adjustment**

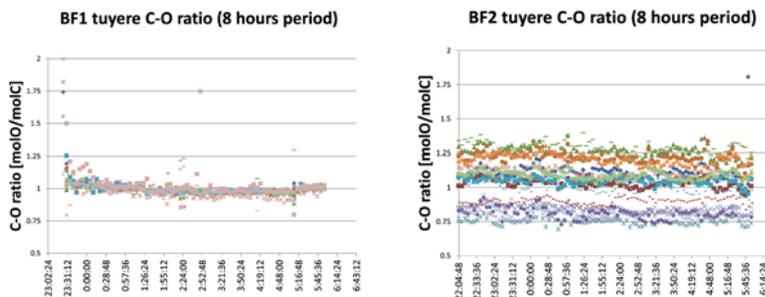
### [Raceway simulator revision to pulverized coal injection and individual lance stoichiometric oxygen-carbon balance control \(Tool 8, page 173\)](#)

A raceway simulation model was updated to meet the criteria stated by PC injection. The model is based on mass and energy balance calculations with necessary chemical reaction information. The model includes information about the burning capabilities of different fuels, to enable

comparison of different fuels or fuel mixtures offline, yielding information about flame temperature, stoichiometric O/C ratio, and tuyère individual behavior, to mention just a few items. Online mode is applied to visualize current operation characteristics in the blast furnaces. The simulation results of the tuyère-raceway simulation tool show the versatility of the tool in finding proper values for operating the tuyère set and individual tuyères.

Each tuyère received an individual volume flow of hot blast. To enable the uniform burning characteristic of PC, the calculation of a stoichiometric ratio between air oxygen and PC carbon was implemented in the automation system. A calculated individual C/O ratio was implemented in the control circuit of each tuyère injection line.

Figure 8 shows the C/O ratios for the individual control circuits in operation for BF1 but not for BF2. The difference in the stoichiometric C/O ratio is very small in BF1, indicating uniform combustion possibilities for PC. The difference in the stoichiometric C/O ratio is large between the tuyères in BF2. Even burning conditions enable higher injection rates and thus bring about significant economic benefits. To further increase the injection rate, several technologies have been reported in the literature, either using an additional oxygen supply or improved mixing of the PC and the blast. Based on the industrial experiences using different technologies, a two-lance configuration was selected to be developed further. In this project, the work on finding the optimal configuration by CFD modeling was started.



**Figure 8. Individual C-O control in the tuyères in operation in BF1 but not in BF2**

### Tuyère-raceway combustion model (Tool 9, page 174)

Computational fluid dynamics were used as a method to create a tuyère-raceway combustion model for pulverized coal injection in the blast furnace. The tool was used to improve the injection system and to find limiting factors for pulverized coal combustion. The combustion model predicted the combustion degree of pulverized coal in a test rig with good accuracy.

The results were compared to experimental results. The model was found to work well with medium and high volatile coals, and can be used to predict the combustion condition in the blast furnace tuyère-raceway area.

Improved combustion of pulverized coal in the blast furnace means that higher levels of auxiliary fuel injection can be used to replace coke, lowering the costs of ironmaking. The tool can be applied to design the new double-lance injection system for pulverized coal. With CFD modeling, experimental work can be reduced, which lowers the design costs and also the risk of unwanted incidents during the implementation phase.

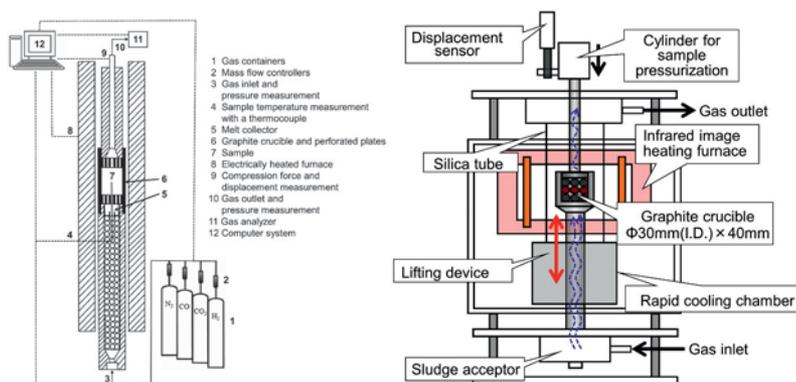
### **Industrial and laboratory-scale testing (Tool 10, page 175 and Tool 11, page 176)**

The choice of raw materials with appropriate performance in the process provides a significant opportunity for cost savings. Comprehensive testing is needed to improve the metallurgical properties of BF iron burden materials. Different physical and metallurgical properties need to be investigated, including cold crushing strength, low-temperature disintegration, reducibility, reduction-swelling behavior, and softening behavior. The laboratory-scale reducibility and reduction-swelling tests, as well as the industrial Advanced Reduction under Load (ARUL) test, are fine-tuned experiments with gas and temperature controls in order to simulate the actual BF conditions more accurately than ISO standard tests, which are mostly carried out under constant temperature and atmosphere conditions. Comprehensive testing of materials has been carried out in the Process Metallurgy Research Unit at the University of Oulu, and at the SSAB Raahe Steel Works.

Lots of benefits are seen in material testing. Basically, burden material tests are used to select and develop materials, as well as to understand material behavior in the process. Material testing enables the choice of burden materials before making a delivery contract. Material properties together with other value-in-use factors determine the purchase order. For instance, more than 20 alternative pellet grades were tested before a transition from acid pellets to magnesite fluxed pellets at the SSAB Raahe Steel Works in 2016, and a dozen PCI coal grades were tested before transition to pulverized coal injection at the SSAB Raahe Steel Works in 2015.

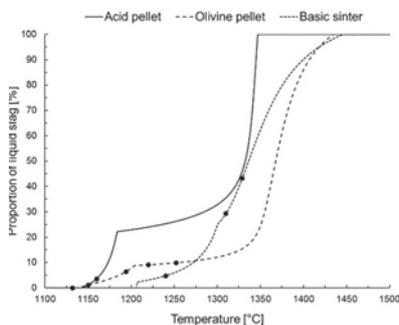
In this project, the focus was mostly on the softening of iron burden materials. The ferrous burden loses its permeability in the cohesive zone of the blast furnace due to softening and melting. Thus, the formation of the cohesive zone has a significant effect on the efficiency of gaseous reduction in the BF shaft, which affects the efficiency of the whole process. There are various ferrous BF burden materials with different chemical compositions and softening properties. It is desirable that the iron burden softens at as high a temperature as possible.

A thermodynamic-based tool was developed to estimate the softening of iron burden materials in the blast furnace. With the tool, the solidus and liquidus temperatures can be calculated, and liquid formation behavior can be estimated using the original chemical composition of the iron burden material. The FactSage-based tool has been validated by industrial Advanced Reduction under Load test apparatus at Raahe Steel Works and a laboratory-scale Cohesive Zone Simulator (CZS) at Kyushu University (see Figure 9).



**Figure 9. Left: Industrial Advanced Reduction under Load test apparatus. Right: Laboratory-scale Cohesive Zone Simulator**

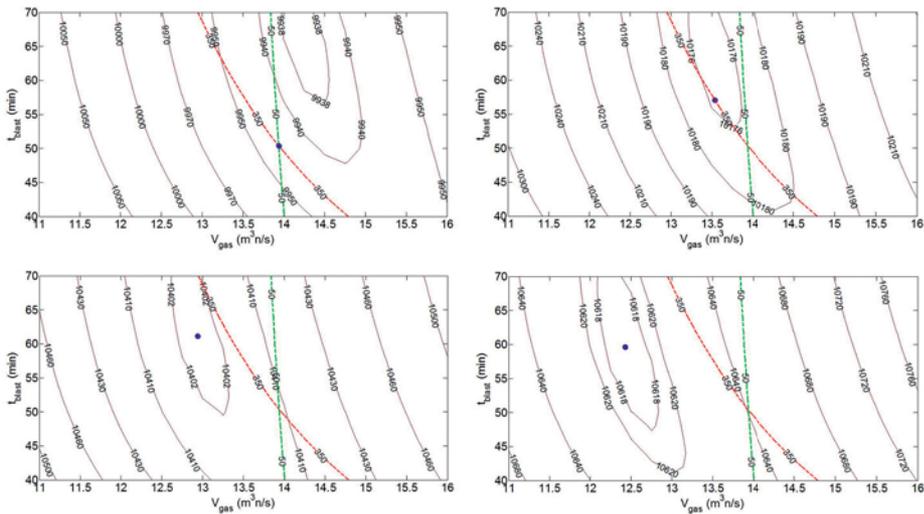
The FactSage computations and the ARUL reduction-softening apparatus have been used in optimizing the compositions of iron ore pellets with the overall goal of improving the BF efficiency and productivity at the SSAB Raahe blast furnaces. Figure 10 shows a FactSage-computed example of the evolution of liquid slag phase in three different types of iron burden materials. There is a large difference between materials. However, all three iron burden materials are current or past charge materials of the blast furnaces at Raahe Steel Works.



**Figure 10. Comparison of softening-melting behavior of three types of BF iron burden materials (acid pellet, olivine fluxed pellet, and basic sinter) estimated by FactSage**

## Hot stove optimization (Tool 12, page 177)

The operation of the hot stoves used for preheating the blast in the blast furnace has a strong effect on the consumption of reductants, economic performance, and CO<sub>2</sub> emissions from the steelmaking site. Generally, it is recommended to maintain as high a blast temperature as possible, because this minimizes the rate of reductants in the blast furnace. Another economic use of BF gas is to use it in the power plant to produce electricity (and heat). The blast temperature is affected in a complex way by the time periods of heating and cooling of the stoves, and by the amount of gas combusted in the stoves. Furthermore, as the hot stoves show degraded performance with age, it is a non-trivial task to select optimal operation parameters for the stoves. The hot stove model addresses this computationally by applying a one-dimensional heat-transfer model of the hot stoves for optimization of the performance of the system. One example of usage is shown in Figure 11, where the model has been applied to optimize a cost function that considers the positive effect of a higher blast temperature on the coke rate in the blast furnace, but also the negative effect of burning BF gas in the stove set for electricity production in the power plant. The abscissa indicates the BF gas flow to the stoves “on gas” and the ordinate the duration of the “on blast” period. Contour plots show the objective function, constraints are depicted by red and green curves, and the best operation point of the stove set is shown by blue dots for different electricity prices.



**Figure 11.** Contours of the economic objective function versus gas flow rate and duration of the “on blast” period for three identical stoves for an electricity price of 30 €/MWh (top left), 40 €/MWh (top right), 50 €/MWh (bottom left), and 60 €/MWh (bottom right). The stove temperature and the pressure drop constraints are depicted by red and green dashed lines, respectively, and the optimal solution by the blue solid circle (Helle & Saxén 2016)

### **Hot metal desulphurization model (Tool 13, page 178)**

The objective of this work was to develop a mathematical model that can predict the desulphurization of hot metal based on available operating and technological parameters. The model is based on the assumption that desulphurization takes place simultaneously at the metal-reagent and metal-slag interfaces. In its current state, the model can be applied to injection of lime, calcium carbide, and soda, as well as to mixtures of these. The next step of the modeling work is to extend the model to desulphurization using industrial reagent mixtures. Thereafter, the model will be validated more exhaustively and coupled with a graphical user interface. In the future, the model will be employed for optimizing the reagent, as well as its injection practice, thus contributing to decreasing process variance and costs associated with reagent injection.

### **Optimization of coking blend and coke oven leakage detection**

#### **Optimization of coal blend (Tool 14, page 179 and Tool 15, page 180)**

The SSAB Raahe coking plant processes over one million tons of coal annually. The coal blend is typically mixed using 5 to 6 different coal qualities. These coal types have individual chemical and physical properties that are reflected in coke quality and coal blend behavior during the coking process. Based on these factors or properties, the coal blend calculation is used to achieve desirable chemical composition and physical properties of the coal blend, ensuring a fluent and sustainable coking process, targeted coke properties, and economical operation.

The project created a system that utilizes all available history data from the coking process, used coal blends, and produced coke analyses, enabling development of separate prediction models used in coal blend calculation. Individual effects of factors can be studied to support production planning. The main process factors, such as coking time and oven heating wall temperatures (set by the production rate) or pushing force levels during oven discharge, as well as the effect of seasonal high moisture, can now be used in the coal blend calculation. The changes required in the process settings to achieve new blend properties can also be calculated.

The new coal blend calculation system has created a solid platform for coal blend optimization that can be used to calculate optimum coal blend on the basis of available coal types, based on production rate, estimated blend process behavior, and quality outcome. Furthermore, the system enables the development of prediction models and supports future coke research. It is currently in use for coal blend behavior studies and monitoring purposes.

### **Coke oven leakage detection (Tool 16, page 181)**

The SSAB Raahe coking plant, with 70 coke ovens, has worked systematically in aiming for minimum coke oven door gas leakages, which mainly occur through slits between door seals and oven frames. A significant part of the emissions from the coking plant originates from these crude gas leakages, making leakage detection a high-priority issue under strict environmental controls that call for less than 10% of visible fugitive emissions to be from oven doors. Visual leakage inspection is executed daily, but no actual data is available on these non-captured emissions. An automatic system for leakage detection was needed to eliminate the inaccuracy caused by human subjectivity in making the estimates, to provide for more accurate and continuous leakage estimates, to improve safety, and also to reveal a need for oven door and frame maintenance.

The project aimed to create a basis for an automated machine vision system that is able to detect leakage areas on individual ovens, present online information for maintenance purposes, and generate leakage reports for environmental control. At the current stage of the ongoing project, SSAB and VTT are testing different solutions for imaging and machine vision application. Originally, thermal imaging was tested for leakage detection, but due to homogeneous temperature areas, the current detection and measurement algorithm is based on the visible light region. The system applies MATLAB algorithms and video imaging.

The coke oven leakage detection system provides a unique automated system, presenting information and actual data reports on crude gas leakages, and guides the need for maintenance of coke ovens. The system will also improve safety and working conditions at the coking batteries by minimizing gas leakages. A standardized coke oven leakage detection system can also enable a comparison of leakage levels at different coking plants.

### **Intelligent ferroalloy production process**

The main target was to integrate and simplify ferroalloy production process measurements and control applications so that these systems could truly and efficiently interact with each other, providing more process knowledge. The aim was to create an intelligent system platform that enables fast flow of information, serves the operators and the managers at the plant in the daily decision-making, gives a great user experience, and supports plant-wide expert system development. As the sintering and smelting technology itself was already mechanically rather mature, this digital integration was now seen as essential for optimized process conditions, improved process performance, high product quality, and sustainability.

### ACT platform (Tool 18, page 183)

During the project, several individual online measurements, like pellet size, profile scan, and a furnace lining monitoring system (FLMS), were rebuilt and set up on a common platform called ACT. ACT is Outotec's own intuitive, graphical, and modular development environment for advanced process control applications. ACT reads measurements, runs the logic, and writes set points. It is easy to use, it has a simple flowchart-based programming language, and it is compatible with any process measurement or control system.

A great achievement in the project was the upgrading of the green pellet size measurement system used for steel belt sintering (SBS). Outotec's Pellet Size measurement system is a highly precise machine vision-based process monitoring tool for online pellet size distribution. It enables more efficient pelletizing and sintering processes with consistent quality of pellets, and it has a positive influence on the availability and lifetime of the steel belt.

Outotec's new Pellet Size system was installed at Outokumpu Tornio Steel Works. The pellet size camera located in the front of the sintering furnace continuously takes pictures from the green pellet flow to the furnace. The average pellet size is calculated from the observed images by specifically designed algorithms. The results are presented graphically in a trend next to the live image. The histogram shows the pellet size distribution in different time frames: the last minute, the last hour, and the last eight hours. Previously, the Pellet Size system was only able to monitor the pellet size. After the ACT upgrade, the results can be shared easily up to the plant automation and information system levels, including a connection to an external network in the case of remote monitoring.

The latest development was the system extension to traveling grate pelletizing technology, typically used for iron ore pelletizing, with a production capacity roughly ten times bigger than in ferroalloy production. This was now possible because the new system was able not only to monitor the pellet size, but also to give control signals to pelletizing circuit equipment (material feed rate, pellet disc rotation speed, water additions, etc.) based on the observed pellet size via ACT. In this way, automatic control of pellet size distribution became feasible for the first time. The new Pellet Size system is considered to be an extremely promising product for the markets in the near future. The first pilot-scale tests were successfully made in 2015 at Outotec Research Center in Frankfurt. Now the first plant-scale trials are ongoing at a customer site in India.

## Company impact



“Close collaboration on the furnace lining monitoring system (FLMS) has presented the advantages and challenges related to almost all modern work in global set-ups. Cross-functional collaboration is easier than ever before, but it requires an open mind and resilience. Keeping your eyes and ears open can bring out new possibilities – an idea from elsewhere can work for you too.”

*Tapani Keronen, Product manager, Automation, Outotec (Finland) Oy*

### Ilmenite smelting in a pilot-scale DC furnace (Tool 19, page 184)

The electric arc furnace is used to upgrade ilmenite into a suitable titanium feedstock for pigment and sponge producers. During the process, iron oxides present in the ilmenite are reduced to metallic form with carbon as a reductant. A slag rich in  $\text{TiO}_2$  (and low in  $\text{FeO}$ ), together with pig iron, is a saleable product. A pilot-scale DC furnace test was successfully carried out at Outotec Research Center in Pori (Finland) in 2014. The aim was to develop DC technology further and to study energy-optimized smelting methods for ilmenite.

During the campaign, ilmenite concentrate and pre-reduced ilmenite (produced separately in a rotary kiln) were tested as feed materials. Good-quality slag and pig iron were produced. The furnace was easy to control. The carbon content in pig iron was found to be lower as pre-reduced ilmenite was used. The energy consumption of the smelting process was 27% lower for pre-reduced ilmenite than for raw ilmenite. The active power distribution between the open electric arc and the current flowing through the molten slag was found to be 85% to the arc and 15% to the slag.

An emission spectrometer, based on the elemental Ti and Fe peaks emitted from the plasma, provided good online prediction of slag  $\text{FeO}$  content. The suitability of the slowly cooled and granulated slag produced for both sulfate and chloride route pigment production was studied with XRD tests and sulfate leaching tests. In both cases, iron titanium oxide and anatase were identified as dominant phases. In the sulfate leaching tests, high yields of 90%  $\text{TiO}_2$  were obtained with both slags.

### Monitoring of ferrochrome tapping (Tool 20, page 185)

Submerged arc furnaces (SAF) are used to produce ferrochrome at Outokumpu Chrome Oy, Tornio. The furnaces are tapped every 2.5 hours, with one tapping taking from about 20 to 40 minutes. Tappings need to be closely monitored for safety and maintenance reasons, but observations are also important for efficient furnace control. Because of the outside location and extreme heat radiation, with smoke and fumes from the

melt, visual observation through visors is challenging. A clear image of the melt is not achievable using traditional monitoring camera technology, which can be seen in Figure 12 (left).

Sapotech is an SME offering smart and cost-efficient solutions for online monitoring and quality assessment of high-temperature processes for the metallurgical industries. During the project, Sapotech's Reveal TAP system for monitoring ferrochrome tapping was successfully conducted at FeCr smelter no. 3, followed by a pilot for further testing of the system. The Reveal TAP platform combines high-definition cameras, advanced software, and the Internet of Things. The system is able to produce highly detailed images of the melt surface with very little interference from smoke and fumes, as can be seen in Figure 12 (right).



**Figure 12. An image of FeCr tapping from a traditional monitoring camera (left) and from Sapotech's Reveal TAP system (right)**

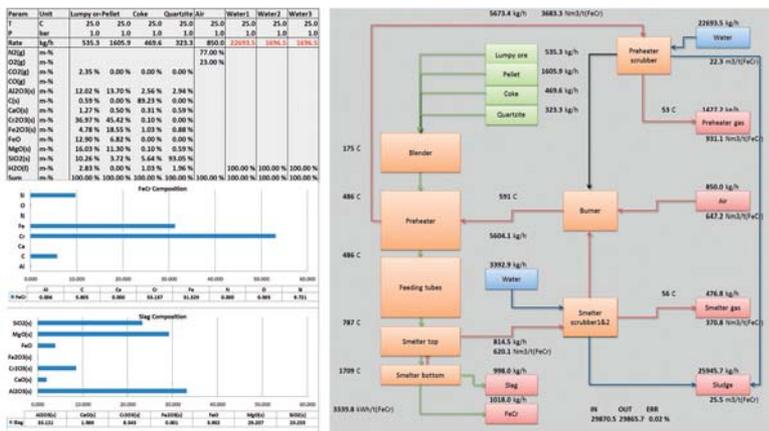
A clear image makes it possible to easily differentiate metal from slag and to detect detailed phenomena at the melt surface (e.g., flow patterns and bubbles) that are important for safe and efficient operation. This makes training of new operators easier, as the details are visible from the first day on. In addition, as all tapping videos are stored, it is possible afterwards to study rare events and show them to personnel. The most important benefit of a detailed image is better avoidance of metal ending in slag granulation, which would imply lost product and would also involve a risk of steam explosion.

### [Crom – Simulation tool for high-temperature reactors \(Tool 22, page187\)](#)

The developed tool is a general simulator platform using multi-phase multi-component chemistry for processes with high-temperature reactors and particulate material flows. It combines the thermodynamic equilibrium and particle kinetics to calculate the local state of the material

flows. The tool can be used for the calculation of mass and energy balances, as well as for raw material and energy optimization. It can be used to predict the behavior of minor elements like heavy metals (distributions between phases, condensation, vaporization, emissions, effluents, etc.). It helps to increase the theoretical and practical knowledge of the processes and their fundamental phenomena, yielding optimized process conditions and superior product quality.

In this work, the tool has been applied to the Outokumpu Tornio ferrochrome process. An offline simulation model was made for the submerged arc furnace for the production of liquid ferrochromium. The flowsheet of this model involves several unit operations, and it was validated using industrial data provided by Outokumpu Tornio (see Figure 13).



**Figure 13. Flowsheet and example results of the VKU2 furnace process at Tornio Outokumpu**

Additionally, a dynamic model of the SAF process was implemented and combined with the Crom simulator (including dynamic versions of the feed bin, preheater, feeding tubes, and submerged arc furnace). Many problematic conditions in the operation of submerged arc furnaces are related to time-dependent behavior. The dynamic SAF model can provide valuable information about the process operations that cannot be provided by a steady state model. It is a great tool for simulating different kinds of scenarios and procedures that cannot be tested in the real furnace without a risk of unnecessary operational disturbances.

### Introduction of cement-bonded briquettes to SAF

Large amounts of dust and scale are formed in the Outokumpu Stainless and Outokumpu Chrome production lines at the Tornio works. These by-products contain valuable metals such as iron and chromium that could

be utilized in steel production, but this is prevented by the fine size of the by-products, which are mainly dusts. In this research, these steelmaking by-products were agglomerated in an effort to produce new raw materials for ferrochrome production in the SAF process. Rapid Portland cement was used as a binder for the produced agglomerates.

Briquettes from two recipes containing raw materials from stainless steel and ferrochrome production plants were produced at the University of Oulu. The compression strength tests showed high enough values for the laboratory-manufactured briquettes. The next step is to produce a set of briquettes on production scale and test them in the laboratory, followed by a production-scale test with briquettes at the Tornio Works in 2017.

### Next steps

It is extremely important for the metal industry that fruitful collaboration between enterprises and academia continues and gives the possibility for the industry to grow and develop.

### Industry impact

"... The Finnish metal industry has been active in taking the next step after the SIMP program. The work has been coordinated by the Association of Finnish Steel and Metal Producers. A national R&D program entitled Metal Ecosystem (MECO) has been initiated and consists of three different packages, including FLEX (Flexible and Adaptive Unit Operations in Metal Production). It is granted by TEKES for one year and directed at cost-efficient and disturbance-free metals production. FLEX is a direct continuum of SIMP and the idea is to develop and refine ideas started in SIMP, together with universities and SMEs..."

Another initiative is a Horizon 2020 SPIRE 07 call, which is an innovation action concentrating on an integrated approach to process optimization for raw material resource efficiency. SSAB, Outokumpu, and VTT have formed a European consortium and have made a proposal entitled Model-based Optimization for efficient use of Resources and Energy (MORSE).

Research on further improvements to blast furnace control using new measurements from blast furnace off-gases and dust will be started in July 2017 in an RFCS project DuMiCo (dust minimization and control at the blast furnace). Partners in this project include all the main steel producers and research institutes, including SSAB, LKAB, Swerea MEFOS, thyssenkrupp AG, Tata Steel Ltd., ArcelorMittal SA, Salzgitter AG, BFI-Betriebsforschungsinstitut GmbH, and RWTH Aachen University.

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**Further  
information****KEY PUBLICATIONS:**

Iljana, M., Kemppainen, A., Paananen, T., Mattila, O., Heikkinen E-P. & Fabritius, T. 2016. Evaluating the Reduction-Softening Behaviour of Blast Furnace Burden with an Advanced Test. *ISIJ International* 56, 1705–1714.

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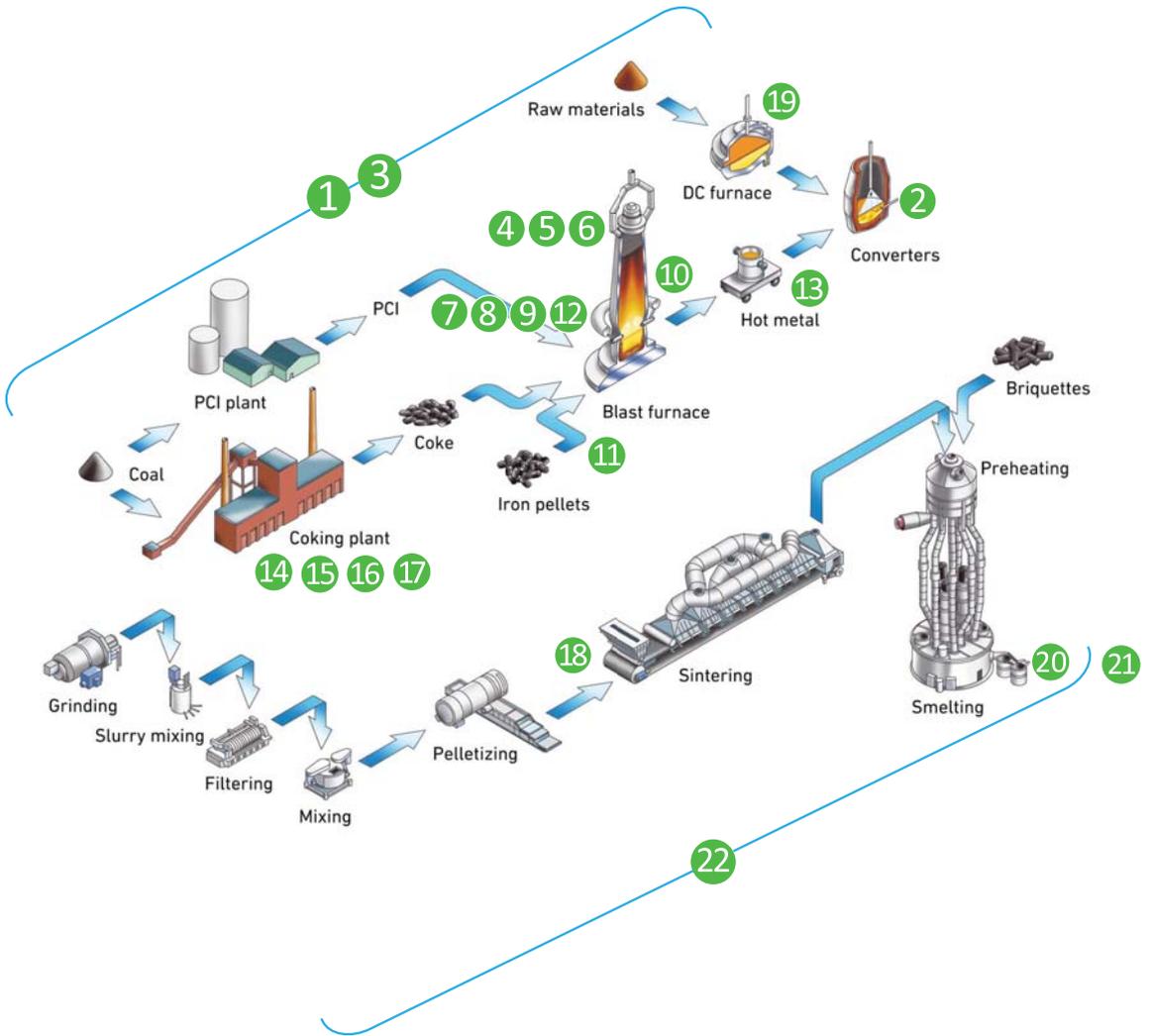
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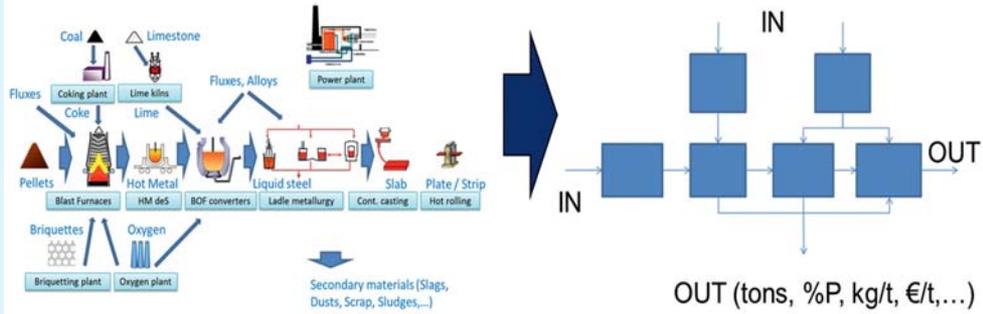


**Figure 14. The numbered bullets in the process scheme represent the tools developed in Showcase 3. The tools are described in the following pages**

1

PROCESS INTEGRATION TOOL FOR OPTIMIZATION OF STEEL WORKS PROCESSES

SHOWCASE 3



Description of the tool

The tool is developed for cost optimization of the production system, including material and energy costs at SSAB Raahe Steel Works. In addition to optimizing material selection regarding costs, the model can be used for calculating a number of key parameters of the process (recycling rates, energy consumption, behavior of impurities, CO<sub>2</sub> emissions etc.)

Application

The model works offline and input data sets are prepared manually. Production data has been utilized to find the distribution of elements in different phases, in addition to the distribution of outputs to the next processing steps. The model was validated for certain steel grades on the basis of production data. The accuracy of the model is highly dependent on the accuracy of material analysis.

Technologies

The optimizing tool is built into an existing ASP platform called SWD-PES, developed by SW-Development Oy. The model is modular and new sub-modules are easy to add. The material balance of the converter process has been developed by the Control Engineering Research Unit at the University of Oulu, using linear multivariate regression analysis in Matlab.

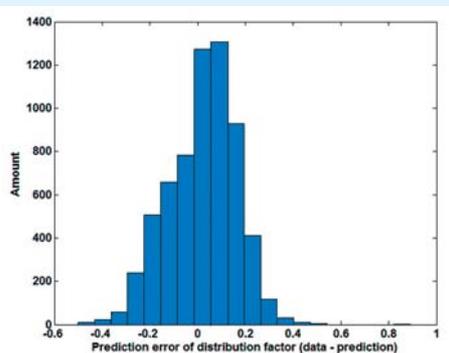
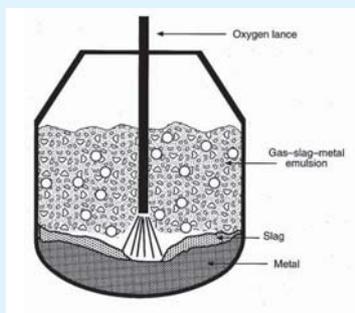
Scope of application

The model can be used for raw material selection, assessment of the effect of raw material composition on costs, investment calculations, changing the method of operations, estimating CO<sub>2</sub> emissions, changing of secondary flows, and so on. The modeling principle can be applied to any other metal producing process.

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## SHOWCASE 3



### Description of the tool

The aim is to predict the amounts of chemical components in steel and slag in the basic oxygen furnace (BOF). The most important chemical components are iron (Fe), carbon (C), manganese (Mn), and sulfur (S).

### Application

The modeling was done for SSAB Raabe's steel converters. A vast amount of industrial process data (over 30,000 heats) was used for model development and validation. The offline model obtained can be used for predicting the chemical compositions of steel and slag.

### Technologies

Multivariate linear regression was used as the modeling method. All the computations were carried out in the Matlab environment.

### Scope of application

Similar technology can be utilized in any industrial process.

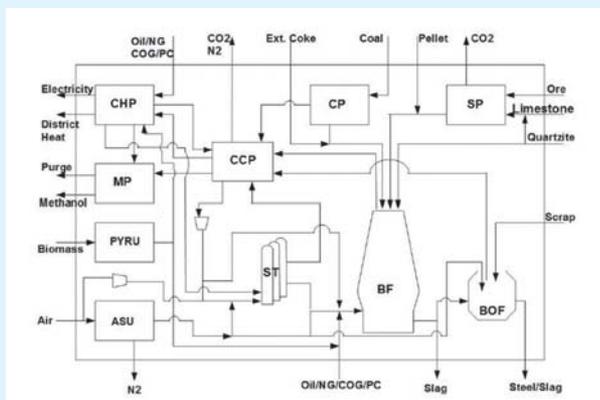
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#### Additional Information/ Publications

Sorsa, A., Ruuska, J., Lilja, J. & Leiviskä, K. 2015. Data-driven multivariate analysis of basic oxygen furnace used in steel industry. IFAC-PapersOnLine, 28(17), pp. 177–182.  
Dvorak, J. 2016. Combining data-driven and mechanistic modelling approaches for a basic oxygen furnace process. M.Sc. thesis. University of Chemistry and Technology Prague, Process Engineering and Informatics. Prague. 107 pp.  
Vuolio, T. 2015. Mittausaineiston monimuuttuja-analyysimenetelmät ja niiden soveltaminen teräskonvertteriaiaineistoon. B.Sc. thesis. University of Oulu, Process Engineering. Oulu. 29 pp.

## SHOWCASE 3



### Description of the tool

A tool for the optimal design of a treatment plant for process gases from a future steel plant has been designed. The tool is based on a structural optimization of an entity for CO<sub>2</sub> separation and methanol synthesis, with optional process units. The steel plant may act as a conventional plant or may have a blast furnace with top gas recycling, operating under different modes (low, medium, or high oxygen enrichment of the blast; low, medium, or high recycling of the top gas; different types and injection rates of auxiliary fuels, etc.).

### Application

The tool is developed to give indications of the future potential to reduce emissions in steelmaking, while keeping the steelmaking operations profitable.

### Technologies

The models of the unit processes are programmed in GAMS, and the process design problem is expressed as a General Disjunctive Programming task, solved as a mixed integer nonlinear programming (MINLP) problem.

### Scope of application

The tool can be used for scenario analyses of emerging or future steel plant concepts.

#### Contact person – Inventor

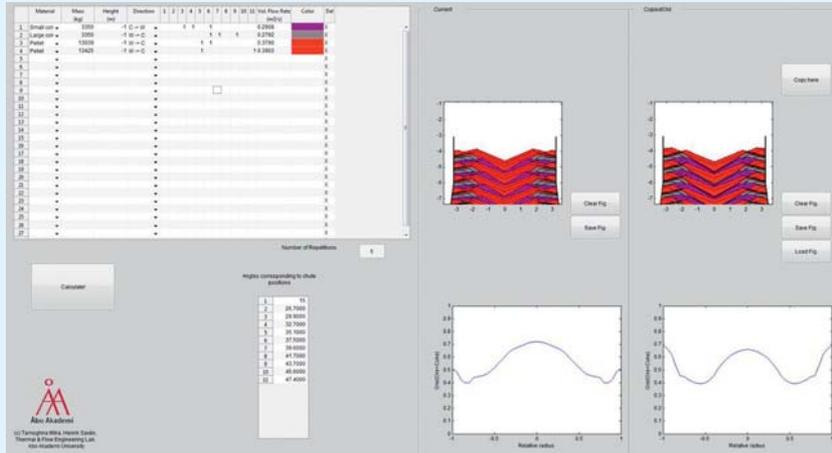
Henrik Saxén, hsaxen@abo.fi, +358 40 544 3301, Åbo Akademi University

#### Additional Information/ Publications

Ghanbari, H., Petterson, F. & Saxén, H. 2015. Sustainable development of primary steelmaking under novel blast furnace operation and injection of different reducing agents. *Chemical Engineering Science* 129, 208–222.

Ghanbari, H. 2014. Sustainable Steelmaking by Process Integration. Ph.D. thesis. Åbo Akademi University, Thermal and Flow Engineering Laboratory. Turku. 66 pp.

SHOWCASE 3



Description of the tool

The tool is intended for the design of burden distribution in a blast furnace, using a bell-less rotating chute (PW) charging system. Since burden distribution is one of the primary ways of controlling the BF, but the formation and descent of the layers are complex, the tool acts as the main decision aid for plant engineers and operators. Using the tool, the general behavior of rings charged on the burden surface can be understood, and the effect of control actions on burden distribution can be studied in a few seconds of computational time.

Application

The tool was verified by small-scale experiments in a pilot charging model. The tool can be used to learn about the general principles of layer formation in the blast furnace shaft, and for more sophisticated purposes, such as in the design of new charging programs and for “what if” studies, where the outcome of shifting one or several rings of burden radially is analyzed.

Technologies

The tool has been realized in Matlab and has been equipped with a graphical user interface.

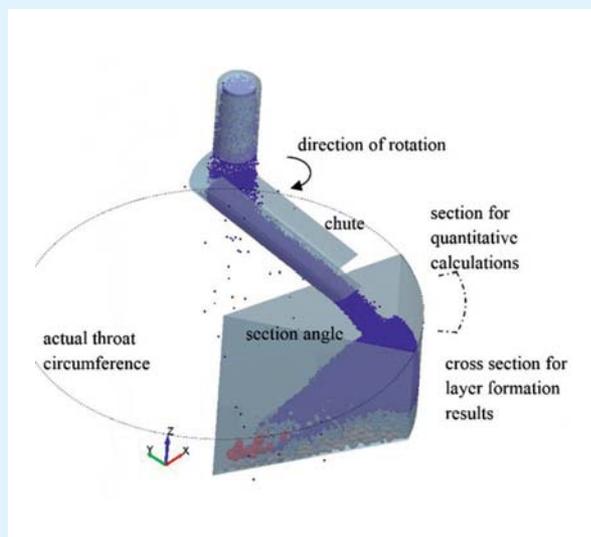
Scope of application

The tool is quite specific to blast furnace burden distribution because of the special type of chute feeding applied in the process. The burden descent model incorporated in the tool applies to shaft-like processes where the shaft diameter changes with height.

**Contact person – Inventor** Henrik Saxén, hsaxen@abo.fi, +358 40 544 3301, Åbo Akademi University

**Additional Information/ Publications** Mitra, T. & Saxén, H. 2014. A model for fast evaluation of charging programs in the blast furnace. Metallurgical and Materials Transactions 45B, 2382–2394.

## SHOWCASE 3



### Description of the tool

The tool is based on DEM and simulates the charging of a limited number of rings of burden that fall within a slice-shaped domain. The burden descent is not modeled, but only the layer formation process, where different materials (coke, pellets, briquettes, etc.) are charged in sequence, and the arising rings are controlled radially by setting the chute angles. 3D views and cross-sectional views of the arising bed layers help to understand how the layers form and how a new dump affects the burden surface and possibly how the particles percolate into the lower layers.

### Application

The tool is developed to give detailed insight into phenomena during charging. It has been applied to study charging patterns relevant to the SSAB Raahe blast furnaces with pellet burden.

### Technologies

The tool has been implemented in EDEM.

### Scope of application

The tool can be used with slight modifications to study the piling of particulate matter in any other industrial process.

**Contact person – Inventor** Henrik Saxén, hsaxen@abo.fi, +358 40 544 3301, Åbo Akademi University

### Additional Information/ Publications

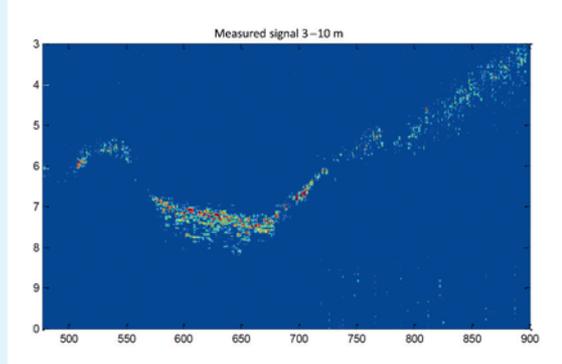
Mitra, T. & Saxén, H. 2016. Discrete element simulation of charging and mixed layer formation in the ironmaking blast furnace. *Journal of Computational Particle Mechanics* 3, 541–555.

Mitra, T. 2016. Modeling of burden distribution in the blast furnace. Ph.D. thesis, Åbo Akademi University, Thermal and Flow Engineering Laboratory. Turku. 75 pp.

## 6

## BF BURDEN SURFACE MEASUREMENT

### SHOWCASE 3



### Description of the tool

Blast furnace burden surface measurement is crucial for optimal BF burden distribution control. Current radar systems suffer from a harsh process environment, producing lagged and noisy signals in a single point, thus preventing optimal burden control. To overcome the burden measurement problem in a dusty environment, frequency-modulated continuous-wave (FMCW) signals were tested in a material silo environment. The FMCW radar system was selected for blast furnace testing through the inspection hatch on the BF top. This signal is able to detect the burden material surface at long distances in a very dusty environment.

Measurements were made in real process conditions during the BF process start-up phase, which applies a high material feed rate leading to the highest possible dust liberation rate in the gas phase.

### Application

Measurements were made in real process conditions during the BF process start-up phase, which applies a high material feed rate leading to the highest possible dust liberation rate in the gas phase.

### Technologies

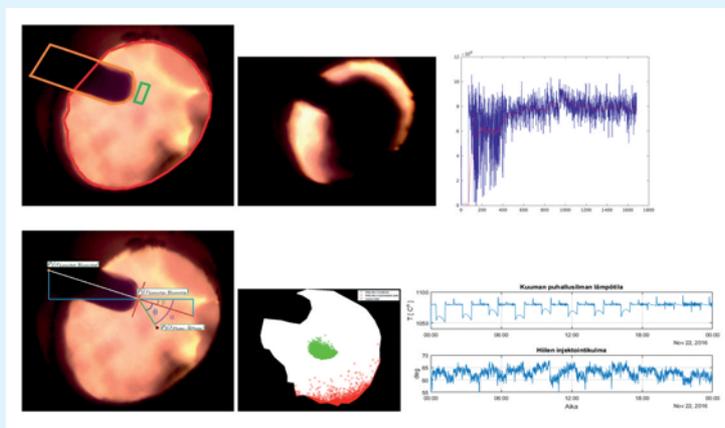
The FMCW signal was produced and measured using a Siversima RS3400K/00 24 GHz FMCW Transceiver Evaluation Kit, which is more familiar in aeronautic measurement environments.

### Scope of application

The ability of the FMCW radar system to produce the required signal was tested. The signal can be arranged to produce an online 3D image of the BF burden surface. To protect the measurement head from the harsh environment prevailing inside the BF, the scanning radar system, with a limited number of measurement heads, seems to be the only viable option.

**Contact persons – Inventors** Olli Mattila, olli.mattila@ssab.com, +358 20 593 8709, SSAB Europe Oy; Pasi Laakkonen, pasi.laakkonen@rocsole.com, +358 40 147 8797, Rocsole Ltd

## SHOWCASE 3



### Description of the tool

Tuyère cameras were installed primarily to monitor the flow of pulverized coal (PC) in the process, the location of PC flow in relation to the tuyère, and scaffold formation on the tuyère surfaces, in addition to monitoring the start-up and shut-down phases of the blast furnace process.

### Application

The mixing conditions between the blast and PC can be detected in the tuyère images. This is associated directly with the burning capability of the auxiliary fuel. Boundary detection with suitable masks gives information about mixing conditions, as well as injection stability. The developed coal plume injection angle detection revealed the influence of an unstable blast temperature on the injection angle, and thus the possibility of scaffold formation.

### Technologies

Image analysis was made in Matlab using the Image Processing toolbox. Data obtained from image analysis is automatically stored for further investigation. At the moment, the tool is working offline to detect injection phenomena using calculation-intensive routines.

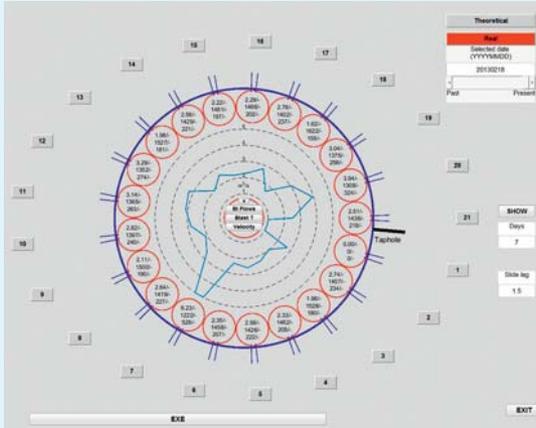
### Scope of application

Image analysis can provide valuable information about the primary injection process. Adding the historical perspective to image analysis, the injection conditions and the process parameters affecting injection conditions can be optimized. Further development of image thermal information can bring about better insight into the internal state and operation of the BF.

**Contact person – Inventor** Olli Mattila, olli.mattila@ssab.com, +358 20 593 8709, SSAB Europe Oy

**Additional Information/  
Publications** Vares, S. 2017. Masuunin hormin ilmiöiden kuvantaminen ja mittaus. M.Sc. thesis, University of Oulu, Electrical Engineering, Oulu. 91 pp.

## SHOWCASE 3



### Description of the tool

The tool builds on a simplified simulation model of gas distribution to individual tuyères from the bustle main under different injection patterns. In online mode, the differential pressure over the tuyère necks is used to estimate the local blast flow rates and the flow resistance of the bird's nest/bosh coke bed above each tuyère. This gives an interpretation of flow maldistribution, and the tool can next be used to study, for example, how to distribute the blast more uniformly. The offline model is based on idealized conditions and can be used for "what if" analysis.

### Application

The tool was further developed to consider PCI instead of oil injection, and was applied in the SSAB BF's in Raahé. With the aid of the tool, the combustion conditions of PCI particles in each tuyère can be monitored. The model can also estimate the burning rate of coke in an individual tuyère, which affects the descent rate of the burden in the shaft.

### Technologies

The tool has been implemented in Matlab.

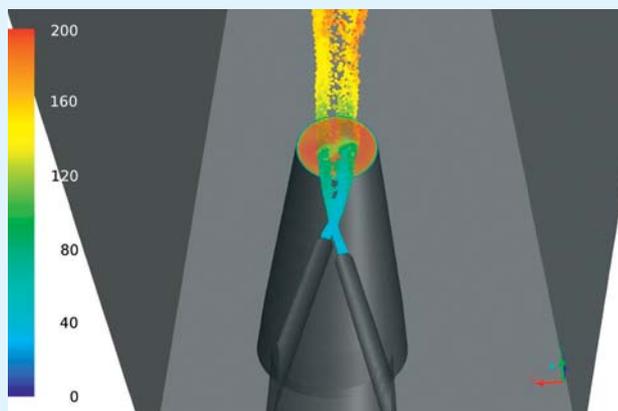
### Scope of application

The tool is applicable to furnaces with tuyère-like feeding of the combustion air.

**Contact person – Inventor** Henrik Saxén, hsaxen@abo.fi, +358 40 544 3301, Åbo Akademi University

**Additional Information/ Publications** Damén, C. 2015. Measuring and modeling of the tuyere-raceway system in the SSAB Raahé blast furnaces. M.Sc. thesis. Åbo Akademi University, Thermal and Flow Engineering Laboratory. Turku. 65 pp.

## SHOWCASE 3



### Description of the tool

Computational fluid dynamics (CFD) are used to create a tuyère-raceway combustion model for pulverized coal in the blast furnace. The tool can be applied to the design of new double-lance injection methods for pulverized coal. Its results can be used to aid decision-making in the new injection system. Improved combustion of pulverized coal in the blast furnace means that higher levels of auxiliary fuel can be used to replace coke, which lowers the costs of ironmaking.

### Application

The combustion model was created based on an experimental rig at BHP Billiton-BlueScope Steel. Results from the modeling were compared with the experimental results, and the model predicted the degree of combustion with good accuracy. Three different types of coal were modeled with different injection rates. The model works well for medium and highly volatile coal, and can be used to predict the combustion conditions in the blast furnace tuyère-raceway area.

### Technologies

The CFD model was created with Ansys Fluent, but to solve the combustion chemistry CHEMKIN solver is used.

### Scope of application

The combustion model can be applied in coal combustion of different kinds. For example, it could be used to model coal injection and combustion in an electric arc furnace.

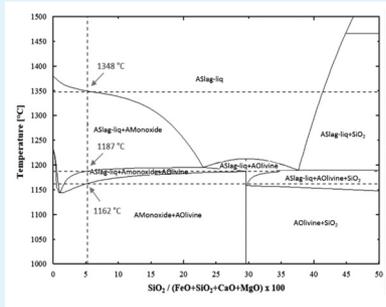
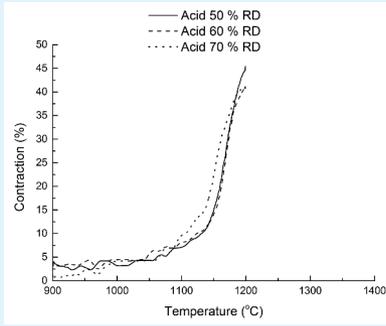
#### Contact persons – Inventors

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Olli Mattila, olli.mattila@ssab.com, +358 20 593 8709, SSAB Europe Oy

#### Additional Information/ Publications

Vuokila, A., Mattila, O., Keiski, R. & Muurinen E. 2016. CFD modelling of pulverized coal combustion in blast furnace test rig. *Industrial Combustion*, Article Number 201603, <http://www.ifrf.net/page/online-journal>.

SHOWCASE 3



Description of the tool

The estimation tool for BF burden softening can be used to estimate the softening temperatures of different ferrous burden materials and also to find optimal burden compositions. The developed tool is based on a number of laboratory trials and thermodynamic calculations made with FactSage and its FToxid database. The FeO-SiO<sub>2</sub>-CaO-MgO-Al<sub>2</sub>O<sub>3</sub> system of the burden material is used as an input value for the tool, with assumptions on the state of the burden in the conditions of the BF cohesive zone.

Application

The tool was validated by industrial Advanced Reduction Under Load (ARUL) tests at the SSAB Raabe Steel Works and a laboratory-scale Cohesive Zone Simulator (CZS) in Kyushu University. The tool has been applied in the selection of new ferrous BF burden materials.

Technologies

The following technologies were utilized in the development of the tool: FactSage v. 7.0 software for thermodynamic calculations, custom-made laboratory furnaces with gas and temperature controls, mass balance and sample shrinkage measurements for laboratory trials, and optical and electronic microscopes as analytical tools.

The model is used for the optimal selection of burden materials with desired softening and melting properties. It could also be applied to other iron and steelmaking processes with various materials and conditions.

**Scope of application** The model is used for the optimal selection of burden materials with desired softening and melting properties. It could also be applied to other iron and steelmaking processes with various materials and conditions.

Contact persons – Inventors

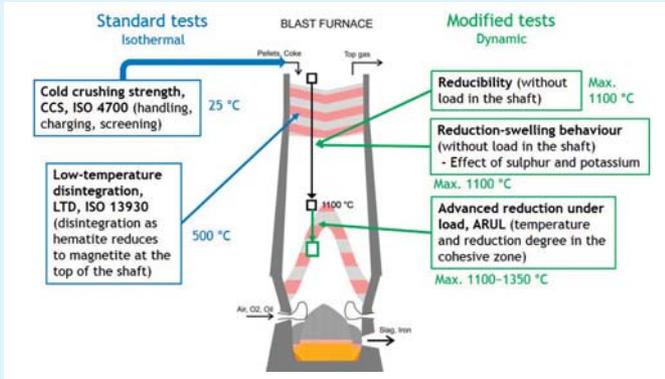
Antti Kemppainen, antti.kemppainen@oulu.fi, +358 50 350 3968, University of Oulu;  
 Mikko Iljana, mikko.iljana @oulu.fi, +358 50 576 0711, University of Oulu;  
 Eetu-Pekka Heikkinen, eetu.heikkinen@oulu.fi, +358 50 350 2488, University of Oulu

Additional Information/ Publications

Kemppainen, A., Ohno, K-i., Iljana, M., Mattila, O., Paananen, T., Heikkinen, E-P, Maeda, T., Kunitomo, K. & Fabritius, T. 2015. Softening behaviors of acid and olivine fluxed iron ore pellets in the cohesive zone of a blast furnace. ISIJ International 55, 2039–2046.  
 Iljana, M., Kemppainen, A., Paananen, T., Mattila, O., Heikkinen E-P & Fabritius, T. 2016. Evaluating the Reduction-Softening Behaviour of Blast Furnace Burden with an Advanced Test. ISIJ International 56, 1705–1714.  
 Heikkinen, E-P, Kemppainen, A., Iljana, M., Mattila, O., Paananen, T., Ohno, K-i., Kunitomo, K., Maeda, T. & Fabritius, T. 2016. Estimation of softening behavior of BF burden materials using computational phase diagrams for multicomponent systems. In: CALPHAD XLV, Awaji Yumebutai, Japan, 29.5–3.6.2016.

11 R&D TOOL TO IMPROVE BF IRON BURDEN MATERIAL PROPERTIES

SHOWCASE 3



Description of the tool

The intended use of the method is to provide a set of tests to characterize the main metallurgical properties of iron burden materials for blast furnace use. Burden material tests are used to select and develop materials and to understand the material behavior in the BF process.

Application

The method contains metallurgical tests to determine the most important properties of BF pellets, including cold crushing strength, low-temperature disintegration, reducibility, reduction-swelling behavior, and softening behavior.

Technologies

The following technologies are included in the method: metallurgical tests to determine the material behavior under simulated process conditions, optical and electronic microscopes as analytical tools, and FactSage v. 7.0 to estimate the effect of chemical composition on material softening.

Scope of application

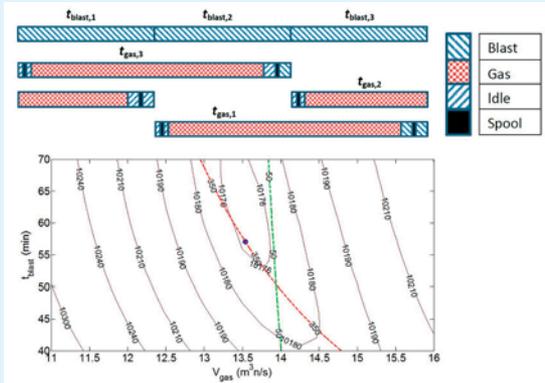
The tool has been used at SSAB Raahe to improve the behavior of blast furnace pellets. It could also be adapted to the SAF process.

**Contact persons – Inventors** Mikko Iljana, mikko.iljana@oulu.fi, +358 50 576 0711, University of Oulu; Antti Kempainen, antti.kempainen@oulu.fi, +358 50 350 3968, University of Oulu; Timo Paananen, timo.paananen@ssab.com, +358 20 592 1669, SSAB Europe Oy; Olli Mattila, olli.mattila@ssab.com, +358 20 593 8709, SSAB Europe Oy

**Additional Information/ Publications** Iljana, M., Kempainen, A., Paananen, T., Mattila, O., Pisiä, E., Kondrakov, M. & Fabritius, T. 2015. Effect of Adding Limestone on the Metallurgical Properties of Iron Ore Pellets. International Journal of Mineral Processing 141, 34–43.  
Kempainen, A., Iljana, M., Heikkinen, E-P., Paananen, T., Mattila, O. & Fabritius, T. 2016. Recent development in the evaluation of the high temperature properties of iron ore pellets. In: SCANMET V, Luleå, Sweden, 12–15.6.2016.

# 12 HOT STOVE OPTIMIZATION MODEL

SHOWCASE 3



### Description of the tool

The simulation model of the hot stove set and the optimization tool built on the model are developed to shed light on how the performance of the hot stove set is affected by the choice of parameters, such as the duration of the periods (see top panel of figure) and the BF gas flow rate to the stoves. An optimal choice of these factors reduces costs and lowers the fuel rate in the blast furnace. By using the tool, the optimal control variables can be determined under different costs and constraints.

### Application

The tool can be used for setting the time periods of or the gas flow rates to the stove set. By tuning the parameters, the simulation model can be adapted to mimic the true operation of the stove set, where usually at least one stove shows worse performance due to degradation and/or clogging of the checkerworks.

### Technologies

The tool has been realized in Matlab, where efficient methods for solving nonlinear constrained optimization problems are available.

### Scope of application

The tool is specific to a set of regenerative heat exchangers.

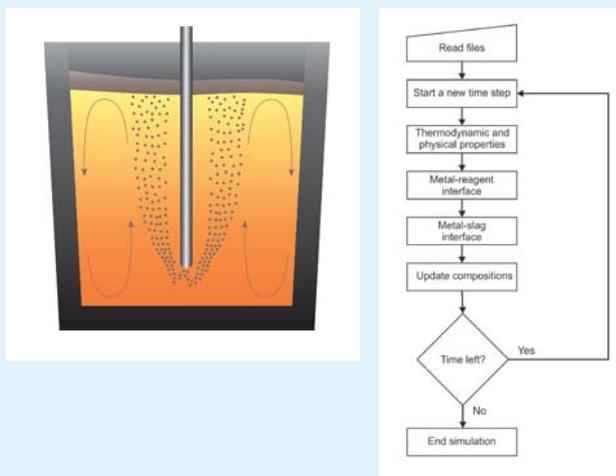
**Contact person  
– Inventor**

Henrik Saxén, hsaxen@abo.fi, +358 40 544 3301, Åbo Akademi University

**Additional Information/  
Publications**

Helle, M. & Saxén, H. 2016. Simulation and optimization of hot stoves in a steel plant. Proceedings of SCANMET V, Luleå, Sweden.

## SHOWCASE 3



### Description of the tool

The objective of this work was to develop a mathematical model that can predict the desulphurization of hot metal based on available operating and technological parameters. The model is based on the assumption that desulphurization takes place simultaneously at the metal-reagent and metal-slag interfaces.

### Application

In its current state, the model can be applied to the injection of lime, calcium carbide, and soda, as well as their mixtures. The next step of the modeling work is to extend the model to desulphurization using industrial reagent mixtures. Thereafter, the model will be validated more exhaustively and coupled with a graphical user interface.

### Technologies

The simulator is based on a thermodynamic-kinetic description of the main phenomena in the hot metal desulphurization process. The simulator is executed in C++.

### Scope of application

The modeling approach shares similarities with previously developed sub-models for the AOD and CAS-OB processes.

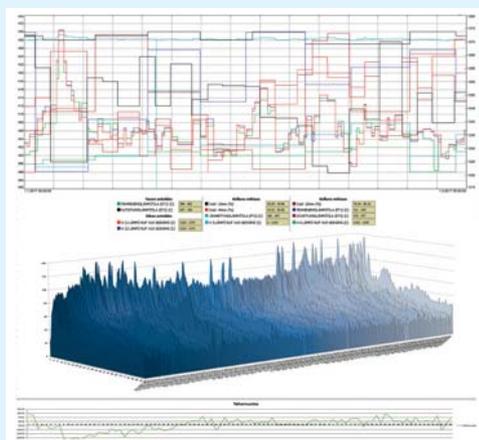
#### Contact persons – Inventors

Ville-Valtteri Visuri, ville-valtteri.visuri@oulu.fi, +358 50 350 7611, University of Oulu;  
Petri Sulasalmi, petri.sulasalmi@oulu.fi, +358 50 350 7027, University of Oulu

#### Additional Information/ Publications

Vuolio, T. 2017. Improvement potential of primary hot metal desulphurization. Master's thesis. University of Oulu, Process Metallurgy. Oulu. 162 pp.

## SHOWCASE 3



### Description of the tool

The SSAB Raabe coking plant processes more than one million tons of coal annually. Coal blend calculation is used to achieve a desirable chemical composition of coal qualities, physical properties such as dilation and fluidity, and volatile and ash contents of the coal blend, ensuring a fluent and sustainable coking process, targeted coke properties, and economical operation.

The project created a system that utilizes all available history data from the coking process, used coal blends, and produced coke analyses, and enables the development and study of separate prediction models. Individual effects of factors can be studied to support production planning.

### Application

The tool is based on an online connection to the coking plant automation system and production management system (laboratory), collecting the required data. The tool uses an interface to existing data sources, its own database, calculations, and a client-based UID.

### Technologies

The main utilized technologies are OPC and ODBC-based communication for data collection, an MS SQL Server database, a Savcor Wedge process analysis system, and MS Visual studio C# codes.

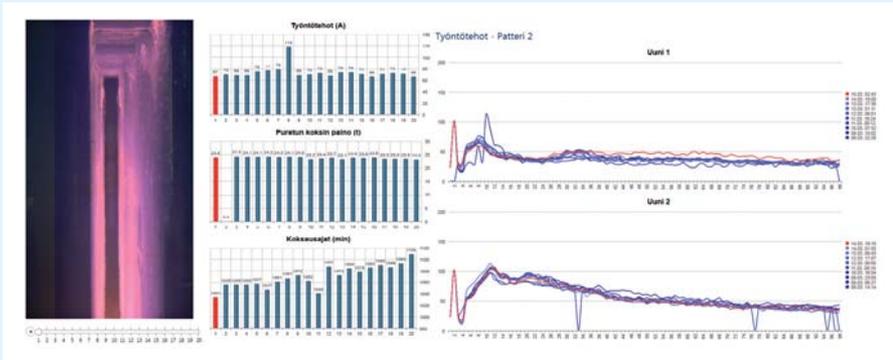
### Scope of application

The tool is partly in use in coal blend behavior studies and monitoring.

**Contact person** – Inventor    Jukka Pelttari, jukka.pelttari@ssab.com, + 358 20 592 3159, SSAB Europe Oy

15 COKE OVEN MONITORING SYSTEM

SHOWCASE 3



Description of the tool

The SSAB Raabe coking plant has the world's oldest PVR 7 meter batteries. A guarantee of the ongoing long campaign life is a well-managed process that ensures minimal mechanical stress in the coke ovens.

The project created a system that helps to avoid high forces in the coke oven by monitoring the levels of the main factors affecting the ovens, and especially changes in them. Dynamic listings are presented to the operators, showing identified risks and changes around the main factors in individual ovens. Conditions for alarms were defined for the tool. The main value for the customer is an extended coke oven campaign life and more efficient coke production.

Application

The tool is based on an online connection to the coking plant automation system, collecting the required data for monitoring. It uses its own database, analyses or calculations, and a web-based UID.

Technologies

The main utilized technologies are OPC and ODBC-based communication for data collection, an MS SQL Server database, MS Visual studio C# codes, and a JJS7 webserver. The alarm system uses email and SMS service providers.

Scope of application

The tool is used in decision-making and supports oven stress control.

Contact person – Inventor Jukka Pelttari, jukka.pelttari@ssab.com, + 358 20 592 3159, SSAB Europe Oy

## SHOWCASE 3



### Description of the tool

The SSAB Raabe coking plant has worked systematically, aiming for minimum coke oven door leakages. A significant part of the emissions from the coking plant originates from these raw gas leakages, making leakage detection a high priority issue under strict environmental control.

The project created a basis for an automated machine vision system that detects leakages areas in individual ovens, presents online information for maintenance purposes, and creates leakage reports for environmental control. At the current stage of the project, SSAB and VTT are testing different solutions for imaging and machine vision application.

### Application

The tool is based on imaging technology, a machine vision algorithm, and an online connection to the coking plant automation system. The tool uses its own database and a web-based UID.

### Technologies

The main utilized technologies are OPC and ODBC-based communication for data collection, an MS SQL Server database, MS Visual studio C# codes, and a JJS7 webserver.

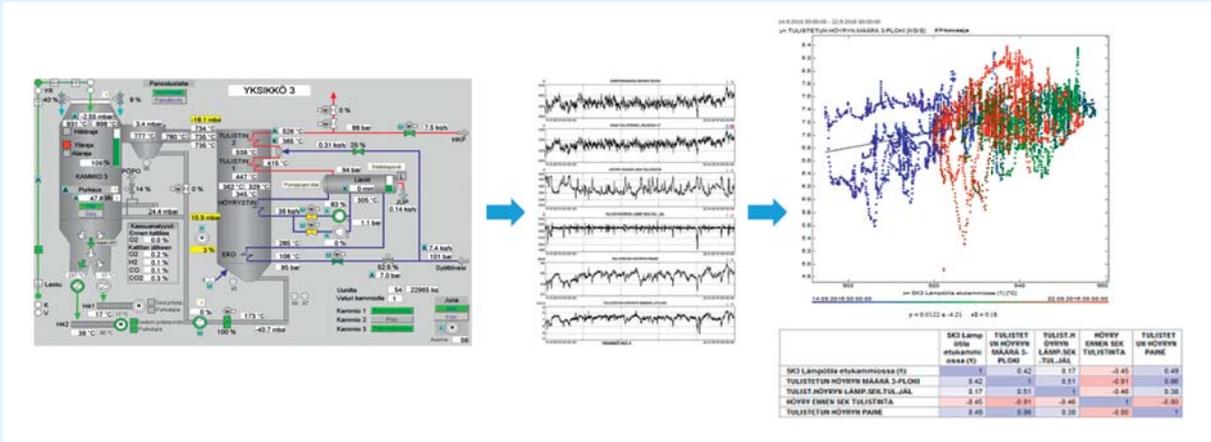
### Scope of application

The tool can be used to detect leakages in various environments.

**Contact person** – Inventor Jukka Pelttari, jukka.pelttari@ssab.com, + 358 20 592 3159, SSAB Europe Oy

# 17 COKE DRY-QUENCHING MONITORING SYSTEM

SHOWCASE 3



## Description of the tool

At the SSAB Raahe coke ovens, coke is primarily quenched by dry quenching, CDQ. The CDQ plant has three quenching units that should have uniform quenching capacity, but this has not been the case. The difference between the units' quenching performance has been up to 10%. By reaching optimal performance for each unit, the amount of required wet quenching, and therefore also energy loss, can be minimized.

The project's target was to create a system that monitors each quenching unit's main performance-related factors and supports process optimization by revealing deviations and correlations. The main factors are coke charge distribution and surface leveling, circulation gas distribution and temperatures, boiler units, discharging equipment and sector feathers control, and discharged coke mass temperatures.

## Application

The tool is based on an online connection to the CDQ plant automation system, collecting the required data for monitoring. It uses its own database, analyses or calculations, and a client-based UID.

## Technologies

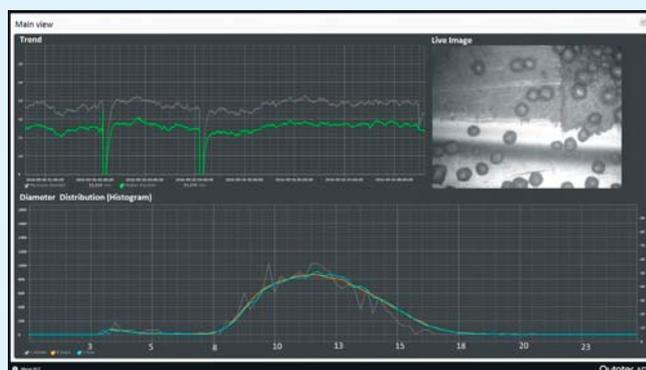
The main utilized technologies are OPC and ODBC-based communication for data collection, an MS SQL Server database, a Savcor Wedge process analysis system, and MS Visual studio C# codes.

## Scope of application

The tool is under commissioning.

**Contact person – Inventor** Jukka Pelttari, jukka.pelttari@ssab.com, + 358 20 592 3159, SSAB Europe Oy

## SHOWCASE 3



### Description of the tool

Outotec's ACT platform can be used to integrate and simplify any process measurements and control applications. The intelligent platform enables the fast flow of information, and serves operators and managers at the plant in daily decision-making, with a great user experience. Several individual online measurements, like pellet size, profile scan, and the furnace lining monitoring system (FLMS), are running on the common platform.

### Application

Pellet size measurement for steel belt sintering (SBS) technology is a highly precise machine vision-based process monitoring tool for online pellet size distribution. It enables an efficient pelletizing and sintering process with consistent pellet quality. The average pellet size is calculated from the observed images using specific algorithms. A histogram shows pellet size distribution in variable time frames.

### Technologies

The ACT platform is a graphical and modular development environment for advanced process control applications. It is easy to use, it has a simple flowchart-based programming language, and it is compatible with any process measurement or control system.

### Scope of application

The latest application extension has been in traveling grate pelletizing technology, used worldwide for iron ore pelletizing, with a production capacity roughly ten times bigger than in ferroalloy production. The new system is able to not only monitor the pellet size, but also to control pelletizing equipment (material feed rate, pellet disc rotation speed, water additions, etc.) and thus also pellet size distribution.

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**– Inventor** Outotec (Finland) Oy

## SHOWCASE 3



### Description of the tool

The direct current (DC) pilot furnace can be used for investigating energy-optimized smelting processes of various raw materials in fine form without pre-treatment.

### Application

During the test campaign, ilmenite concentrate and pre-reduced ilmenite were successfully smelted. Good-quality slag and pig iron were produced. An emission spectrometer, based on the elemental Ti and Fe peaks emitted from the plasma, provided good online prediction of slag FeO content. In the sulfate leaching tests, good yields of 90% TiO<sub>2</sub> were obtained with both slags. The results are valuable and they can be directly used for industrial scale solutions.

### Technologies

The pilot DC furnace is based on DC plasma arc technology. The DC technology has efficient power utilization and low electrode consumption.

### Scope of application

The DC pilot furnace at the Outotec Research Center in Pori was originally developed and built for smelting of fine chromite ores. The DC technology was developed further. The next interesting task for the DC pilot furnace would be the treatment of process dusts and residues.

#### Contact person – Inventor

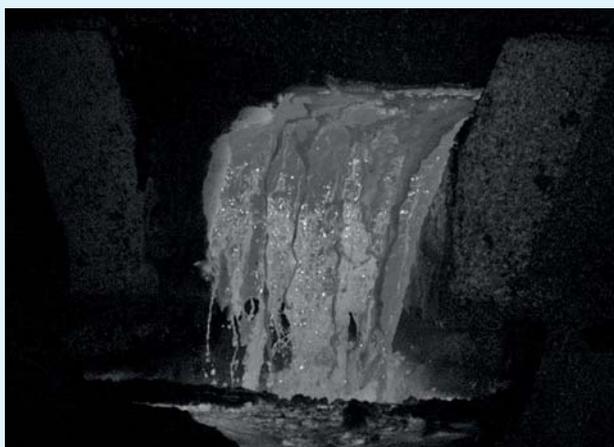
Suvi Rannantie, suvi.rannantie@outotec.com, + 358 40 589 1985, Outotec (Finland) Oy

#### Additional Information/ Publications

Pisilä, S., Palovaara, P., de Jong, A. & Aula, M. 2015. Ilmenite Smelting in a Pilot Scale DC Furnace. In: Proceedings of the Fourteenth International Ferroalloys Congress. Ukraine, Kiev. 31.5–4.6.2015. 202–209.

Aula, M., Pisilä S. & Fabritius T. 2015. On-line analysis of process conditions in ilmenite smelting with optical emission spectrometry. Proceedings of EMC 2015. Dresden, Germany. 16–22.8.2015.

## SHOWCASE 3



### Description of the tool

The tool was designed to improve visibility while tapping. Another aim was to make it easier to distinguish slag and metal. The benefits are better working conditions, better tapping control, and the possibility to analyze tapplings afterwards using video information.

### Application

Reveal TAP is an advanced application that is able to visualize molten metal and slag in a heavily dusty environment.

### Technologies

New camera technology and Sapotech's image processing software are utilized.

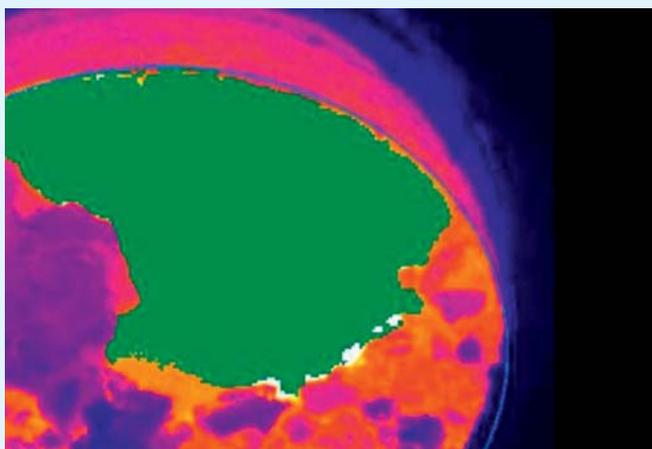
### Scope of application

The application has also been tested in the tapping of EAF and AOD processes before the SAF. The largest benefit was achieved in the tapping control of the SAF process. The tool can be applied to practically any melting process with a tapping operation.

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## SHOWCASE 3



### Description of the tool

The tool is designed for monitoring ladle deslagging. The benefits are to minimize metal loss, and maximize and stabilize the slag cleanliness of metal.

### Application

A test campaign at Outokumpu revealed that the application can be utilized to monitor ladle deslagging, but that it needs some adjustments to be able to distinguish slag and metal.

### Technologies

The tool utilizes a thermal camera system, near-infrared camera, and software that continuously analyses the images.

### Scope of application

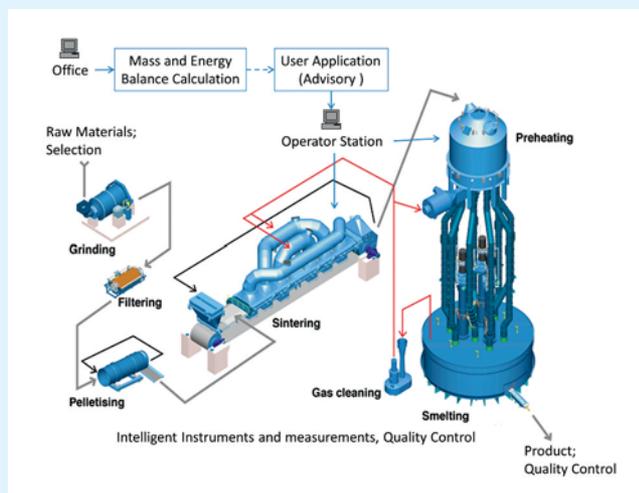
The application is a ready product for monitoring the ladle deslagging process.

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## SHOWCASE 3



## Description of the tool

The developed tool is a general simulator platform using multi-phase multi-component chemistry for processes with high-temperature reactors and flows of particulate material. It combines thermodynamic equilibrium calculation and particle kinetics to calculate the local state of the material flows. The tool can be used for the calculation of mass and energy balances, as well as for raw material and energy optimization. It can be used to predict the behavior of minor elements like heavy metals.

## Application

The tool has been applied to the Outokumpu Tornio ferrochrome process. An offline simulation model was developed for the submerged arc furnace, for the production of FeCr melt. The model was validated using industrial data.

## Technologies

The tool has been implemented in Microsoft Visual Studio with an Intel Visual Fortran Compiler. The ChemApp library by GTT-Technologies in Germany has been used for the calculation of the local thermodynamic equilibria in the processes. Thermodynamic data is from FactSage databases.

## Scope of application

The tool can readily be applied to any high-temperature process by using its general unit operation models, like feeders, mixers, and splitters. New unit operations can be developed for processes that require special modeling. A version of the tool for solving dynamic cases is being developed in cooperation with Outokumpu Tornio. This will enable online use of the tool.

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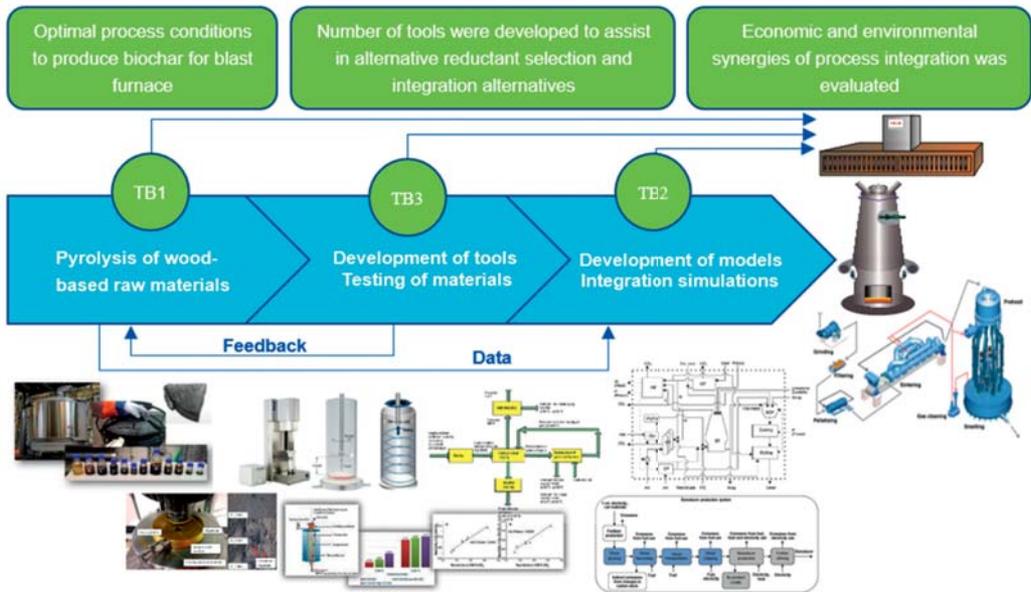
# SYSTEM MODELING TO OPTIMIZE LOW-CARBON FOOTPRINT FUEL USAGE IN THE FINNISH METALLURGICAL INDUSTRY

## SHOWCASE 4

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Mika Järvinen, Thomas Kohl/Aalto University

### Summary of the project's motivation and achievements

The main target of Showcase 4 was to clarify the feasibility of using alternative reducing agents in the metallurgical processes to lower the carbon footprint of metal production without compromising product quality and efficient process operation. The main emphasis in Showcase 4 was placed on the use of biomass-based reductants, which are considered to be sustainable fuels due to their renewability. The prior knowledge concerning the use of biomass-based reductants in modern metallurgical processes is vague, which has restricted wider use of these reductants in the industry. In order to reach the targets set for Showcase 4, the approach described in Figure 1 was taken. In Showcase 4, the feasible physical and chemical properties of biomass-based reducing agents to be used in different metallurgical processes were investigated. New tools and methods to test the properties of reducing agents and to create new specifications for efficient use in metallurgical unit processes were developed. Economic and environmental synergies of several process integration opportunities were also evaluated in the project. As a result of the project, there is now a much better understanding of the limitations and opportunities in using biomass-based reducing agents in metallurgical unit processes. The project results shed light on the economic constraints and the possible CO<sub>2</sub> emission reduction potential.



**Figure 1. Scheme of the project**

The available literature concerning the use of biomass-based reducing agents in metallurgical unit processes is vague and is characterized by theoretical considerations. According to the existing literature, the “theoretical” substitution amounts of fossil-based reducing agents in integrated iron and steelmaking plants are high (Table 1). By theoretical considerations, it is meant that real-life limitations are ignored. For example, in the case of replacing pulverized coal injection with charcoal injection, there might be several limiting factors in current injection and conveying technologies that are ignored in the modeling literature.

**Table 1. Substitution of fossil-based reducing agents in an integrated steel plant**

Application and replaced carbon source	Typical addition rate	Charcoal substitution rate (%)	Charcoal amount (kg/tHM)
Cokemaking (coking coal)	480–560 kg/tHM	2–10	9.6–56 kg/tHM
BF tuyere injection (pulverized coal)	150–200 kg/tHM	0–100	0–200 kg/tHM
BF nut coke replacement	45 kg/tHM	50–100	22.5–45 kg/tHM
BF briquette (coking plant residues)	10–12 kg/tHM	0–100	0–12 kg/tHM
Sintering solid fuel	76.5–102 kg/tHM	50–100	38.3–102 kg/tHM
Pre-reduced iron ore composite pellets	Not currently practiced		18–36 kg/tHM

## Key results and impacts

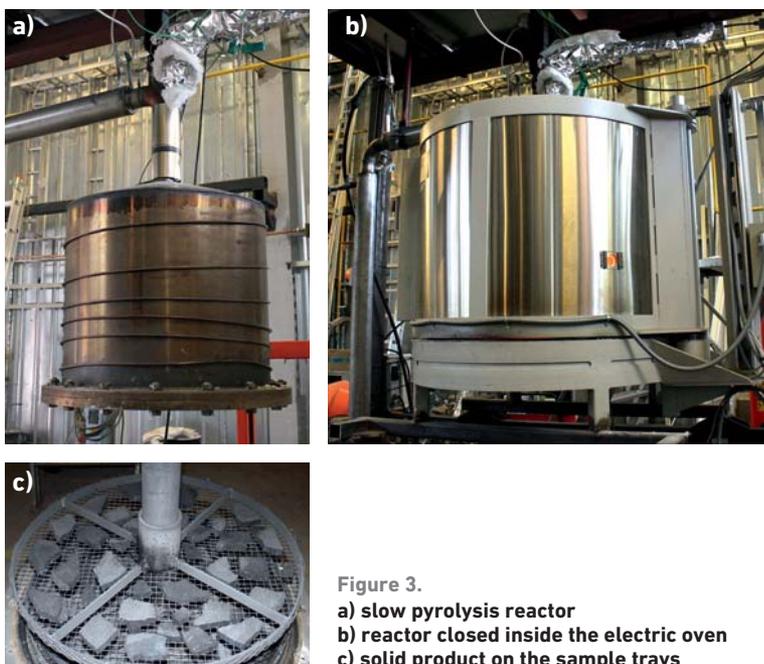
The results of Showcase 4 are presented in the following chapters. They provide a structured description of the research that was done to clarify the feasibility of introducing alternative, more sustainable reducing agents in metallurgical unit processes. The highlights of Showcase 4 are summarized in Figure 2.



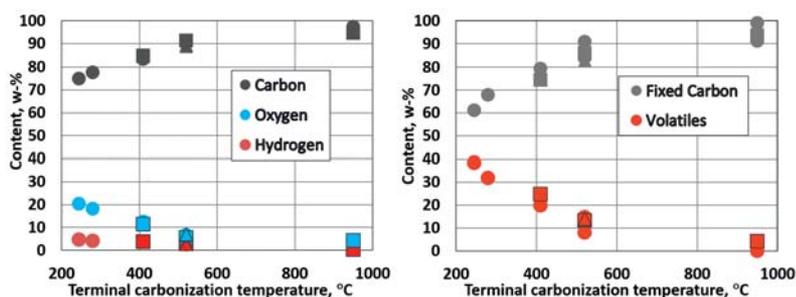
Figure 2. Highlights of Showcase 4

## Pyrolysis of wood-based raw materials for metallurgical processes

Slow pyrolysis experiments were conducted to produce charcoal suitable for blast furnace injection. The objective was to determine the pyrolysis temperature that produces high-quality charcoal, comparable to fossil coal in terms of carbon content and heating value. A bench-scale slow pyrolysis equipment (Figure 3) was used to conduct a total of 15 production test runs (Tool 1, page 215). The test runs were carried out in a temperature range of 245°C to 950°C with different wood raw materials. The liquid and gaseous products from the production test runs were measured and analyzed to produce data for process integration and scale up calculations.



Pyrolysis test runs showed that the temperature should be in the region of 500°C to produce high-quality charcoal for blast furnace injection (Figure 4). When the pyrolysis temperature was 520°C, the yield of the charcoal from birch wood was 28–29% on a dry basis. The carbon content of the charcoal was around 90% and the share of volatiles 8–14%. The gross calorific value of the charcoal was almost 35 MJ/kg (dry basis), which is considerably high. The chemical properties of the charcoal were found to be feasible for blast furnace injection. The carbon content is high (~90%) and oxygen content low (~6%), which are necessary for efficient BF operation. The sulfur content of charcoal produced from lignin was about 0.8%.



**Figure 4. Contents of fixed carbon and volatiles (left) and contents of carbon, hydrogen, and oxygen (right) in solid products at different terminal carbonization temperatures. The shape of the marker defines the raw material used: birch = circle, pine = square, and lignin = triangle**

Liquid and gaseous by-products from slow pyrolysis can be utilized in energy production, but other utilization scenarios have also been identified. The composition of the liquid product, also called distillate, changes as a function of pyrolysis temperature. At temperatures below 150°C, the moisture of the raw material evaporates and mainly water is collected as a liquid product. In the temperature range of 150–280°C, the exothermal decomposition and depolymerization reactions begin and produce distillate containing acetic acid and methanol. Decomposition products of cellulose and lignin form a liquid product containing organics and tars in the temperature range of 280–400°C. The amount of distillate decreases at higher temperatures. Figure 5 illustrates the liquid products collected during a slow pyrolysis test run. Gross calorific values of the distillates in the test runs varied in the range 7–14.3 MJ/kg.



**Figure 5. Liquid product samples collected at 30-minute intervals during the bench-scale slow pyrolysis test run of birch raw material. The final carbonization temperature was 520°C in the experiment**

The main components of slow pyrolysis gaseous products are CO<sub>2</sub>, CO, CH<sub>4</sub>, H<sub>2</sub>, and C<sub>2</sub>–C<sub>5</sub> hydrocarbons. The gases can also contain water, water-soluble compounds, light aromatic compounds, and PAHs. The net calorific value of the gas was calculated to be 8.3 MJ/kg for the gas composition determined.

The properties of the fossil-based fuels and biomass-based energy carriers differ significantly from each other. This has a considerable impact on their use in metallurgical processes. In the project, the advantages and disadvantages of using biomass-based reducing agents in the coke plant and in the blast furnace were reviewed (Table 2). In addition, experimental work was conducted to verify the information found in the literature. This also led to the development of several new tools that can be utilized in the selection of suitable reducing agents for metallurgical processes.

**Table 2. Pros and cons of using biomass in iron and steelmaking applications**

Application	Advantages of using biomass	Disadvantages of using biomass
Biomass in coking	<p>Typically (wood-based) biomasses have low ash content, typically 0.4–2.0 wt-%, which for coals is around 10%. Biomasses have basic (CaO, MgO) ash, which may decrease the need for limestone use in the BF.</p> <p>Biomasses have considerably lower sulfur content than fossil coals.</p> <p>Higher reactivity (CRI) of bio-cokes could be utilized to lower the temperature of the thermal reserve zone by nut coke replacement.</p>	<p>Bio-cokes have lower CSR than cokes produced from coking coals. The maximum limit of charcoal in coal mix is estimated to be around 5%.</p> <p>Biomass might increase the amount of Na<sub>2</sub>O, K<sub>2</sub>O, and P in the input, depending on the biomass type.</p> <p>High reactivity bio-coke may react too early in the BF shaft, resulting in inefficient reducing agent utilization and increased dust emissions.</p>
Biomass in BF injection	<p>A high share of pulverized coal could be substituted with charcoal in the injection.</p> <p>Charcoal is easy to pulverize when the pyrolysis temperature sufficiently high.</p> <p>Calorific value, carbon content, and volatile matter content of the charcoal can be adjusted with the pyrolysis temperature. Charcoal can outperform fossil coals; the coke replacement ratio of charcoal can be higher compared to coal.</p> <p>Combustibility of biomass and biomass-derived chars is usually higher compared to fossil coals. Higher combustibility may enhance the burnout degree in the raceway, leading to a lower amount of unburnt char.</p> <p>Typically, biomass ash content is low 0.4–2 wt-%, the ash is basic (CaO+MgO content is higher than SiO<sub>2</sub>+Al<sub>2</sub>O<sub>3</sub>), and sulfur content is low. This results in a lower need for limestone in the charge, which leads to lower slag volume in the BF.</p>	<p>Raw biomass and torrefied biomass have low carbon content, high volatile content, and low heating value, which results in a higher coke rate in the BF.</p> <p>The low density of the biomass and biochars requires large storage facilities. There is also a considerable risk of self-ignition. Biomass and biochars easily take up moisture during storage.</p> <p>The low density of the biochar may prevent the attainment of sufficient mass flow rate with existing injection systems.</p> <p>Raw biomass and torrefied biomass have a fibrous structure, which weakens their grindability. There may be difficulties in co-grinding fossil coals and biochars to the desired particle size (distribution).</p> <p>Biomass might increase the amount of Na<sub>2</sub>O, K<sub>2</sub>O, and P in the input, depending on the biomass type.</p>

There are several requirements for injected reducing agents. The first set of requirements is stated by the primary process in which the injectant is utilized. In the blast furnace, the primary requirement is the carbon content needed to produce a hot and reducing gas atmosphere in the BF (the larger the better). The secondary requirements come from harmful elements causing evaporation-condensation cycles inside the BF. These elements are S, Na, K, and Zn (the lower the better). The ternary requirement comes from the elements V, Cr, and P affecting steel quality (the lower the better). The final requirements are for the slag-forming elements CaO and SiO<sub>2</sub> requiring balancing with other raw materials to reach the desired final slag composition.

The second set of requirements is set by the manufacture and transport of coal powder if a brown field arrangement is utilized. The grinding and drying (GAD) process imposes limitations on the hardness (HGI > 45) of the material it is able to grind. The chemical composition of carbon-based material can be detrimental in the thermal-based drying process if heavy tar-based components are evaporated and condensed inside the process, thus blocking the filtration unit. A method for thermal analysis of coal was developed to screen suitable injectant materials to predict tar-based problems (Tool 2, page 216).

The third set of requirements is set by the transportation of powder having multiple process steps (silo compaction, fluidization, aeration, pneumatic transfer, etc.), also setting major obstacles. For long-term usage, the abrasiveness of the substituting material may also affect the economics. Laboratory apparatus was purchased to analyze the rheological properties of powders (Tool 3, page 217).

**Table 3. Comparison of charcoals produced from different wood-based materials with fossil coals**

Analyzed coal	C	H	N	O	S	Ash	HHV (MJ/kg)
Charcoal, pine 520°C	91.4	2.8	0.3	5.5	Na	0.9	34.7
Charcoal, pine 950°C	94.6	0.3	0.9	4.2	Na	2.1	33.5
Charcoal, birch 520°C	91.4	2.7	0.5	5.4	Na	0.9	34.0
Charcoal, birch 950°C	94.6	0.2	0.9	3.4	Na	1.0	33.6
Charcoal, lignin 520°C	89.5	2.8	0.3	6.6	0.8	3.0	33.9
PC (SSAB)	81.1	5.06	2.3	2.01	0.26	9.3	NA
PC (literature)	80.6	4.35	1.65	5.35	0.45	10.9	NA

The experimental work conducted and analysis made for biomass-based chars confirmed that different wood-based raw materials are suitable from the perspective of chemical composition to be applied in BF injection (Table 3) (Tool 1, page 215). The main concerns for lignin raw material, derived from the pulp industry, are high Na and S contents. This might limit the use of lignin derived from the Kraft pulp process in high quantities in ironmaking. Virgin wood-based materials seem to be suitable for BF injection, as the share of harmful elements in the ash are at an acceptable level.

In the case of bio-coke and hybrid coke production, laboratory- and pilot-scale trials were conducted to confirm the literature findings and to propose some measures to increase the proportion of biomass in the coal blend (Tool 4, page 218). The aim of these tests was to determine if it is possible to use coke fines and charcoal in the coal blend, and how they will affect the quality of blast furnace coke. Petroleum coke is used in the coal blend, and replacing it with coke fines would decrease the sulfur content of coke, raise the recycling rate, and reduce coking costs.

Coking experiments were done with a 7 kg small-scale coking oven. The coal blends used contained different amounts of coke fines and charcoal. The blends were made with a ball mill and jaw crusher. The coal blend particle size distribution was made very similar to that of the production-scale blend. Coke quality (CRI and CSR) was measured with the Nippon Steel method. The pore structure of coke was also investigated with an optical microscope. The particle size distribution of production coal blends was measured and the sulfur content of specific fractions was determined, identifying petroleum coke by optical microscope. The amount of petroleum coke in the coal blend fractions was calculated using a point counting method.

Coking experiments started with the coking of reference blends. It was observed that the bulk density of the coal blend has a large impact on coke quality. The quality of the reference-level coke was not as high as that of normal laboratory-scale coke. The bulk density of self-made coal blends was 13% higher than in production coal blends. In this study, this was still chosen as the reference.

The results showed that coke fines (0–3 mm) can be used to replace (1%, 3%, and 5%) petroleum coke and that they did not decrease coke quality. The pore structures of these cokes were also similar to the reference. Charcoal produced at different pyrolysis temperatures (280°C, 520°C, 950°C) was used at 3% and 5% in the coal blend. For the 3% portion (280°C and 520°C) the reactivity of coke increased to some extent, but for the 5% portion (950°C), the quality of the coke decreased a lot and the structure was weak. Structures observed at larger magnification (20x) revealed that the charcoal particles were bound well to the coke matrix. Charcoal can be used to replace petroleum coke up to 3% if the reactivity

of the coke is allowed to increase. All the charcoals produced at different pyrolysis temperatures were investigated with an optical microscope and the structures looked similar. Even for the highest pyrolysis temperature, the cellular structure of the charcoal was recognized.



## Company impact

"The knowledge we got from biomass slow pyrolysis test runs and analysis of biomass-based chars confirmed that good-quality reducing agents can be produced for blast furnace injection."

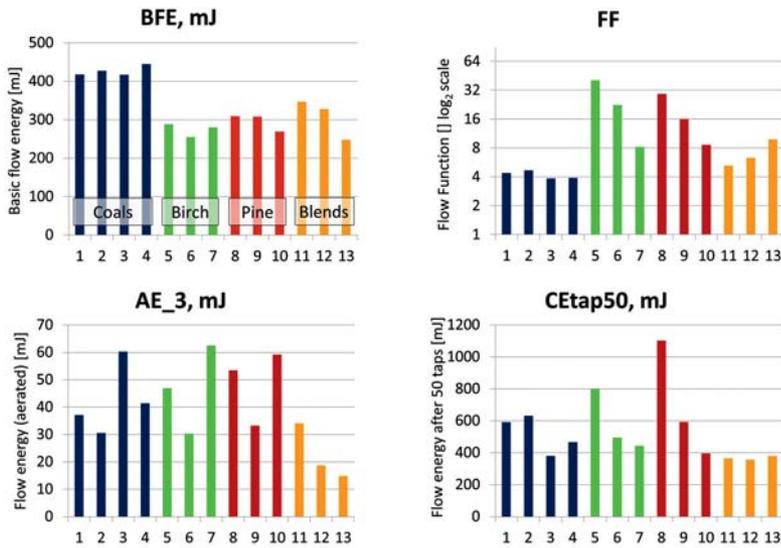
*Olli Mattila, development engineer, Ironmaking, SSAB Europe Oy*

## New tools to assist raw material selection

### Pulverized coal injection

The substitution of fossil coal with charcoal or other carbon-based materials, completely or partially, leads to changes in the flowability properties of the injected mixture. The flow properties of mixtures should meet the criteria stated by the process designed for fossil coal in the first hand. With Freeman Technology FT4, flow property requirements stated by the process can be assessed and flow properties of mixtures can be validated ([Tool 3, page 217](#)). Measurements in FT4 are made by accurately measuring the force and weight of samples during numerous measurements with associated accessories. To evaluate the potential of charcoal injection in the blast furnace, the grindability, flow, and transport properties of charcoals were measured using various methods, as a function of wood type and wood carbonization temperature. Grindability tests were made with a laboratory-scale bar mill and a laser diffraction particle size analyzer.

The grindability parameters and transport parameters determined have been compared with the properties of two different types of fossil injection coals, as well as charcoal and pulverized coal mixtures (Figure 6). Based on the measurements, the carbonization temperature used to produce charcoal clearly changes the transport properties. Carbonization of birch at 520°C leads to the most similar flow and transport properties compared to the measured PC grades. The results suggest that it is possible to use charcoal together with PC in the grinding and drying facility, as well as to co-inject charcoal and PC into the BF. The results also suggest that the optimal charcoal content in a mixture of PC and charcoal could be in the range of 10–50 wt-%, although pilot-scale tests and full-scale tests are definitely needed to confirm this.



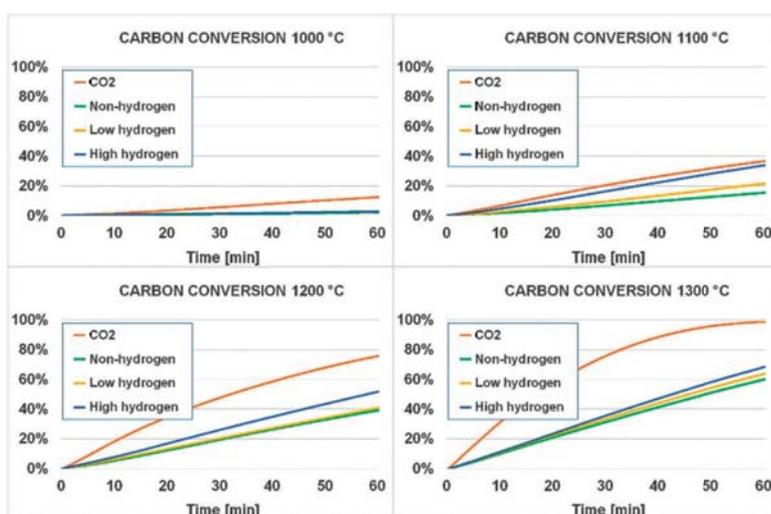
**Figure 6. Flow property indices of PC, charcoals, and their blends**

Thermal analysis of carbon-based material is required to identify possible tar-based problems. A Netzsch STA409PC Luxx (or STA449F3 Jupiter) + Aëolos QMS403C was used to study the liberation of tar fractions of different coal grades, to seek a suitable coal grade for pulverized coal (PC) manufacture (Tool 2, page 216). The PC manufacture process involves simultaneous drying and grinding, in which tar components can be liberated followed by condensation onto the filtration surfaces of the powder separation unit. Numerous coal grades were ranked using the method.

Blocking of pipes is a common problem in blast furnace auxiliary fuel injection. The injectability parameter of BF auxiliary fuel can be estimated using a hot-stage microscope (Tool 5, page 219). The temperature of the injection pipe increases toward the blast furnace tuyère and is subject to change under different injection conditions. The hot-stage microscope reveals the transformation temperature at which the particles transform from solid and hard to sticking ones, thus blocking the injection pipes. Different fuels can be measured and the applicability to BF injection can be estimated. Different components in the sample, such as macerals in the case of pulverized coal, can be identified. Injectability parameters of a new auxiliary fuel for the blast furnace can be measured and compared with known ones. The results will be used to screen suitable blast furnace auxiliary fuels based on their applicability to the fuel delivery system. The developed method can also be used to study the coking behavior of different coals or coal substitutive materials. The method could also be utilized outside the metallurgical industry (e.g. in coal-fired power plants) to select appropriate coals and operating conditions.

## Coke reactivity

Coke reactivity, one of the most important properties of coke, is commonly measured using the CRI (Coke Reactivity Index) test in 100% CO<sub>2</sub>. The actual blast furnace gas is radically different, and also contains H<sub>2</sub>O as a gasifying element. In this task, a new method was developed to measure coke reactivity in simulated blast furnace gas conditions with all of the main blast furnace gas components (N<sub>2</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O) in realistic ratios (Tool 6, page 220). It was discovered that H<sub>2</sub>O strongly increases coke reactivity at a temperature around 1100°C (Figure 7). However, the reactivity-increasing effect of H<sub>2</sub>O was low at 1000°C and begins to fade as temperature is further increased.



**Figure 7. Reactivity of blast furnace coke in 100% CO<sub>2</sub> and in three simulated blast furnace shaft gases with various amounts of H<sub>2</sub>/H<sub>2</sub>O, and at temperatures 1000–1300°C**

One of the main findings of this task was that the coke reactivity in 100% CO<sub>2</sub> did not directly correlate with reactivity in the simulated blast furnace gases. This indicates that the CRI test, which is utilized worldwide, may not accurately predict coke reactivity in the actual industrial process. It is important for both economic and process efficiency reasons to accurately estimate the coke reactivity in the blast furnace process. Since the method developed in this task improves the reactivity assessment, it could lead to economic benefits in the future. The next step is to find a practical way to apply the new method in the industry. Ideally, the new coke reactivity testing method could be validated by basket sample tests in the Experimental Blast Furnace (EBF) in Luleå, Sweden. Another important future step is the development of a post-reaction strength test for coke after gasification in a simulated blast furnace gas.



## Company impact

"The project and the developed tools enabled production to evaluate the impact of different PCI coal alternatives on value in use and to predict the influence on the blast furnace process, including quality changes in hot metal and slag composition."

*Timo Kallio, Raw material specialist, SSAB Europe Oy*

## Behavior of alternative reducing agents in metallurgical processes

In the project, one of the main targets was to evaluate the behavior of alternative reducing agents in metallurgical processes. This was done in the laboratory and on an industrial scale.

### Ramp-up of pulverized coal injection on industrial scale

The behavior of alternative reducing agents in the blast furnace was evaluated on industrial scale and laboratory scale. Full industrial-scale pulverized coal injection (PCI) was adopted at SSAB Europe Raahe BF1 in September 2015 and at BF2 in October 2015 (Figure 8). Several tools and analysis methods were developed to evaluate the performance of the pulverized coal injection. Some of the tools were developed to assist in coal selection (Tools 2–3, 5) and some were developed to evaluate the performance of the coal combustion in the blast furnace.

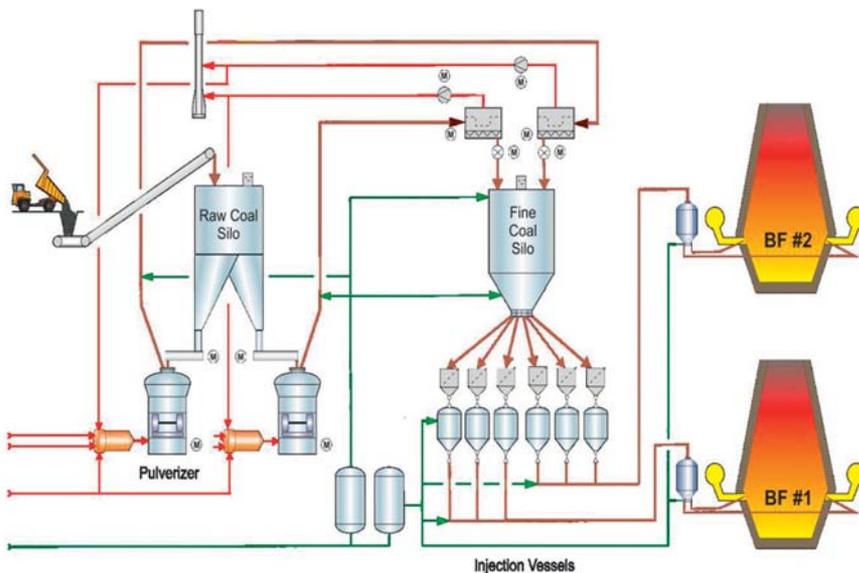
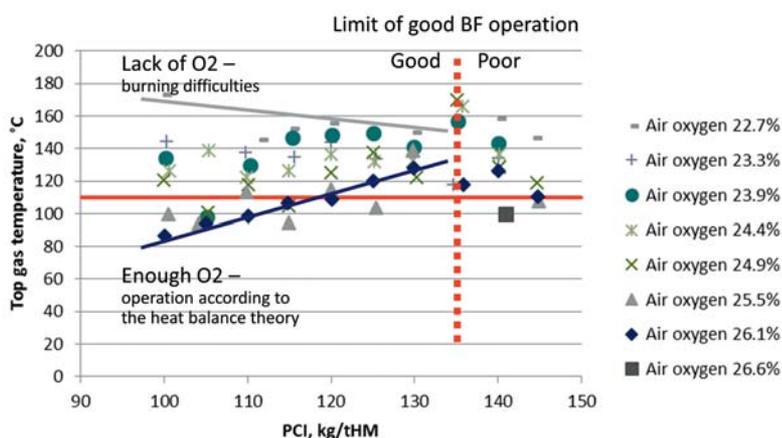


Figure 8. Pulverized coal injection system

The blast furnace operation was monitored during the PCI start-up period, and unburnt pulverized coal char from flue dust and sludge were characterized. Accurate determination of unburnt char in dust and sludge samples could be used as the basis for decision-making when controlling the PCI rate and other essential BF operational parameters. The blast furnace operation was monitored with various PCI and blast oxygen levels with respect to the effects on top gas temperature, flame temperature, gas utilization, and burden descent (Figure 9). In addition, an overview of the PCI start-up period and a few periods with stable and unstable blast furnace operation were covered.



**Figure 9. Blast furnace operation with different pulverized coal injection rates and oxygen enrichment**

A total of 13 sludge samples and 14 dust samples for different prevailing BF conditions were collected and analyzed for chemical and physical properties. The results were compared with respect to blast oxygen content, PCI, and coke rates. Characterization of carbon from a different origin by TGA was based on the difference in combustion rate of PC char, coke, and soot, which were thought to be present in sludge, whereas dust was taken to contain no soot.

Carbon characterization by QXRDA was based on carbon graphitization degree. With an increased pyrolysis temperature, the carbon crystallite structure becomes more ordered, which can be seen as an increase in the average carbon crystallite height and diameter. A calibration curve for char content estimation of a received sample was formed between the char and coke standards.

Carbon content analysis of dust samples revealed moderate correlation between blast oxygen content and carbon content. A correlation

between carbon content of sludge samples and operation parameters was found, but it was not as definite as for dust samples. Particle size distribution was split into fractions <75 µm, 75–150 µm and >150µm. Against expectations, the 75–150 µm fraction showed a strong correlation with the PCI rate for both samples. Carbon characterization with TGA revealed PC char contents of 17.2% to 73.9% of total carbon in dust samples and 17.8% to 41.1% of total carbon in sludge samples.

### High reactive coke use in blast furnace and the role of pellet-coke direct contact

The use of high reactive coke has been a hot topic in blast furnace research during the past few years. In theory, proper application of high reactive coke could decrease the temperature of the thermal reserve zone and lead to an improvement in the gas utilization rate and a decrease in the total fuel consumption. However, the possible benefits of the use of highly reactive coke are also strongly tied to the reducibility of different iron ores.

It was found that the reducibility of all three pellet grades notably improved in the case of high reactive coke (Table 4). In the BFS tests, the final reduction degree was about 35% in the case of regular coke and 41% in the case of high reactive coke. The TGA tests indicated that some differences may exist between the pellet grades in different stages of the reduction process, but further testing is required in order to draw definite conclusions (Tool 7, page 221). The preliminary results also indicated that sinter reducibility could be improved even more compared to the pellets. The only raw material that clearly suffered from the high reactive coke was the blast furnace briquette.

**Table 4. Reducibility of three industrial pellet grades with two different reduction programs simulating the use of low and high reactive coke**

Pellet grade	Regular coke		High reactive coke	
	Mass change [%]	Reduction degree [%]	Mass change [%]	Reduction degree [%]
KPH	- 9.3	34.5	- 10.8	40.6
BSA	- 9.4	34.9	- 11.1	41.9
MPBO	- 9.7	35.4	- 11.1	41.2

In the industrial blast furnace process, coke and iron ore are charged from the top in sequential layers, which are partially mixed as the charge descends. Hence, a direct contact can be found between iron ore pellets and coke lumps throughout the solid zone of the blast furnace. However, little research exists on the role of this contact in the process of iron ore reduction and coke gasification. In a past modeling study performed for SSAB Raahe, it was found that the reducibility of iron ore was lower on laboratory scale than was expected, which created the incentive to study the role of direct reduction.

In this task, the impact of direct contact between coke and pellet was measured using thermal gravimetric analysis (TGA). Four different cases were tested: 1) all coke; 2) all pellet; 3) pellet on bottom – coke on top; 4) coke on bottom – pellet on top. It was found that both coke gasification and pellet reducibility increased marginally when they were layered on top of each other. Coke weight loss was around 2 wt-% individually, compared to around 3 wt-% when in contact with pellets. The final reduction degree of pellets was 82% individually compared to 84% (pellet on bottom) and 92% (pellet on top) when in contact with coke. According to the TGA graphs, direct contact influences reducibility of iron ore at higher temperatures (above 1000°C). No notable influence of direct contact was seen on reduction to magnetite and to wüstite. These results could be verified on a larger scale by using the Blast Furnace Simulator (BFS), and also performed in a gas including H<sub>2</sub> and H<sub>2</sub>O.

### Ejector venturi pilot-scale scrubber model to evaluate gas cleaning in different reducing agent use scenarios

As alternative reductants are likely to burden process off-gas cleaning systems more than traditional fossil reducers (because they tend to form more dust and they may include some harmful tar-containing components), Outotec has built a physical pilot-scale ejector venturi scrubber model to evaluate the impact of alternative reducers used in the submerged arc furnace (SAF) process ([Tool 8, page 222](#)). With the help of the model, gas cleaning systems can now be developed further to address possible challenges in process off-gas cleaning, along with the use of alternative reductants.



#### Company impact

"In this DIMECC SIMP program project, we have certainly developed our future products. These are simultaneously intelligent, clean, and effective."

*Lauri Närhi, VP, PL Ferroalloy, Outotec (Finland) Oy*

### Anthracite test trials in submerged arc furnace

The use of anthracite instead of metallurgical coke as a reductant for the SAF can be justified by the facts that it is cheaper and has lower electrical conductivity. The main compositional difference between coke and anthracite is in the amount of volatile components. Preliminary studies with the HSC Chemistry program suggested that under SAF conditions, the volatile hydrocarbons are cracked into methane, which then reacts with carbon dioxide. The use of anthracite results in an increased amount of hydrogen measured in the off-gases.

In terms of strength, anthracite is weaker than coke. Impact resistance tests have resulted in values of 1–2 with the scale's maximum being 3. The average for anthracite is about 1, while the average for coke is over 2. Electrical conductivity at lower temperatures is clearly lower for anthracite than for coke; the ratio of the conductivities is about 1:5. However, the electrical conductivity of anthracite increases with temperature and is equal to the value for coke at high temperatures.

Anthracite was used in production tests in all three submerged arc furnaces ([Tool 9, page 223](#)). The amount was 10–30% of the total reductant charge. For SAF1, the most notable difference was an increased hydrogen level in the furnace off-gas, while the effects on electrical behavior were indefinite. The variances of the electrodes' impedances increased a little. SAF2 experienced a lining burn-through during the test period, so the data was incomplete, though it was clear that the hydrogen level in the off-gases increased with the amount of anthracite charged. Tests with SAF3 did not give any further information, mainly because the portion of anthracite was smaller than in the other two tests.

Based on the observations, anthracite use complicates the operation of the SAF mainly by the more difficult interpretation of the hydrogen level in the off-gases: an increased level of hydrogen is commonly perceived as a sign of water leakage inside the furnace. It remained unclear whether the use of anthracite increased the electrical resistance of the burden.

### Laboratory investigations of charcoal use in chromite pellet sintering

Sintered chromite pellets are used as a raw material in the submerged arc furnace. Chromite fines are agglomerated in the steel-belt sintering process. Sintering requires a high temperature, which is generated by burning carbon-bearing materials. Coke is the main carbon-bearing material in the sintering process, and its use causes CO<sub>2</sub> and SO<sub>x</sub> emissions. One possible measure to reduce emissions is to use charcoal. The main purpose of the study was to identify a substitution ratio of coke with charcoal in the chromite pellets that does not lead to a significant decrease of the cold compression strength (CCS) of the pellets. Another objective

of the study was to study how charcoal substitution affects the sintering process (Tool 10, page 224).

The chromite pellets were produced in a laboratory-scale pelletizing disc. The chromite ore was from the Kemi mine, coke used in this research was a mixture of separately ground metallurgical coke and coke dust from off-gas filters, and charcoal was made from birch chips, which were heated in an air-free atmosphere until the temperature in the middle of the reactor reached 900°C. The pellets were fired in a tubular furnace until the temperature of the thermocouple in the sample basket reached 1,300°C. The cold compression strength (CCS) of the pellets was measured using a Zwick/Reoll Z100 testing machine, which gives accurate data about the force needed to break the pellet. The effect of charcoal addition on the cold compression strength of the sintered pellets is shown in Figure 10. According to the results of this study, 50% of the coke in the pellets can be substituted with charcoal without a significant decrease in the cold compression strength of the pellets. With this substitution ratio,  $SO_x$  emissions could be significantly decreased. It also seems that there is an optimal grain size for charcoal of 90–250 µm; both coarser and finer charcoal resulted in weaker pellets and also the peak temperature was lower.

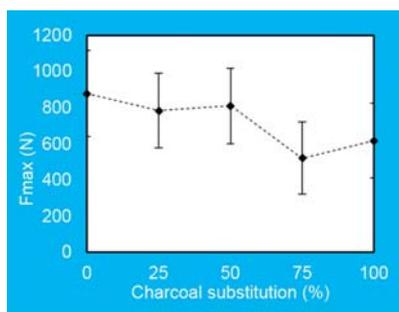


Figure 10. Effect of the charcoal substitution rate on the cold compression strength of the pellets

## Company impact

"In Showcase 4, we have expanded our theoretical and practical knowledge concerning the use of alternative reducing agents in our production processes. A great example of the project results is the full-scale anthracite tests conducted in our submerged arc furnaces. Flexibility in reducing agent use ensures our competitiveness in the future."

*Mika Päätaalo, R&D manager, Ferrochrome Works, Outokumpu*

## Biomass-based reducing agent production – Increased efficiency with process integration

### Biomass thermochemical conversion system integrated in a sawmill

A scale-up of a slow pyrolysis process to two industrial-scale plant sizes was studied in the project (Tool 11, page 225). The plant sizes were selected for two blast furnace injection scenarios in which the charcoal injection would be 20–50 kg per ton of hot metal (thm). The corresponding plant sizes are 24 kton/a and 60 kton/a. Three different raw materials were evaluated, namely bark, logging residues from final fellings, and forest residues from forest thinnings. As a result, a total of six cases were calculated.

The data needed for the scale-up evaluation was produced using VTT's bench-scale slow pyrolysis test facilities (Tool 1, page 215). Mass and energy balances for industrial-scale pyrolysis processes were evaluated case-specifically by spreadsheet calculations (MS Excel). Finally, the biochar production costs were evaluated with a spreadsheet program based on the annuity method. The cost estimation of biochar production was based on a former extensive review of torrefaction technologies. The unit operations and equipment needed in the slow pyrolysis and torrefaction processes are quite similar except for the carbonization temperature, which is lower in torrefaction. As a result of the scale-up evaluation, block flow diagrams for each calculated case were produced. An example block flow diagram is shown for biochar production from bark in Figure 11.

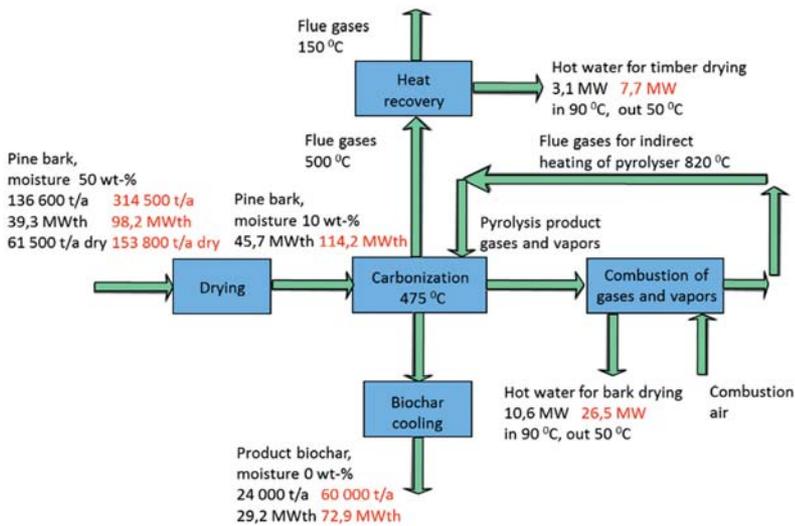


Figure 11. Block flow diagram of slow pyrolysis plant producing biochar from pine bark (24000 t/a and 60000 t/a biochar, 7200 h/a)

The cost estimates were used to calculate the production cost for different bioreducers. It seems that biochar produced from bark has the lowest production costs (312 €/t). Production costs for biochar produced from logging residues from final fellings and forest residues from forest thinnings were 340 €/t and 376 €/t, respectively. The breakdown of the calculated production costs of biochar for each case is presented in Figure 12. In cases 1–2, bark is used as raw material with 24000 t/a and 60000 t/a plant sizes. In cases 3–4, logging residues are used as raw material with 24000 t/a and 60000 t/a plant sizes. In cases 5–6, forest residues are used as raw material with 24000 t/a and 60000 t/a plant sizes. The total investment is lowest for the bark case, because the biochar yield is higher for slow pyrolysis of bark compared to the other raw materials. The process condition range for large-scale charcoal production has been determined in the project based on the use of bench-scale technology tools.

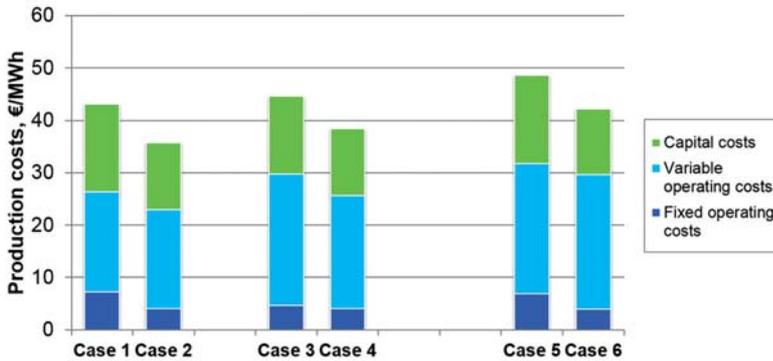
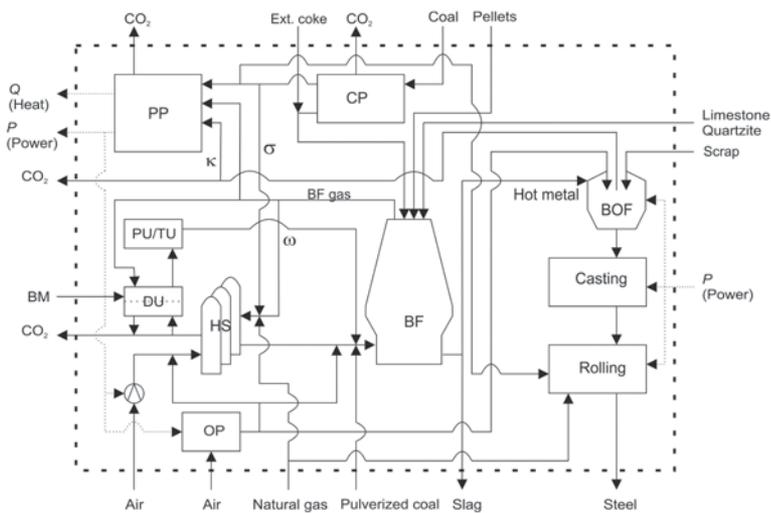


Figure 12. Breakdown of production costs for cases 1–6

### Biomass thermochemical conversion system integrated into steel plant

In order to use biomass efficiently in a steel plant, possible synergistic effects should be utilized to make the use economically feasible. One possible way of reducing the pretreatment costs is to use waste heat from the steel plant for the energy-consuming drying step needed before a conversion, where the heating value is upgraded and the composition is adjusted to be suitable for injection in the blast furnace. In order to evaluate the economic feasibility of the three conversion alternatives, the drying, conversion, and grinding models were integrated with a holistic model of the steel plant, as depicted schematically in Figure 13 (Tool 12, page 226). The model of biomass conversion includes three alternatives: torrefaction, slow pyrolysis, and fast pyrolysis (Tool 13, page 227).

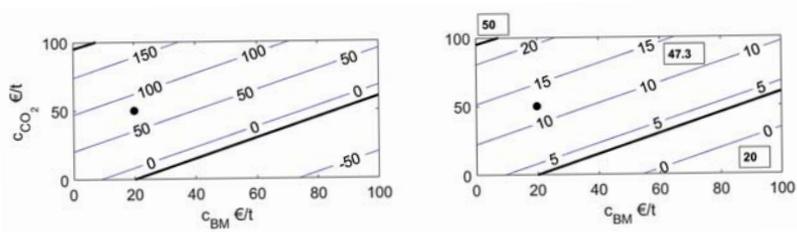
A mathematical model was applied to close the mass balances based on data reported in the literature. This makes it possible to assess the impact of biomass pre-treatment and injection on the economic performance and emissions of the whole plant. Depending on the quality (heating value and composition) of the converted biomass, different operation conditions of the blast furnace are required (e.g., different oxygen enrichment) to stay within reasonable operation limits. This and the impact on the coke rate together affect the other flows in the plant and therefore also the production economics. The liquid fraction of the pyrolysis unit (“bio-oil”) was assumed to be used in other parts of the steel plant to partially replace external gas. For a fixed steel production rate, the plant equations were solved with the objective of maximizing the net present value (NPV) of the project, where the plant is equipped with the biomass pre-treatment units, considering investment costs and operation costs. A steel plant operating with a blast furnace with a specific pulverized coal injection rate of 150 kg/thm was taken as the reference for the study.



**Figure 13. Steel plant model integrated with process units for biomass conversion (DU: drying unit, PU/TU: Pyrolysis/torrefaction unit)**

As an example of the findings, Figure 14 shows the optimization results for the most promising conversion concept studied, namely slow pyrolysis, for different values of the price of biomass (dry basis, abscissae) and specific penalties for CO<sub>2</sub> emissions (ordinates). The left subpanel shows contours of NPV of the investment, expressed in M€, and the right panel the decrease in the specific operation costs (€/thm) for the optimized states. The optimal biomass char injection rates are depicted as

regions limited by the thick solid lines and reported in the small boxes (in kg/thm) in the right panel. For the region in the lower-right corner (low emission costs, high biomass price), the lower injection limit (20 kg/thm) is reached. This region, which is also characterized by  $NPV < 0$ , in fact implies that the injection is infeasible. In the main region of the diagram, an injection rate (47.3 kg/thm) close to the upper imposed limit (50 kg/thm) is optimal. For instance, at a biomass price of 30 €/t (dry basis) and an emission penalty of 20 €/t, the model estimates  $NPV \approx 10$  M€, meaning a (slightly) feasible investment. The results demonstrate that biomass char injection is not yet feasible at the present biomass price and emission penalties.



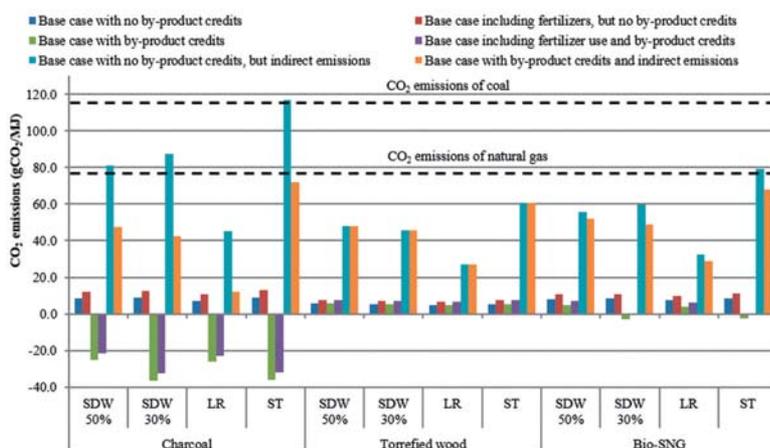
**Figure 14. NPV (left panel) of the investment in biomass drying, conversion by slow pyrolysis, and grinding, expressed in M€ (contours) and specific economic benefit in operation costs (right panel) for different values of the price of biomass (abscissa) and penalty of emission (ordinate)**

### CO<sub>2</sub> reduction on a life-cycle basis

In order to evaluate the environmental sustainability of bioreducers used as reductants in ironmaking, life-cycle impacts of bioreducer production and use were evaluated. In the project, a developed carbon footprint (CFP) model (Tool 14, page 228) was utilized to evaluate the life-cycle CO<sub>2</sub> emissions of torrefied wood, charcoal, and Bio-SNG. The study was conducted to get comparable information about three bioreducers, produced from raw materials available in close proximity to the Finnish steel production plant.

An overview of the CO<sub>2</sub> emissions per produced unit of energy (gCO<sub>2</sub>/MJ), with different life-cycle stages taken into account, is presented in Figure 15. The base case includes fertilizer production, but no indirect emissions results in CFP of 10.8–12.9, 6.7–7.5, and 9.7–11.1 gCO<sub>2</sub>/MJ for charcoal, torrefied wood, and Bio-SNG, respectively. If the indirect carbon stock change (CSC) is taken into account, but no by-product credits, the CO<sub>2</sub> emissions increase to 45–117 gCO<sub>2</sub>/MJ, 27–61.0 gCO<sub>2</sub>/MJ, and 32–79 gCO<sub>2</sub>/MJ for charcoal, torrefied wood, and Bio-SNG, respectively. The large variation in the CO<sub>2</sub> emissions is due to the fact that logging residues (LR), small-diameter wood (SDW), and stumps (ST)

have different emission factors for CSC within a 100-year time horizon. For instance, the decomposition rate of logging residues is higher than that of stumps, which results in lower indirect emissions. As mentioned, by taking the by-product credits into account, the CO<sub>2</sub> emissions of bioreducer production become negative in all charcoal production scenarios and in two Bio-SNG scenarios. From Figure 15, where the life-cycle CO<sub>2</sub> emissions of natural gas (75 gCO<sub>2</sub>/MJ) and coal (115 gCO<sub>2</sub>/MJ) are also depicted, we can see that if indirect emissions from carbon stock change are strongly accounted, CO<sub>2</sub> emissions of bioreducer production become considerable. Compared to natural gas, charcoal produced from small-diameter wood and stumps has higher life-cycle CO<sub>2</sub> emissions per produced unit of energy (gCO<sub>2</sub>/MJ); charcoal produced from stumps even exceeds the life-cycle CO<sub>2</sub> emissions of coal. However, it is unlikely that bioenergy carriers produced from energy wood will face such severe accounting of indirect emissions in the near future. The CFP calculations showed that there is substantial potential to decrease the fossil CO<sub>2</sub> emissions of steelmaking by utilizing bioreducers in the BF.



**Figure 15. CO<sub>2</sub> emissions of bioreducer production depending on system boundaries**

### Evaluation of the project and direction for future studies

The project brought together experts from different fields of technology to evaluate the potential of utilizing alternative reducing agents in metallurgical processes. The main emphasis in the project was placed on biomass-based reducing agents. The reason for this is that biomass is considered to be a nearly carbon-neutral fuel, thus providing possibilities to reduce CO<sub>2</sub> emissions in the carbon-intensive steel production industry.

Besides biomass-based reducing agent research, fossil-based reducing agents providing sustainability advantages from an economic perspective were examined in the project. During the project, the SSAB Europe Raahé steel plant changed from oil injection to pulverized coal injection in the blast furnaces, which enhanced the company's competitiveness on the global market. Increasing the injection rate of pulverized coal decreases coke consumption, which is beneficial from an environmental point of view. Outokumpu Chrome carried out trials with anthracite use in all submerged arc furnaces in Tornio.

The project was successful in many ways. The feasible technology (slow pyrolysis) and pyrolysis temperature to produce good-quality charcoal with respect to carbon and oxygen content, and heating value for blast furnace injection, were determined in the project. Charcoal produced from pine or birch at around 500°C was found to outperform pulverized coal in blast furnace injection with respect to composition and energy content. Lignin from the Kraft pulp process was also evaluated as a possible raw material for char production. The yield of lignin char was higher than for virgin wood, but especially the Na and S content of the lignin char may inhibit its use. These elements originate from the Kraft process, in which chemicals are used to extract from wood the components cellulose, hemicellulose, and lignin.

Several experimental tools and methods were developed to assist in the selection of alternative reducing agents for certain unit processes (Figure 16). The developed tools and methods provide crucial information that it is not possible to access with standard methods. Some of these tools have already been introduced in everyday industrial application, thus providing added value for the production processes. Utilization of the tools developed in the Showcase 4 project is not restricted to their current application, but can also be utilized in other applications to increase production efficiency. An excellent example is the use of a test tool developed for PCI injection in the development of a desulphurization process.

In the project, the behavior of alternative reducing agents was evaluated by means of simulated process conditions on a laboratory scale, by utilizing process modeling, and by testing alternative raw materials on an industrial scale. During the project, the SSAB Europe Raahé steel plant switched from oil injection to pulverized coal injection, which facilitates solid biomass-based reducing agent injection. The flowability and grinding results suggest that up to 50% of charcoal could be applied in the existing plant infrastructure, which is designed for fossil coals. Outokumpu Chrome investigated the use of anthracite in industrial submerged arc furnaces. The proportion of anthracite was 10–30% of the total reducing agent use.

Economic evaluations made in the project suggest that the economic competitiveness of biomass-based reducing agents compared to cheap fossil-based reducing agents is challenging. This could be offset by a higher carbon tax or other incentives. Scale-up evaluations and process integration studies revealed that by integrating biomass-based reducing agent production with existing industries, such as saw mills or steel plant, the economics of biomass-based reducing agent production could be enhanced. Benefits from integration include utilization of flue gas waste heat from hot stoves in biomass drying. The carbon footprint calculations showed that the carbon footprint of fossil-based fuels (natural gas and coal) is around tenfold compared to biomass-based reducing agents.

Future studies in the field of alternative reducing agents, specifically biomass-based reducing agents, should continue with well-planned pilot or industrial trials. Today, there is little information available about the behavior of biomass-based reducing agents in modern pellet or sinter-based blast furnaces. This gap needs to be filled to advance development in this field. After verification, optimization toward the use of biomass-based reducing agents could be continued. There is also a need to further investigate other possible raw materials for metallurgical processes. By-products from the pulp industry are one possibility, but additional treatment to remove harmful elements (such as sodium and sulfur) may be needed. One additional source of good-quality lignin is from bio-ethanol production. Lignin is separated after hydrolysis of waste biomass. Compared to Kraft-lignin, there are no Na or S-containing chemicals used in this process. More emphasis should be placed on the evaluation of the most efficient biomass-based reducing agent supply chain. Economic and environmental evaluations should be done for different configurations in which biomass is converted either in close proximity to forest operations, in connection with an industrial site producing waste biomass as a by-product, or integrated with steel production. The future development steps should be taken together with other industrial actors to develop methods for upgrading all the by-products from biomass conversion.

The results of the project were actively disseminated through selected information channels. This was seen in, for example, the SCANMET V conference in Luleå, Sweden, where the project made a strong contribution in different research fields, including coke, alternative reductant, and pellet research. The SHOK programs have been efficient in developing industry-research institute co-operation platforms to create new and remarkable technological leaps.



## Company impact

“Reduction of greenhouse gas emissions is a true challenge for the steel industry in the coming decades. SSAB has set both short-term and long-term targets for the reduction of CO<sub>2</sub> emissions. The SIMP program has shown that innovations in process control can bring substantial short-term improvements in CO<sub>2</sub> emissions. Biomaterials have great potential for the steel industry in Finland, and it is important that this option is considered and investigated in detail.”

*Harri Leppänen, head of EHS, SSAB Group*

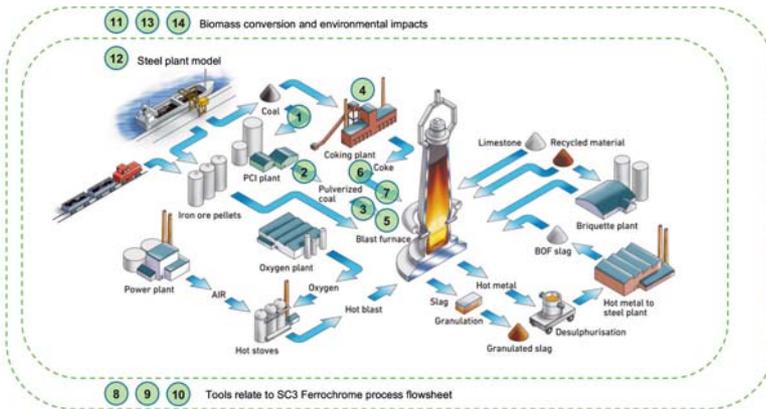


Figure 16. Process flowchart of integrated steel plant and developed tools

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## Further information

### KEY PUBLICATIONS:

Haapakangas, J. 2016. Coke properties in simulated blast furnace conditions – Investigation on hot strength, reactivity and reaction mechanism. Doctoral thesis, University of Oulu.

Haapakangas, J., Suopajarvi, H., Iljana, M., Kemppainen, A., Mattila, O., Heikkinen, E. P., Samuelsson, C., & Fabritius, T. 2016. Coke Reactivity in Simulated Blast Furnace Shaft Conditions. *Metallurgical and Materials Transactions B*, 47(4): 2357–2370.

Kohl, T. 2016. Improving Municipal CHP Production Efficiency by Integrating Biomass Upgrading. Doctoral thesis, Aalto University.

Mattila, O., Vuorenmaa, V., Paananen, T. 2016. Grinding and transport properties of wood char together with blast furnace PCI. SCANMET V, 5<sup>th</sup> International Conference on Process Development in Iron and Steelmaking, 12–15 June, Luleå, Sweden.

Sakaranaho, M., Hietava, A., Suopajarvi, H., Päätaalo, M., Fabritius, T. Charcoal use in chromite pellets – Effect on sintering process, pellet properties and electrical conductivity. *Steel Research International* (to be submitted).

Suopajarvi, H. 2015. Bioreducer use in blast furnace ironmaking in Finland – Techno-economic assessment and CO<sub>2</sub> emission reduction potential”. Doctoral thesis, University of Oulu.

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Wiklund, CM., Helle, M., Saxén, H. 2016. Economic assessment of options for biomass pretreatment and use in the blast furnace. *Biomass and Bioenergy*, 91, 259–270.

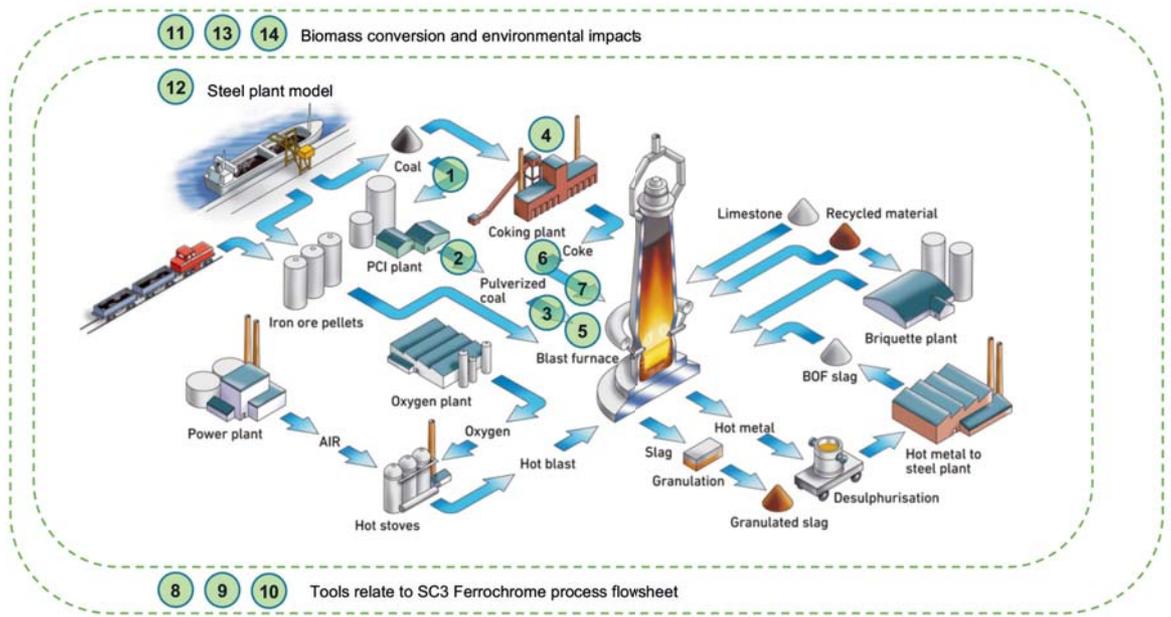


Figure 17. The numbered bullets in the process scheme represent the tools developed in Showcase 4. The tools are described in the following pages

## SHOWCASE 4



### Description of the tool

VTT's bench-scale slow pyrolysis test facilities were modified for the production of biomass-based reducing agents for metallurgical applications. The facilities enable the production of charcoal samples under selected and well-controlled process conditions up to a final carbonization temperature of 950°C. The distillates and gaseous fractions can be collected during the test runs. The products and collected process data can be used in evaluating possibilities to reduce fossil CO<sub>2</sub> emissions in the metallurgical industry by means of using biomass raw materials.

### Application

The tool was used to produce charcoal samples at different carbonization temperatures from different biomass raw materials for the determination of their physical and chemical properties. In addition, mass and energy balance data was provided for further use in modeling tasks.

### Technologies

A raw material sample (max. 6 kg) is placed in the slow pyrolysis reactor and the test run is conducted according to a predetermined temperature program. Liquid products are collected between certain temperature levels and non-condensable gases are continuously analyzed using an online Micro-GC-analyzer. Appropriate laboratory analyses are carried out for raw materials and all the product fractions.

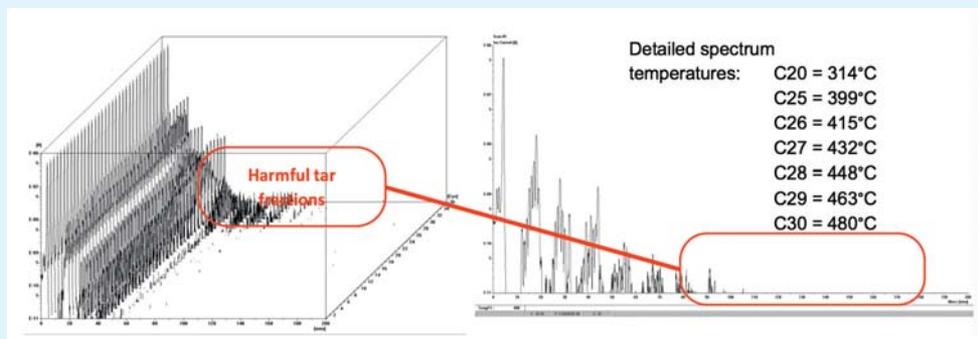
### Scope of application

The developed tool can be used to evaluate the behavior of different raw materials in the slow pyrolysis process, and to assess the quality and properties of different product fractions.

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**– Inventors**            Centre of Finland Ltd.

**Additional Information/**    Fagernäs L., Kuoppala E., Tiilikkala K., Oasmaa, A. Chemical Composition of  
**Publications**            Birch Wood Slow Pyrolysis Products. *Energy & Fuels*, Vol. 26 (2012), No. 2,  
    p. 1275–1283.

## SHOWCASE 4



### Description of the tool

A Netzsch STA409 + QMS was used to study the liberation of tar fractions of different coal grades to find a suitable coal grade for pulverized coal (PC) manufacture. The PC manufacture process involves simultaneous drying and grinding, in which tar components can be liberated, followed by condensation onto the surfaces of the powder separation unit. Ranking of numerous coal grades was done using this method. The left-hand image shows the full spectrum during the measurement of a single coal grade (X-axis: atomic mass unit, Y-axis: QMS intensity, Z-axis: scan number). The right-hand image shows one QMS spectrum of liberated molecules at a certain temperature, and the scan number.

### Application

The ranking of different coal grades ruled out several coals that otherwise were deemed promising. The final selection was made from the coal grades that passed this test. The threshold value was measured from the known good-quality coal grade with negligible tar-based problems in the process chain of PC manufacture.

### Technologies

Thermal analysis and thermogravimetric analysis together with quadrupole mass spectrometer were used in the method.

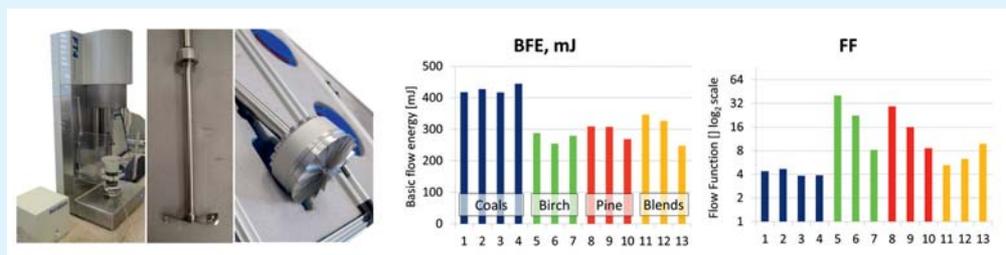
### Scope of application

Selection of carbon-containing material with volatile species in the PC manufacture process. Material preparation including heat treatment can utilize this method to track volatile and condensing species.

**Contact person – Inventor** Olli Mattila, SSAB Europe Oy, Raahе, Finland, olli.mattila@ssab.com

**Additional Information/ Publications** Pikkuaho J. 2015. Jauhettujen kivihiilten ominaisuuksien vaikutus hiilipölyn valmistettavuuteen ja injektoitavuuteen. M.Sc. thesis, University of Oulu.

#### SHOWCASE 4



#### Description of the tool

The substitution of fossil coal with wood char, completely or partially, leads to changes in the flowability properties of the powder mix. The flow properties of mixtures are required to meet the criteria stated by the process designed to use fossil coal in the first case. With FT4, the flow properties stated in the process requirements can be measured and the flow properties of mixtures can be validated.

#### Application

Prior to measurements, two coal types and two wood types with three different slow pyrolysis temperatures were selected. Three mixtures of coal and wood char with a single pyrolysis temperature were measured to seek the most promising blend ratio of coal and wood char enabling co-injection of fossil and non-fossil carbon into the BF. Suitability assessment was made by comparing the flow properties of fossil fuels with the properties of renewable fuels. Industrial validation is done when enough information on the real process requirements has been gathered.

#### Technologies

Measurement in FT4 is done by accurately measuring the force and weight of the sample through numerous measurements.

#### Scope of application

The flow properties of powder have to be controlled in a precise manner in every process using powders. With the aid of FT4, the fluidization gas supply or silo design can be optimized, in addition to the powder manufacture process itself.

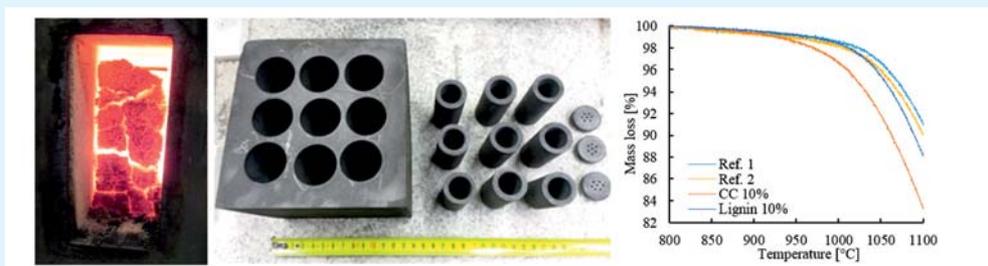
#### Contact persons – Inventors

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Gloucestershire, GL20 8DN, United Kingdom

#### Additional Information/ Publications

Mattila, O., Vuorenmaa, V., Paananen, T. Grinding and transport properties of wood char together with blast furnace PCI. Scanmet V conference 13.–15.6.2016 Luleå, Sweden.

## SHOWCASE 4



### Description of the tool

The use of bio-coke or hybrid coke in blast furnace ironmaking could decrease the CO<sub>2</sub> emissions and increase the internal recycling of carbonaceous by-products in the coal blend. High reactive bio-coke could also lower the fuel rate and increase the gas utilization rate in the blast furnace. The purpose of this tool is to estimate the effect of adding heat-treated biomass and coke fines to the coal blend on the resulting coke quality.

### Application

This tool was used to estimate the feasible proportion of heat-treated biomass and coke fines in the coal blend to maintain the cold strength of the coke and the coke strength after reaction (CSR). The impact of adding biomass and coke fines on the reactivity of the coke was measured with the standardized CRI method and modified isothermal and dynamic temperature conditions.

### Technologies

Coking was conducted in a small-scale pilot oven with 7 kg charge and in a laboratory-scale coking battery. CRI and CSR were determined according to the standards. The modified reactivity tests were performed using a custom-built TGA furnace.

### Scope of application

This tool can be further utilized to assess the quality of alternative coal blends for blast furnace charging.

#### Contact persons – Inventors

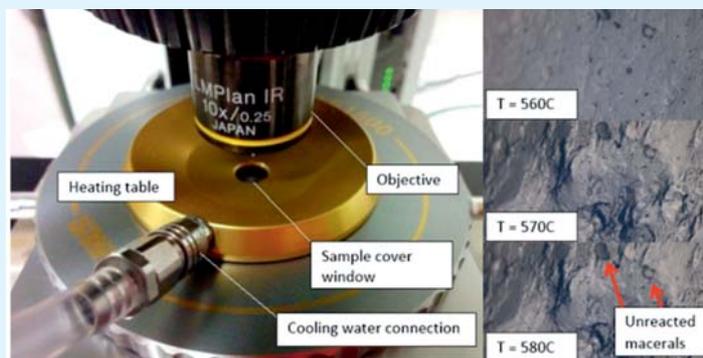
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#### Additional Information/ Publications

Riskilä, T. 2015. Koksialitteiden ja biohiilen käyttö kivihiiliseoksessa. M.Sc. thesis, University of Oulu.  
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## UTILIZATION OF HOT-STAGE MICROSCOPY TO STUDY INJECTABILITY OF AUXILIARY FUEL MATERIAL PARAMETERS FOR A BLAST FURNACE

### SHOWCASE 4



#### Description of the tool

A method based on hot-stage microscopy was developed to study the injectability of auxiliary fuel materials for the blast furnace. The blocking tendency of distribution pipes can be estimated by photographing the material surface under constant temperature increase.

#### Application

The tool is used in the selection of fuels for blast furnace injection. Different components of the sample, such as macerals in the case of pulverized coal, can be identified. The tool is used in combination with other measurement techniques to assess the quality of the injectant.

#### Technologies

The method requires a solid sample, which is mounted on epoxy or another suitable material to enable polishing of the surface for maceral analysis prior to heat treatment and photographing. A thin 1-mm section is separated using a fine-saw, and a small piece of the sample is detached from the slice carefully and put on the heating table. Microscopic images are recorded continuously during the experiment, together with the sample temperature. Inspection of the images revealed clearly the temperature at which the transformation affecting injectability begins.

#### Scope of application

The tool was used to evaluate the behavior of coal macerals during sample heating. The tool can also be utilized to investigate similar changes in coking coal heat treatment or the behavior of biomass-coal samples.

#### Contact persons – Inventors

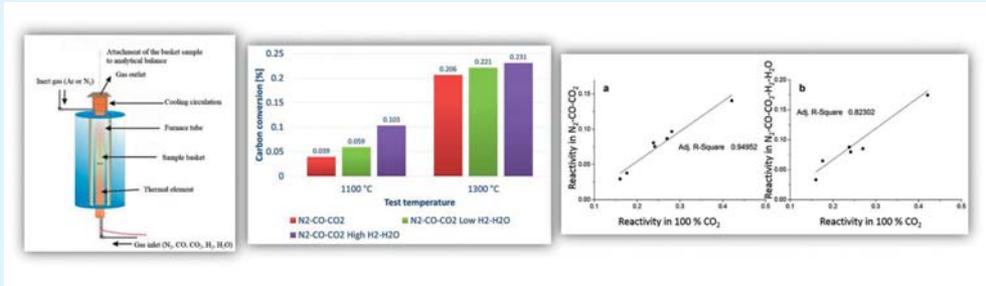
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#### Additional Information/ Publications

Vuorenmaa, V. 2015. Coal macerals and their behavior in PCI process.  
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## A NEW METHOD TO MEASURE COKE REACTIVITY FOR THE BLAST FURNACE PROCESS

### SHOWCASE 4



### Description of the tool

Chemical reactivity is one of the most important properties of coke. The developed method is an improvement over the standard Coke Reactivity Index (CRI) test, which is currently used worldwide. The method measures the chemical reactivity of blast furnace coke in conditions simulating the actual blast furnace shaft gas. Compared to the CRI test, the developed test takes into account the influence of the other main gas components in addition to CO<sub>2</sub>, most importantly the influence of H<sub>2</sub> and H<sub>2</sub>O, which leads to more accurate results. More accurate assessment of coke reactivity in the BF facilitates technical and economic benefits in suitable coke and coal grade selection.

### Application

The method has been verified to be suitable for industrial use. Application in industry is a future task.

### Technologies

Mass balance calculations (Excel) combined with thermodynamic calculation software (HSC Chemistry 7.0) were used to determine the gas profiles used in reactivity testing. A custom-built thermal gravimetric analyzer (TGA) was used to measure the reactivity of multiple coke grades under different blast furnace injection conditions.

### Scope of application

The tool is applicable for the blast furnace, but it could be modified to suit different processes.

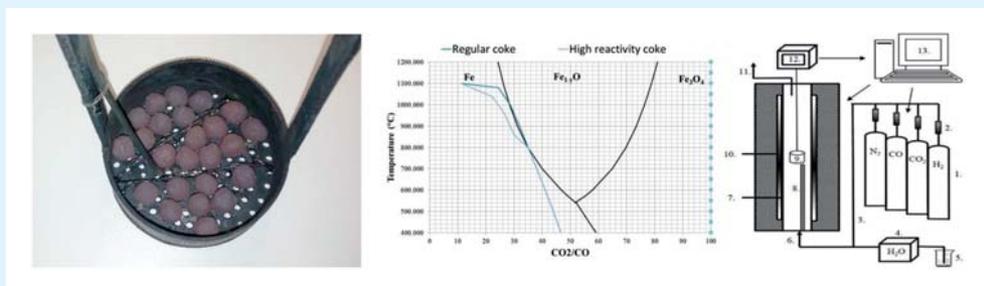
#### Contact persons – Inventors

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Olli Mattila, SSAB Raahe, olli.mattila@ssab.com

#### Additional Information/ Publications

Haapakangas, J., Suopajarvi, H., Iljana, M., Kemppainen, A., Mattila, O., Heikkinen, E-P., Samuelsson, C., Fabritius T. 2016. Coke reactivity in simulated blast furnace shaft conditions. Metallurgical and Materials Transactions B, Vol. 47, No. 4, p. 2357-70.

## SHOWCASE 4



### Description of the tool

The use of high reactive coke has been identified as a possible method to lower the fuel rate and increase the gas utilization rate in the blast furnace process. However, the potential benefits also depend on the reducibility properties of iron ores. The purpose of this tool is to estimate the effect of reactive coke use on the reducibility behavior of various iron ore raw materials. Two different gas and temperature profiles were used, simulating low and high reactive coke charging. The tests are done using two different custom-made lab-scale furnaces.

### Application

This tool was used to estimate the effect of high reactive coke charging on the reduction behavior of multiple iron ore raw materials provided by SSAB Europe Raahe: three different industrial pellet grades, blast furnace briquettes, and sinter.

### Technologies

The conditions of the reactivity testing were determined by Excel-based mass balance calculations and using the thermodynamic calculation software HSC Chemistry 7.0. The tests were performed using two unique custom-built furnaces: the TGA furnace and the Blast Furnace Simulator.

### Scope of application

This tool can be further utilized to assess the implications of reactive coke on multiple other types of raw materials potentially used in the blast furnace.

#### Contact persons – Inventors

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 Timo Paananen, SSAB Europe Raahe, timo.paananen@ssab.com

#### Additional Information/ Publications

Haapakangas, J. 2016. Study of highly reactive coke use in the blast furnace on reducibility of different iron ores, and the role of direct contact in reduction of iron ore – Final Report. University of Oulu.

## SHOWCASE 4



### Description of the tool

The developed two-stage ejector-venturi scrubber is a device for cleaning metallurgical flue gases with water. The purpose of the device is to achieve lower particulate matter emissions simultaneously with decreased energy and water consumption. The modular structure of the scrubber makes it possible to study the influence of scrubber structure and operational parameters on scrubber performance.

### Application

The scrubber was utilized in experimental particle and droplet separation tests in laboratory conditions. The test results indicate that high separation efficiency of particulate matter was obtained via enhanced droplet separation. Emission levels in test runs are notably lower than industry and legislation requirements.

### Technologies

The scrubber acts as a jet pump by pressurizing gas flow with a water jet. Particle and droplet concentrations are measured at inlet and outlet by isokinetic gas sampling methodology, and the cleaning efficiency by differential dust concentrations between inlet and outlet. Water consumption and energy efficiency are examined by measuring gas and water pressures and temperatures.

### Scope of application

The developed scrubber model is primarily intended for use in metallurgical smelting plants, but it could also be applied in other fields. Experimental test findings from scrubber structure and operation have been utilized on an industrial scale already. Improved gas cleaning efficiency enables more efficient utilization of CO gas for energy production.

#### Contact persons – Inventors

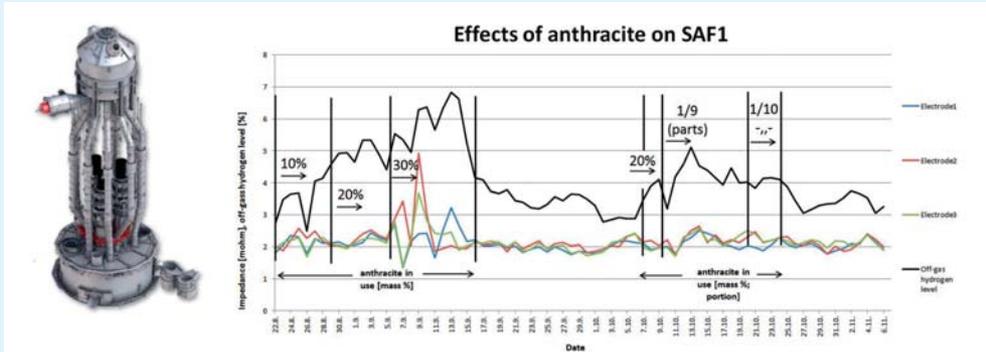
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#### Additional Information/ Publications

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## INDUSTRIAL TEST OF ANTHRACITE IN A SUBMERGED ARC FURNACE

### SHOWCASE 4



### Description of the tool

The use of anthracite instead of metallurgical coke as a reductant for the submerged arc furnace (SAF) can be justified by its lower price and lower electrical conductivity. The main compositional difference between coke and anthracite is the amount of volatile components, which affects the furnace behavior. There are also differences in physical properties: anthracite is weaker than coke, the bulk density of anthracite is nearly 1.5 times that of coke, and electrical conductivity at lower temperatures is clearly lower than for coke.

### Application

Anthracite was used in production tests in all three SAFs at Outokumpu Tornio. The proportion of anthracite varied between 10% and 30% of the total reductant charge. During the production tests, off-gas composition and impedance of the electrodes were measured and analyzed.

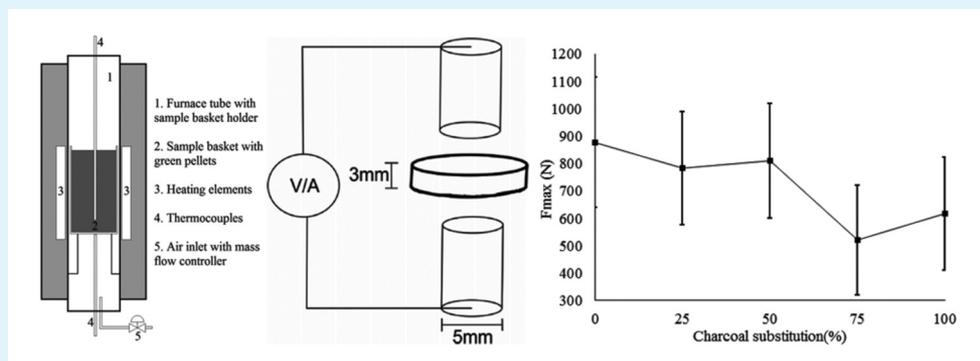
### Technologies

Based on the analyses made in the production tests, the feasible proportion of the anthracite in the reducing agent charge was found to be around 20% for sustained and stable ferrochrome production. Based on the observations, anthracite complicates the operation of the SAF mainly by making it more difficult to interpret the hydrogen level in the furnace.

### Scope of application

The industrial trials have shown that part of the coke can be replaced with cheaper anthracite. This enhances the economic sustainability of ferrochrome production. Test trials also showed that it is possible to use reducing agents with slightly higher volatile content in the SAF. These findings also indicate that the use of biochar could be feasible, if the strength is sufficient.

## SHOWCASE 4



### Description of the tool

Partial replacement of coke with charcoal could lead to lower CO<sub>2</sub> and SO<sub>x</sub> emissions in chromite pellet sintering. The impact of replacing coke with charcoal on the sintering process, the strength of the sintered chromite pellets, and the electrical conductivity of the pellets before and after reduction in an atmosphere simulating a submerged arc furnace were evaluated.

### Application

Chromite pellets were pelletized with a laboratory-scale disc. The proportion of charcoal in the total fuel in the pellet mix was 0, 25, 50, 75, and 100%. The preliminary results indicated that charcoal could replace up to 50% of the coke used in chromite pellets without problems in pellet quality. The strength of the sintered pellets and the electrical conductivity of the pellets before and after partial reduction remained at an acceptable level compared to the reference pellets.

### Technologies

Charcoal for the pellets was produced using an in-house built pyrolysis unit. The pellets were sintered in a tubular furnace until the temperature of the thermocouple in the sample basket reached 1,300°C. A custom-built TGA was used in the reduction tests. Electrical conductivity measurements were conducted using a GW Instek LCR-817 LCR meter.

### Scope of application

This testing methodology can be further utilized to assess different recipes and fuels for chromite pellets.

#### Contact persons – Inventors

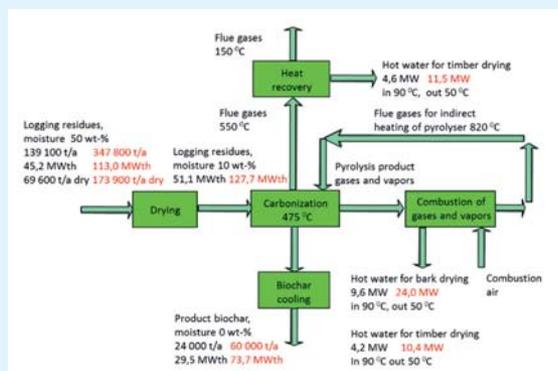
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#### Additional Information/ Publications

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## SCALE-UP ESTIMATION OF A SLOW PYROLYSIS PLANT PRODUCING BIOREDUCER FROM BIOMASS

## SHOWCASE 4



## Description of the tool

A tool has been developed to estimate mass and energy balances, and costs of an industrial-scale slow pyrolysis plant producing bioreducers from different biomass raw materials.

## Application

The developed tool is based on an adaption of torrefaction technology, which is integrated into a sawmill exporting sawn timber. The cost estimation of biochar production is based on previous work on torrefaction technologies (see publications).

## Technologies

The initial data needed for modeling is produced using VTT's bench-scale slow pyrolysis test facilities. Mass and energy balances for industrial-scale pyrolysis processes are evaluated case-specifically using a spreadsheet program (Excel). Finally, the biochar production costs are evaluated using a spreadsheet program (based on the annuity method).

## Scope of application

The same model has been applied to evaluate the utilization possibilities of forest industry side-streams as raw materials for the production of torrefied pellets.

Contact persons  
– Inventors

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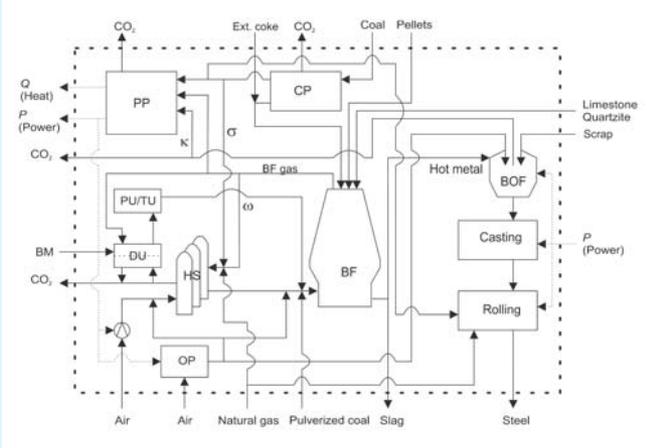
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# 12 STEEL PLANT MODEL

SHOWCASE 4



Description of the tool

The tool models a steel plant with the integration of biomass including units for biomass drying, conversion, and grinding. The conventional units are described by simple expressions, except for the blast furnace, for which a more detailed model is used. Excess heat from the steel plant is used to dry the biomass, which is converted to char by torrefaction, or slow or fast pyrolysis. The model optimizes the economic condition

of the plant, considering a fixed steel production rate but variable coke rate, and oxygen enrichment of the blast. The model can also be applied to optimize the injection rate of biomass after selecting the conversion method. This optimization can be done with respect to operating costs or the net present value (NPV), including the investment costs of new processing (e.g., pyrolysis) units.

Application

Preliminary analysis has demonstrated the slow pyrolysis concept to be the most promising conversion alternative for conditions like those at SSAB Raahe.

Technologies

The tool has been realized in Matlab.

Scope of application

The tool is quite general for a "typical steel plant" and can be adapted to new conditions, but this requires tuning of the submodels (mainly the BF model).

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**Additional Information/ Publications** Wiklund, C., Helle, M., Saxén, H., Economic assessment of options for biomass pretreatment and use in the blast furnace, Biomass and Bioenergy 91 (2016) 259–270.  
Wiklund, C., Helle, M., Kohl, T., Järvinen, M., Saxén, H., Feasibility study of biomass use in a steel plant through process integration, Journal of Cleaner Production 142 (2017) 4127–4141.

## SHOWCASE 4



### Description of the tool

Based on the ultimate composition of the reactant and the yield of certain chosen product compounds, the model closes the mass and energy balances. The heat of reaction (thermal requirement) of the process can then be calculated based on the difference in the heat of formation between reactants and products. Starting values for the product composition are set based on experimental or literature data and are varied within user-set boundaries. The yield of major compounds can be adjusted using a multi-objective optimization approach in order to give realistic results.

### Application

The tool has been used to close mass and energy balances for torrefaction and pyrolysis processes based on data available from experiments and/or the literature. Mass and energy balances have been used in large-scale modeling of a steel plant, and in biomass upgrading integration cases.

### Technologies

The model uses the General Algebraic Modeling System (GAMS) to establish closed mass and energy balances that match experimental data based on a pseudo multi-objective optimization approach for product yield adjustment.

### Scope of application

The model can be applied to all thermochemical conversion processes..

#### Contact persons – Inventors

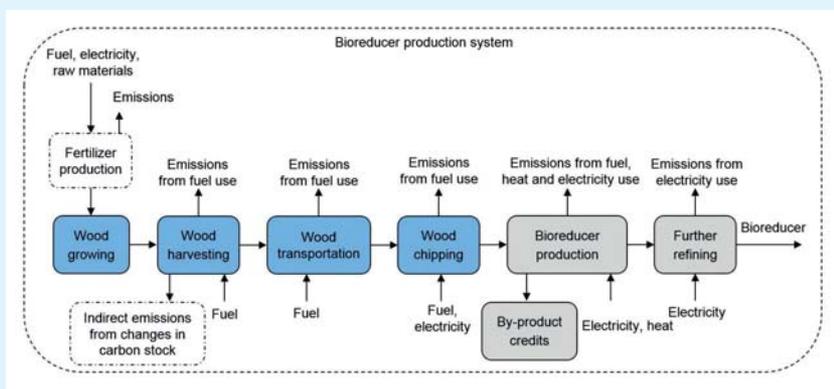
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#### Additional Information/ Publications

Wiklund, C., Helle, M., Kohl, T., Järvinen, M., Saxén, H., Feasibility study of biomass use in a steel plant through process integration, *Journal of Cleaner Production* 142 (2017) 4127-4141.

Kohl, T., Sapei, E., Rocha I.M., et al., Modeling of fast pyrolysis of wood for prediction of bio-oil composition. *APCCChE* 2015.

## SHOWCASE 4



### Description of the tool

A carbon footprint (CFP) model was developed to describe and evaluate the CO<sub>2</sub> emissions resulting from biomass-based reducing agent production. The studied system includes all the energy and fuel inputs to produce bioreducers from different wood-based raw materials. The raw material supply chain (blue boxes in the figure) operations are modeled based on productivities and energy consumptions in an actual forest chip production system. The bioreducer production stage models (gray boxes) are based on simple mass and energy balance expressions. Besides the carbon footprint, the model can be used to estimate the energy efficiency of bioreducer production, which in this case is evaluated by an energy return on investment (EROI) index. EROI is defined as the ratio of energy embodied in the products (bioreducer and energetic by-products) and the energy embodied in fossil-based fuels utilized to produce it.

### Application

The CFP tool has been used to evaluate the CFP and EROI of torrefied wood, charcoal, and Bio-SNG. By combining the CFP results with reductant cost data, the CO<sub>2</sub> mitigation cost was calculated when fossil-based reductants in an integrated steel plant are replaced by biomass-based reductants.

### Technologies

The tool has been realized in the Factory Simulation Tool.

### Scope of application

The CFP model can be used to assess different wood-based supply chain scenarios.

#### Contact person – Inventor

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University of Oulu

#### Additional Information/ Publications

Suopajarvi, H., Pongrácz, E., Fabritius T., Bioreducer use in Finnish blast furnace ironmaking – Analysis of CO<sub>2</sub> emission reduction potential and mitigation cost. Applied Energy 124 (2014) 82–93.

## Graduated PhD students in DIMECC SIMP

Name	University	Title of Doctoral thesis	Graduation Year	Professor
Joseph Hamuyuni	Aalto University	Solubility of high melting temperature oxides (CaO, Al <sub>2</sub> O <sub>3</sub> , Cr <sub>2</sub> O <sub>3</sub> ) in copper oxide liquid	2016	Pekka Taskinen
Thomas Kohl	Aalto University	Improving Municipal CHP Production Efficiency by Integrating Biomass Upgrading	2016	Mika Järvinen
Longgong Xia	Aalto University	Experimental determination of the phase equilibrium in the Cu-O-ZnO-SiO <sub>2</sub> -CaO-MgO system	2016	Pekka Taskinen
Markus Aspiala	Aalto University	A compilation of thermodynamic properties measured with an advanced EMF arrangement	2016	Rodrigo Serna
Rui Zhang	Aalto University	Experimental investigation and thermodynamic description of the BaO-containing oxide system	2016	Pekka Taskinen
Niko Hellstén	Aalto University	Phase equilibria in Cu-O-MgO-A <sub>2</sub> O <sub>3</sub> -SiO <sub>2</sub> systems at copper smelting temperatures	2017	Pekka Taskinen
Satu Tamminen	University of Oulu	Modelling the rejection probability of a quality test consisting of multiple measurements	2014	Juha Röning
Timo Kulju	University of Oulu	Utilization of Phenomena Based Modelling in Operation Design	2014	Esa Muurinen
Hannu Suopajarvi	University of Oulu	Bioreducer use in blast furnace ironmaking in Finland – Technoeconomic assessment and CO <sub>2</sub> emission reduction potential	2015	Timo Fabritius
Mamdouh Omran	University of Oulu	Microwave dephosphorisation of high phosphorus iron ores of the Aswan region, Egypt	2015	Timo Fabritius

Name	University	Title of Doctoral thesis	Graduation Year	Professor
Antti Kempainen	University of Oulu	Limiting phenomena related to the use of iron ore pellets in a blast furnace	2015	Timo Fabritius
Juho Haapakangas	University of Oulu	Coke properties in simulated blast furnace conditions. Investigation on hot strength, chemical reactivity and reaction mechanism	2016	Timo Fabritius
Matti Aula	University of Oulu	Optical emission from electrical arc furnaces	2016	Timo Fabritius
Petri Sulasalmi	University of Oulu	Modelling of slag emulsification and slag reduction in CAS-OB process	2016	Timo Fabritius
Mikko Iljana	University of Oulu	Iron ore pellet properties under simulated blast furnace conditions – Investigation on reducibility, swelling and softening	2017	Timo Fabritius
Ville-Valtteri Visuri	University of Oulu	Mathematical Modelling of Chemical Kinetics and Rate Phenomena in the AOD Process	2017	Timo Fabritius
Hamid Ghanbari	Åbo Akademi University	Sustainable Steelmaking by Process Integration	2014	Henrik Saxén
Carl-Mikael Wiklund	Åbo Akademi University	Optimization of a steel plant utilizing converted biomass	2016	Henrik Saxén
Tamoghna Mitra	Åbo Akademi University	Modeling of Burden Distribution in the Blast Furnace	2016	Henrik Saxén

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Curtin University, Perth, Australia

Cybernetica AS, Norway

Dillinger Huttenwerke, Germany

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