ISSN 1831-9424 (PDF)
ISSN 1018-5593 (Printed)

European Commission

Efficient use of resources in steel plant through process integration

(Reffiplant)

Research and Innovation

EUR 28457 EN

EUROPEAN COMMISSION
Directorate-General for Research and Innovation
Directorate D — Industrial Technologies
Unit D.4 — Coal and Steel

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B-1049 Brussels

European Commission

Research Fund for Coal and Steel

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(Reffiplant)

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Grant Agreement RFSR-CT-2012-00039
1 July 2012 to 31 December 2015

Final report

Directorate-General for Research and Innovation

2017 EUR 28457 EN

Cataloguing data can be found at the end of this publication.

Luxembourg: Publications Office of the European Union, 2017

Print	ISBN 978-92-79-65645-3	ISSN 1018-5593	doi:10.2777/699758	KI-NA-28-457-EN-C
PDF	ISBN 978-92-79-65646-0	ISSN 1831-9424	doi:10.2777/052290	KI-NA-28-457-EN-N

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1 FINAL SUMMARY

1.1 WP 1: Preliminary investigations required for the development of solutions for resource efficiency

The objectives of WP1 are:

- To determine the key processes and factors affecting the resource (materials, water, energy) utilisation and waste generation in a steel plant;
- To identify the techno-economic, engineering and legislative constraints that affect the waste, water and energy management;
- To define the main requirements for benchmarking and transferability of the resource efficiency solutions for the benefit of the EU steel community.
- To identify the most suitable simulation tools for the purpose of the project

Task 1.1: System definition by determination of key processes and factors

An Analysis of the involved steel works plants was carried out with a particular focus on by-products and wastes flows as well as the plant water networks. An inventory of the main flows was pursued: the water networks of all the industrial partners were analysed, the by-products and wastes flows were analysed for only for ILVA and SSAB, as this activity is not a task for TATA Steel. Two lists of Key Processes and factors affecting water and material efficiency, respectively, were produced.

Task 1.2: Analysis of practical and technical issues related to efficiency in dominant processes

In the light of the previously defined Key parameters and performance indicators, each industrial partner identified the potential main directions of investigation in its own facilities for improving the management and exploitation of both water (ILVA, TATA, SSAB) and by-products (ILVA, SSAB). Three priority levels were also defined where level I corresponds to the maximum priority.
The partners also identified 2 lists of practical and technical constraints that affect, respectively, water networks and by-products and wastes reuse and recycling in the steelworks and that could affect also the PI solutions.

Task 1.3: Resources and by-products non-technical constraints

The non-technical constraints that could affect the PI-based solution were analysed and a list of such constraints were produced, which is common to all the industrial partners and it is considered representative to the general situation of the European steelworks.

Task 1.4: Inventory of parameters related to the water, energy, material and waste flows

An analysis was conducted at each industrial partners aimed at pointing out those parameters related to water streams and water treatment processes which need to be considered in the modelling work and therefore also for the data collection. Three lists of measurement points were produced for ILVA, TATA Steel and SSAB together with two common lists of relevant contaminants and main process variables that could be considered in the modelling work.
A similar analysis was conducted by each industrial partners in order to point out the most relevant parameters related to by-products and wastes fluxes and treatment processes. Two lists of measurement points were produced for ILVA and SSAB. Two lists of the main contaminants related to each by-product or waste and of the main process variables were produced, to be considered in the modelling of processes of by-products treatments and reuse for the input and output flows

Task 1.5: Benchmarking of current industrial practices and technologies

An extended benchmarking document on water and by-products was produced with the aim of determining the Best Available Techniques (BAT) and potential benchmark values of water usage in EU steel plants as well as the situation of best performers around the world within the scope of by-products and waste management.

Task 1.6: Analysis of suitability of existing simulation tools to the purpose of the project

Various relevant simulation tools available in the market (both generic and specific softwares) which were suitable to be adopted in the project were reviewed. General-purpose software were considered, which are developed by external software houses, as well as specific ones, that were developed by the research partners and a comprehensive review of all the analysed software was provided. A comparative study of the selected software was carried out. Finally, for chemical water treatment processes, due to the large variety of the treatment processes investigated within the project, Aspen Plus and Aspen Hysys were preferred as they are more generic and flexible. On the other hand, when PI of the total site water network and water reuse strategies are to be considered, WATER was preferred due to the more holistic and high level approach: tailor-made process models were produced for those treatments which were not included in the original model libraries. For by-products and waste management, the reMIND optimization framework was preferred, which embeds MASMOD and TOTMOD to calculate mass balances on specific processes.

1.2 WP 2: Water management

The objectives of WP2 are:

- To collect reliable and substantial data and process knowledge about water and water-associated energy
- To identify potential solutions/technologies for water and energy efficiency
- To identify and verify through simulation the key factors and main outcomes to be taken into account for the simulation of the potential solutions for water efficiency

Task 2.1: Data & process knowledge collection related to material & waste flows

For the processes of interest the relevant variables (e.g. those required for process modelling) were identified and relevant process data were collected and the industrial sites. The first round of data collection and analysis was far more time consuming than expected, but it was completed by the end of 2013, according to the schedule. However, afterwards, due to the realization of data measurement systems that became available within the facilities of some industrial partners, the foreseen duration of this task was extended until the end of the project. Such extra work was actually beneficial for the project overall, as it allowed to collect a considerable amount of fresh data that were used for models and simulations validation. As far as the collection of process knowledge is concerned, technical and process constraints were pointed out for each industrial partners' site.

Task 2.2: Data preparation, analysis, interpretation & reconciliation

The data coming from the three industrial sites were deeply analysed and reconcilied. In order to carry out mass, energy and contaminant balances, PIL, SSSA and MEFOS developed a unified approach that was applied to a case study on each of the three industrial partners' sites. The industrial partners provided a precious support for the data interpretation. Statistical data mining was also applied in some cases to explore correlations among relevant variables (e.g recirculation rate and concentrations of relevant contaminants).

Task 2.3: Modelling and simulation of water treatment processes

An analysis of the industrial partner's sites was conducted in order to identify the main water treatment processes to model. The most relevant water treatment processes were then modelled, in order to realise a models library to be exploited for simulation purposes in WP4.

To this aim, a general model template was realised in order to allow a unified development of the models. Such template can be treated as a "black box", communicating with the incoming and outgoing water streams only the most relevant information (e.g. relevant parameters necessary for the optimisation of the treatment model). The treatment block can embed different models that read as input the values of the incoming parameters (water temperature, flowrate, pH, contaminants properties such as concentration, density, particle diameter) and use them both as variables and boundary conditions to return the output flow conditions (sludge and treated flows). Mass and energy balances should be calculated within the model block itself, which return as output the values of the *n* output water streams parameters to be fed to the subsequent water using operation or treatment. A model library was also developed, including models with two different levels of complexity. Such library also represented a basis for the simulation models developed within WP4.

Task 2.4: Identification of potential solutions/technologies for water and energy efficiency

Both process knowledge collection and modelling and simulation work allowed each industrial partner to identify a list of potential solutions and technologies for water and energy efficiency at their own site. Three lists were compiled (one for each industrial company involved in the project) as a basis for the work in WP4.

1.3 WP 3: Waste minimization

The objectives of WP3 are:

- To collect reliable and substantial data and process knowledge about waste flows and waste-associated energy flows
- To identify potential solutions/technologies for waste recycling and minimization
- To identify and verify through simulation the key factors and main outcomes to be taken into account for the simulation of the potential solutions for waste minimization.

Task 3.1: Data and process knowledge collection related to material and waste flows

For the processes of interest the relevant variables (e.g. those required for process modelling) were identified and relevant process data were collected and the two industrial sites of ILVA and SSAB.

Although the process knowledge collection and the first round of data collection were duly completed by the End of 2013, such as scheduled in the proposal, the industrial partners, also considering the systems which were established for this purpose, decided to prolong the data collection for the whole duration of the project, in order to extend the analysis and acquire new data for the models development, validation and test.

Task 3.2: Data preparation, analysis, interpretation & reconciliation

In the SSAB case, heat-mass-balance modelling (BF, HM desulphurization and BOF) some preparations and surveys were necessary to be performed e.g. detailed BF Zn distribution model – metal/slag/dust/sludge.

According to the priorities expressed by SSAB and ILVA, the focus of the analysis was put on possibilities for a more efficient recovery and treatment of some by-products or waste flows.

The treatment of by-products allows in fact reduction of the volume of waste for disposal, the amount of hazardous waste and the recovery of some raw material for internal or external reuse.

Task 3.3: Identification of potential solutions/technologies for waste recycling

As one of the prior objective of ILVA is the recovery of oily scale after oil removal, two processes were deeply investigated to this aim, namely the R1 process and non-thermal washing. The feasibility of such processes was assessed primarily in a set of lab-scale tests and then models were developed by SSSA in order to assess their viability on a larger scale.

Some solutions for internal recycling of by-products which are currently landfilled were investigated by SSAB and MEFOS. In particular, the application of fine grained BOF sludge to produce briquettes and the use of steel Ladle Slag (LS) as slag former or as complementary binding agent in agglomerates were considered. Finally, as SSAB has no sinter plant, the fine grained material as BF flue dust and fine scrap are recycled via cold bonded briquettes. As the briquette plant has reached its maximum production volume, the possibility to recycle BF dust via direct injection to the BF was explored, in order to free some capacity to increase the total recycling, so that other material can be briquetted. Also the potential utilization of BOF slag to produce fertilizers for agriculture has been taken into account as this was an objective of two ongoing RFC projects where SSSA, ILVA; MEFOS and SSAB were involved.

Task 3.4: Integration of waste treatment processes for waste minimization

SSSA developed some models in Aspen Plus® in order to investigate and evaluate two waste treatment processes, which are of relevant for ILVA: the R1 Process and the Washing Process. Such models, that represent the processes described in Task 3.3, were used to evaluate the potential scalability and re-applicability of the proposed solution in the industry. The showed that the Washing process has a worse performance with respect to the R1 process, but is far simpler and cheaper, as the energy consumption is far lower (no combustion) and the plant is less complex. For SSAB, simulations with the Excel-based TOTMOD model (BF, HM desulphurisation and BOF) were carried out for the recycling into the BF of BF flue dust through direct injection of BOF fine sludge through pelletization and of steel LS as slag former. The simulations showed that the first two options imply major cost savings, while the third one implies minor (or no) cost savings, but all of them are relevant from an environmental point of view as they show a considerable landfill reduction potential.

1.4 WP 4: *Integrated process optimization*

The objectives of WP4 are:

- To analyse a set of PI options for resource efficiency and propose the most suitable ones, or set of optimal ones, by exploiting multi-objective optimisation;
- To produce practical decision-support tools for operational optimisation.

Task 4.1: Development of holistic models suitable for multi-objective optimization

Optimization studies on water networks

SSSA and PIL developed some holistic models aiming at the simplified representation of common unit operations of resources usage to predict the main properties of products flows. These models are inserted in a general-purpose tool for preliminary study of simulation and optimization of industrial water networks (WATER software for water resource) that is implemented by PIL.
Starting from process knowledge and literature state-of-the-art, a simplification of the detailed design procedures was carried out and some Excel-based holistic models of different treatments and processes were developed, related to the wastes and water cycles in iron and steelmaking industry. A holistic models library was added up in common with all the research partners and includes the main treatments and processes representations involved in the industrial case studies to analyse. A superstructure approach was chosen in order to carry out the integrated water network optimisation studies. The unique feature of this approach is that all feasible connections, including water re-use, water regeneration and re-use, water regeneration recycling, local recycling around process and treatment units and pre-treatment of feed-water streams can be considered.
The mathematical model of water network consists of mass balance equations for water and contaminants for every unit in the network. Mixing rules are developed to propagate data from mixer and splitter nodes within the model. The model is suitable studies in both new designs and retrofits: fixed topology studies (no cost solutions), re-use studies involving re-piping opportunities (low cost solutions) or regeneration & reuse studies involving distributed treatments (medium cost solutions). MEFOS and SSAB developed a model for the water network at SSAB plant in Luleå, which is a mass and heat balance in Excel based on the mapping that had been previously done within the project. The model compares available measured values for sources and sinks, to calculated consumption. It can also be used in order to calculate how the water consumption and the flow or quality of the discharge water (temperature and chemical composition) will be affected by a change in the system.

Optimization studies on material flows

The optimisation method used in the modelling work for recycling of secondary materials at both ILVA and SSAB steel production plant is mixed-integer linear programming (MILP) by using the Java-based software reMIND. The model is based on a global mass- and energy balance for the production chain and individual sub-balances for the main processes. The developed model makes it possible to perform total analysis assessing effects from changes in operations regarding the included processes. Analysis using reMIND can be made as multi-objective/multi-criteria analysis and can be made with different time steps. A MILP problem consists of an objective function, variables and constraints. The objective function includes different variables which can be minimised or maximised depending on what is desired. Typical objectives are minimised landfill, cost, CO_2 and energy.
The developed system optimisation model was used by MEFOS and SSSA to investigate recycling strategies for secondary materials to improve the in-plant material efficiency for SSAB and ILVA, respectively. The model generally consists of the steel production routes with the consumption of resources, generation of secondary materials and the material recycling possibilities. Optimisation is made regarding the different recycling options of dusts, sludges and slag, minimising the landfilled amounts, while constraining the energy consumption.

Task 4.2: Implementation of Multi-Objective Optimisation (MOO) techniques

The original choice made in this project at the proposal stage consisted in the application of some GA-based MOO algorithms. Such algorithms were evaluated and it turned out that, to the purpose of the project, GAs showed the drawback of a considerable computational complexity which does not fit well the simulation approach that has been followed in the development of the WATER Int software.
Therefore, finally, an alternative approach was attempted and a MOO module was developed within the WATER software wherein two optimization objectives can be selected at a time. One of the optimization objectives needs to be cost-based (e.g. minimize capital cost, minimize operating cost, or minimize total cost) while the other needs to be flow based (e.g. minimize freshwater

flowrate, minimize treatment flowrate, or minimize discharge flowrate). A series of optimization runs is internally executed with different target value boundaries for flow based optimization objective function. In each of these runs, data set of constraint value and corresponding optimum for cost based objective functions is obtained. These obtained data sets is plotted together and essentially represents the 'Pareto front' for a given problem. This MOO module was implemented within the WATER software with source water flowrate as one of the two objective functions.

Task 4.3: Investigation of case studies and selection of solutions/technologies

Cases-study related to water efficiency

At ILVA, the following subset of options matching the priorities was selected from outlined solutions.

1. reuse of blowdown water from CC No 1 for the off-gas cleaning of the BOF No 1;
2. reuse of blowdown water from 41/2/3 AI for the off-gas cleaning of the BOF No 2;
3. reuse of blowdown water from 33 AI for the TUL1 pipe mill cooling;
4. alternative use of process water streams for off gas cleaning.

Their viability was investigated in detail through process modelling and simulations.
For the analysis of the case studies related to Tata Steel water network, PIL followed a 3 steps systematic work process identify the improvement opportunities and carry out further optimisation work. The following 11 case studies were identified at the end of the second step:
Reuse Solutions:

1. Lagoon Water Segregation
2. Pond A water reuse in Sinter Plant
3. HPM overflow water reuse in Coke Oven 1 and BF OCC via Ancholme water supplies
4. Reuse of Pond A & BF GW water to bowsering tanks
5. TBH blowdown maximisation to BF GW circuit
6. Pond B water reuse in open circuit cooling cycles

Regeneration Reuse Solutions:

7. HC rearrangement to achieve recycled water quality improvements by better capturing of metals and suspended solids
8. Strategic addition of filters to achieve recycled water quality improvements by better capturing of metals and suspended solids.

Regeneration Recycling Solutions:

9. Lagoon 1 water reuse in BF GW circuit followed by Ammonia treatment of its blowdown. Ammonia treatment options considered in this regard are as follows:
   a. Chlorination
   b. Breakpoint Chlorination
   c. Air stripping of ammonia
10. Lagoon 1 water reuse in BF GW circuit followed by RO treatment of BF GW circuit water
11. Demin plant effluent brine concentration

Out of these case studies #3, 8, 9 & 10 were carried forward for stage 3 optimisation. These case studies are merged together under the following 4 headings:

i. Lagoon 1 water reuse in BF GW Circuit
ii. Pond A water reuse in BF GW Circuit
iii. Recycling of the BF GW HCe overflow water with suitable treatment
iv. Heavy Plate Mill (HPM) – Ancholme Water Reuse

Potential solutions for improving water efficiency at SSAB plant in Luleå system concerned

1. the spray-on water used at the CC
2. the BF gas recycling system

Cases-study related to by-products and wastes

For ILVA wastes- and by-product-related issues, some potential solutions include:

1. the distillation and pyrolysis for sludge/scale recovery;
2. a mill scale washing process for not oily scale recovery;
3. the use of BOF slag as fertilizing material and for internal reuse (e.g. pellets for sinter plant).

Simulation of the last additional case study of reuse of BOF slag as fertilizing material was carried out using the holistic models developed by SSSA for material treatment units. The results are promising and show the potential benefits related to the reduction of waste amount and cost saving due to external use as fertilizer. Unfortunately, Italian law dispositions do not allow a manufacturing industry to treat its own wastes without a special permission. For this reason, the obtained results cannot be tested in Italy without the aforementioned permission.
SSAB developed an Excel-based model (TOTMOD) to carry out MEFOS process simulations on preliminary case studies. The method and developed model is based on the Microsoft® Office Excel

spreadsheet model MASMOD. The developed model includes element distribution between slag and metal, and can be used for process simulation and analysis of various operating conditions as well as the influence of specific process parameters.

Task 4.4: Assessment of developed tools for total site analysis based on partners feedback

Water-int™ software is based on linear optimisation framework and hence it does not consider complex ionic interactions between different contaminants. Instead it works on the basis of fixed or linearly varying separation factors which are back-calculated based on the regression of the available plant measurement values. The accuracy of such approach has been validated in the cases study of Tata Steel and ILVA.

The software reMIND, based the MIND method (Method for analysis of INDustrial energy systems), exploits Mixed Integer Linear Programming (MILP). The MIND method was firstly developed to model industrial energy systems, but an upgrade including the development of ad-hoc superstructures allows its Java-based version to be used as a powerful decision support tool also in the steelmaking field. The analyses carried out by MEFOS and SSSA respectively for SSAB and ILVA under different conditions and related to different scenarios represented an assessment of the applicability of reMIND also for analyses aimed at improved by-products and waste re-use and recycling.

Task 4.5: Technology transfer of the methodological approach and of the total site analysis tools

SSSA developed a website reachable at http://www.reffiplant.com with the aims of collecting documentation and data as well as disseminating its goals and public results.

PIL and Tata Steel shared details of the treated case studies, undertaken within Tata Steel, by means of publications. In particular, one of the publications presented at the REFFIPLANT Workshop is specifically aimed at sharing the methodological approach of the BF GW HC overflow recycling related case studies. PIL also produced a document containing generic guidelines for problem types encountered in our case studies. Such guidelines would be useful to engineers from other steel plants who wish to reproduce similar case studies in their respective plants.

SSSA and ILVA shared details of the analysed case studies by means of several publications. In particular SSSA and ILVA presented a paper at the REFFIPLANT Workshop in order to share the followed approach and to communicate how simulation techniques can be powerful instruments in the assessment of an efficient use of different kind of resources. Furthermore SSSA produced a document related to a methodological approach that combining simulation (through different simulation software such as Aspen Plus®, Water-Int or reMIND) and on-site trials supported by collaboration between researchers and plant managers and process engineers can guide steelwork staff to identify potential solutions for a better resource management.

1.5 WP 5: Implementation and assessment of Process Integration solutions for resource efficiency

The objectives of WP5 are:

- To assess the engineering and practical aspects affected by on-site implementation of the new PI solutions at a typical steel plant;
- To investigate the improvements in resource efficiency that could be achieved if the new solutions are implemented at industrial scale;
- To undertake a cost-benefit analysis on the implementation of the potential solutions with the aim of recommending an optimum investment strategy;
- In-depth analysis of the technological and economical constraints and barriers, against the new resource efficient solutions, that would apply to different EU steelmaking sites.

Task 5.1: On-site application of the selected novel solutions for resource efficiency

Water efficiency

ILVA evaluated the possibility to treat and then reuse the wastewater of the coke making area. Indications given by SSSA simulation were followed and tests were carried out in a pilot plant including chemical and physical treatments, where the main separation processes were UltraFiltration (UF) and Reverse Osmosis (RO). Significative results were obtained in terms of contaminants removal by using the global treatment scheme (RO in series to UF). High quality water was obtained and its possible reuse was demonstrated.

Tata Steel carried out magnetic filter trials at the BF GW area, in order to investigate the recycling of the BF GW HC overflow water with suitable treatment to the following aims:

- Improve the Lagoon 1 water quality (e.g. Suspended solids, Ammonia and Chlorides),
- Lower the cost of running the existing dewatering plant,

- Lower the pumping energy costs,
- Improve cooling tower water quality and associated costs – cooling tower performance, Legionella, maintenance.
- Provide substantial water conservation.

However, HC water recycling increases water concentrations (e.g. Suspended solids, Ammonia and Chlorides) within the BF GW water system. Hence, suitable water treatment is needed to reduce the recycled contaminants. Filtration of suspended solids in the recycled HC overflow is a first step. Additional treatment of the water for reducing Ammonia and Chlorides is also necessary - a 10% side-stream of the cooling tower water may be sufficient. A commercially available (Automag Skid) magnetic separation unit was assessed for the filtration of suspended solids in the HC overflow
SSAB pursued a trial campaign on the BF gas cleaning system, in order to investigate the correlations between increased recirculation (reduced sludge flow from clarifier) and conductivity, ammonia nitrogen, chlorides, as well as to find out the behavior of other substances that might affect the process, e.g. due to the risk of fouling. During a few days the sludge flow (water leaving the gas treatment system) was reduced, thereby increasing the degree of recirculation. A series of extra samples were taken and analyzed and the results were compared with historical data.

Resource efficiency related to by-products and wastes
ILVA carried out an extensive experimentation in order to produce Fe-rich pellets maximizing the BOF slag fraction. ILVA laboratory, after some preliminary tests, followed the indications obtained by SSSA through reMIND simulations and good pellets in terms of amount and quality have been obtained with a mixture of pretreated BOF slag and sludge.
SSAB carried out trials on the integrated material recycling at SSAB Luleå. Recycling of three materials, BF dust, BOF dust and LS were considered in the preliminary case studies. BF dust has for several years been recycled via briquettes but in the case study, injection of BF dust was investigated. Almost half amount of the produced BF dust is now injected into the BF and the rest is recycled through briquettes. A first set of on-site trials were devoted to recycling of BOF sludge in the BF via briquettes and involves preparation such as drying, piling and mixing before mixed together with other recycling material in the briquettes. Moreover, SSAB also carried out on-site tests on the addition of Ladle Slag (LS) as slag former in the BF.

Task 5.2: Assessment of improvements made by implemented solutions
The selected PI-based solutions for water efficiency that were investigated through the on-site trials in the involved steelworks were evaluated in terms of contaminants in the related water streams, investment and operating costs and savings (or eventual cost) of fresh water, according to the preliminary analysis that was pursued in Task 1.1 of WP1.
The selected PI-based solutions for resource efficiency through enhanced material recycling, that were investigated through the on-site trials at ILVA and SSAB, were evaluated in terms of overall amount of wastes and by-products that are recovered ad not landfilled and overall amount of saved primary raw materials, according to the preliminary analysis that was pursued in Task 1.1 of WP1

Task 5.3: Evaluation of technological and economical constraints and barriers for a more resource efficient steelmaking practice
The technological and economical constraints of the recommended implementation of each of the considered case studies for ILVA, Tata Steel and SSAB were considered and issues in achieving the different objectives were assessed.
As far as the solutions analysed and implemented in order to improve recycling of materials, it must be underlined that recycling material in the steel industry is common practice and depending on the plant layout, legal restrictions and physical conditions the level of efficient material use can vary between integrated sites. For each plant a specific investigation is needed considering the boundaries and the restrictions that apply for that plant in that specific region. Sometimes the results can be conflicting when trying to minimize deposits with respect to energy consumption and quality parameters in the product.

Task 5.4: Dissemination
All the partners were committed to communicate the results achieved by project to the industrial and scientific community through divulgation material (also available on the project Web site), and scientific papers in international journals and conferences.
In order to give a wider echo and visibility to the REFFIPLANT Workshop, it was organized during the Word Congress on Sustainable Technologies (WCST-2015), a highly qualified conference sponsored, among others, by the IEEE Society which was held in London on 14-16 December 2015.

1.6 WP 6: Coordination and Reporting

The objectives of WP6 are:

- Coordination of project activities, control of project progress;
- Preparation and presentation of progress and final reports.

Task 6.1: Coordination work and meetings

A fruitful and continuous information exchange was established among the project partners via email exchange and telephone conference. Moreover, a private section of the project web site is used for the exchange and storage of the project information such as Grant Agreement, partner presentations and reports. Six physical meetings among the partners also took place.

Task 6.2: Documentation

The minutes of all the partners' meetings were always sent via email. Many documents were developed for data collection.

Task 6.3: Reporting

The First Annual, Mid-Term, Second Annual and Final Reports were delivered in due time. The First Annual and Mid-Term Reports were also discussed and approved in the TGS9 meeting of 2013 and 2014, respectively. The Final Report is being sent to the Commission.

2 SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

2.1 *Objectives of the project*

The overall aim of the project is to improve efficiency of resources (materials, water, energy) in integrated steelmaking plants both by minimising them at source and by finding integrated solutions for recycling, reuse, treatment of waste water, slag, sludge and dust. In order to achieve this ambitious aim, the following objectives were pursued:

- detailed investigations were undertaken at both total site and individual process levels in order to provide the required information for developing novel Process Integration (PI) solutions for resource efficiency;
- several solutions were investigated in order to improve water efficiency at source and available PI options for water systems were analysed; the impacts on energy minimisation and CO_2 footprint were evaluated and the saving potentials were quantified;
- several solutions for improving material efficiency at source through reuse, recycling, and/or treatment of slag, dust and sludge were investigated, in order to identify PI options for a more flexible steel making system through low cost and higher utilisation of secondary raw materials;
- a set of design frameworks were developed in order to generate and analyse alternative process solutions that can lead to the implementation of PI measures. Practical decision-support tools which exploit multi-objective optimization techniques for evaluating the feasibility of different solutions were also implemented.
- The engineering implications, the practical aspects and the resource efficiency improvements associated with the implementation of some of the proposed PI solutions were assessed by undertaking on-site experimental activities at pilot scale and by identifying the constraints for different EU sites.

The project as overall aimed at showing how to exploit PI methods and techniques together with multi-criteria optimisation to identify overall solutions that can help to minimise the steelmaking ecological footprint.

2.2 *Description of activities and discussion*

2.2.1 *WP 1: Preliminary investigations required for the development of solutions for resource efficiency*

Task 1.1: System definition by determination of key processes and factors

An Analysis of the involved steel works plants was carried out with a particular focus on by-products and wastes flows as well as the plant water networks. An inventory of the main flows was carried out: in particular, the water networks of all the three industrial partners were analysed, while the by-products and wastes flows were analysed for only for ILVA and SSAB, as this activity is not shared by TATA Steel.

Description of the industrial facilities

ILVA S.p.A.: ILVA Taranto is an Integrated Cycle Steelworks covering a surface of 15×10^6 m^2: raw materials are discharged at pier to become finished products shipped to several destinations, including other ILVA group works. The following production areas are identified: piers with raw materials storage area; a Pig Iron area including: 1 sinter plant, 4 BFs (BF n.1 is currently not in operation) and, in particular, BF n. 5 is the biggest BF in Europe, 10 Coke Oven Batteries (COBs) (COB n. 2 currently not in operation); Steelmaking area including 2 Basic Oxygen Furnaces (BOFs) with 5 Continuous Casting (CC) lines; Cold Production area with 2 Hot Strip Mills (HSMs), 2 longitudinal Pipe Mill (currently not in operation) and 2 Hot Dip Galvanizing (HDG) lines. In ILVA there is also an Oxygen Plant (revamped in 2011) producing Oxygen gas for the BOFs, and other services such as maintenance shops.

TATA Steel: The Tata Steel integrated steelmaking site, UK, consists of the following main processes: 2 CokePlants (CP), 1 sinter plant, 4 BFs (2 currently operational), 1 basic oxygen plant having, 3 BOF vessels (any 2 vessels operating at a time) and 2 ladle arc furnaces and Concast, 1 Rail mill, 1 plate mill, 1 Medium section mill, 1 Rod mill, 1 Power station for generating electricity, 1 Turbo blower house for blowing air into the blast furnaces. Within and nearby the Tata Steel integrated steel plant there are several companies that support the steel production by supplying or taking materials from site. Tata Steel is only studying the water system. None of the water streams from these companies, except BOC and Caparo, are considered as they have their separate water systems. Hence, only the two companies BOC and Caparo are included within the system boundary for the initial overall study. BOC produces the pure oxygen gas supply for the processes and its excess water is supplied to the steel plant. Caparo produces steel bars and is shown as RM2 in the site water flow diagram.

SSAB: The integrated steel plant in Luleå consists of the following main processes: CP, BF, Desulphurization (DeS), BOF, secondary metallurgy andCC. No rolling mill is included and the final productsare steel slabs. Nearby the integrated steel plant there are other companies involved during the steel production: AGA − the oxygen plant producing pure oxygen to the processes, Nordkalk − lime furnace producing lime to the processes, LuleKraft − the combined heat and power plant firing the excess of process gases. These three units are not included within the system boundary when studying the material, waste and water flows. Flows related to AGA and Nordkalk are considered as external input or output variables of the system. No streams to or from LuleKraft are considered, due to no handling of by-products or wastes flows and a separate water system.

Water networks

ILVA water network

The ILVA Taranto steelworks uses water in its production cycle mainly for plants cooling and for cooling and conditioning materials, process off gases and by-products (such as BF and BOF slag). Both sea water (which is taken from Mar Piccolo) and freshwater (taken from 31 wells and from the two rivers Tara and Sinni) are used. Moreover municipal drinking water is used for civil usage and plant services, but it is a negligible portion and will not be considered in the following. Figure 1 shows a water flow diagram for the overall site.

Sea water undergoes an antifouling treatment through ClO_2 and is sent to the thermal power plants (Taranto Energia) to carry out the indirect cooling and other particular uses (as they need lower temperatures); afterwards it is recovered by the ILVA network Wells and Tara waters have similar features (high salts content and conductivity of about 3000 µS/cm) and thus are conveyed in the same network of industrial water. Some plants exploit water directly extracted from wells that are located nearby. Sinni water has a lower salts content (conductivity of about 450 µS/cm), thus a higher quality is fed to a dedicated distribution network. There is centralized Reverse Osmosis (RO) treatment plant which feeds the same distribution network of the Sinni water (as it has analogous features) as well as three smaller RO plants which produce low salinity water for a dedicated plant.

As far as wastewater treatments is concerned, sea water is used for indirect cooling and directly feed into the sewer as it has not suffered contamination. All the production plants are served by water treatment lines for pollutants removal. Due to the kind of manufacturing processes and the substances which are found in waters, the treatments are mainly aimed at removing suspended solids, oils as well as at cooling.

For suspended solids removal, sedimentation is applied, that separates solid particles from the liquid phase by exploiting the differences in density.

The sludge deriving from CC from HRM undergo two different sedimentation phases: a pre-treatment removing larger particles (in scale pits or hydrocyclones - HCs) and a second refinement phase in which a deeper purification is performed. The secondary sedimentation phase takes place in clarifiers, where pH correction is performed, if required, and where coagulants and flocculants can be added, which favour the aggregation of smaller particles making their separation as sludge easier and quite fast. A further removal of suspended solids is performed through sand filtration under pressure. When the particular manufacturing activity produces oils, additional apparatus are arranged on the sedimentation tanks for conveying the oil into suitable collection systems or for removing it by means of belts and rolls. In order to optimize oil removal, carbon filters are used, which adsorb the particles that are still present in the water after sedimentation de-oiling and sand filtration.

All the wastewaters of the steelworks are released into the open sea (Mar Grande) through two discharge points, that are usually referred to as the first and second discharge channels.

A key step in the overall wastewater treatment system is also represented by the general treatment plants consisting of the end portions of the discharge channels that are, from the functional point of view, longitudinal clarifiers.

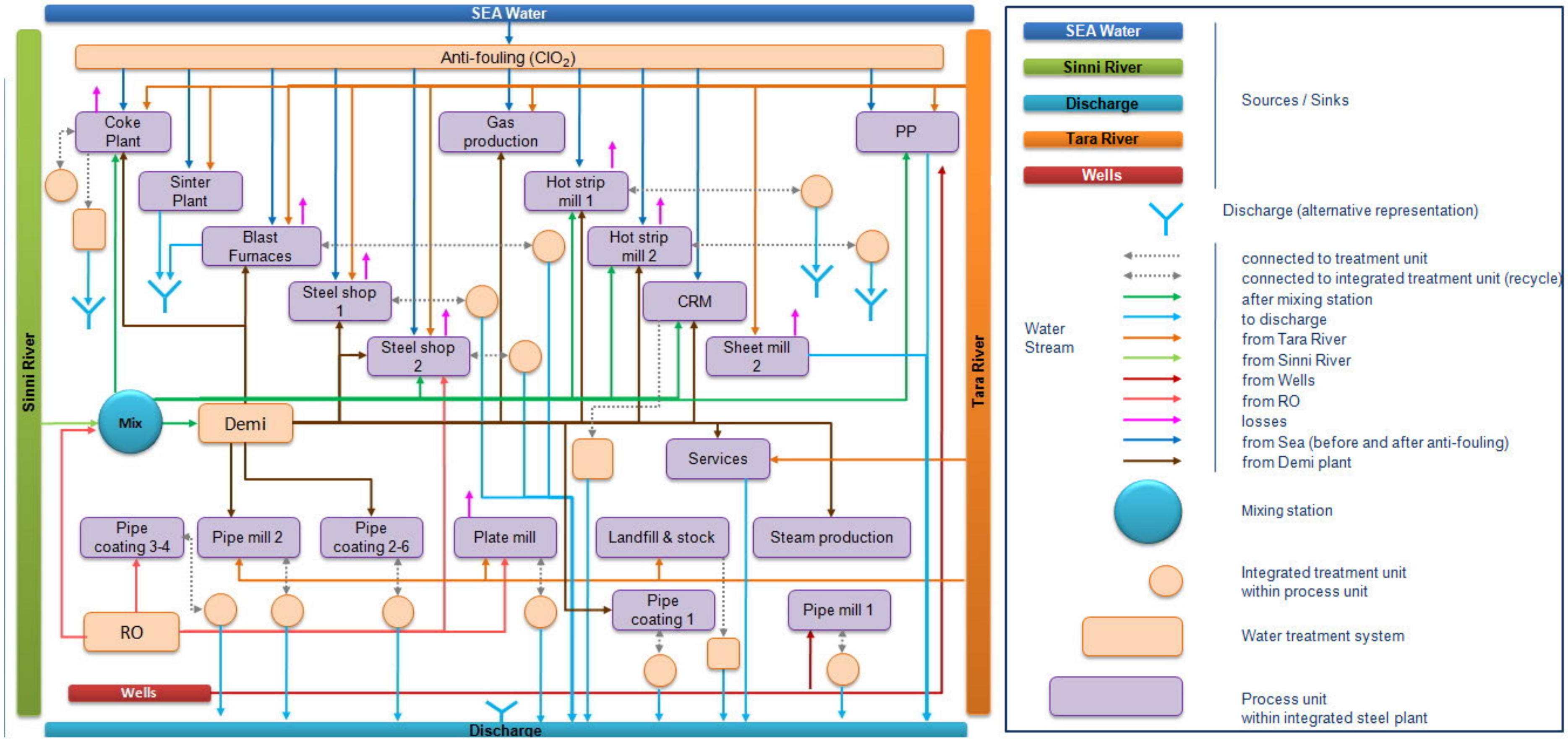


Figure 1: ILVA site overall water flow diagram.

TATA Steel water network

The Tata Steel UK integrated site has a steel production capacity of 4.5 Mt/y, water usage of approximately 2.7 m^3/t steel, approx. 1400 m^3/h fresh water with 200 m^3/h recovered. There are four sources for fresh water abstractions that are between 2.5 and 5 miles from the works: River Trent, River Ancholme, Iron ore Mines water and Boreholes with abstraction limits of 934, 259, 231 and 223 m^3/hr, respectively. The water from the Boreholes is treated in the demineralisation plant to produce high purity water for use as closed circuit cooling make-up water. Figure 2 shows a water flow diagram for the overall site. No temperature variation is foreseen for each freshwater stream; water from Boreholes undergoes a demineralisation process before usage, while only the freshwater from the river Trent that is supplied to CC passes through water softeners before usage. The main water applications are steam generation e.g. power plant, Turbo Blower House (TBH), and cooling (e.g. power plant), TBH, CP, CC, BF and rolling mills. The Biological Effluent Treatment Plant (BETP) treats the waste water from the CP before discharging to the river Trent. The overall site waste water is discharged to rivers at 10 discharge points in compliance with limits for water amount and quality set by the Environment Agency. These water discharge values are currently used as KPIs. Several processes treat their own waste water to either reuse or recover into the site water supply. For instance, at the Heavy Plate Mill (HPM) the waste water is treated and then partly reused within the HPM itself and partly sent to the site Ancholme supply.

SSAB Water network

The cooling water at SSAB EMEA in Luleå is drawn at 2 different points: IV-1 and IV-4. IV-1 distributes cooling water to BF, steel plant and CC and is also used for preparation of boiler water, quenching of coke and cooling of BF and BOF slags. It is also added as make-up water to gas cleaning at BF and steel plant. The cooling at the BF and the steel shop are closed systems that recirculate the primary cooling water, where the IV-1 and IV-4 water is used for cooling in heat exchangers and is not in direct contact with the processes. The water from IV-4 is only used as cooling water at the CP, i.e. in heat exchangers at the by-product plant.

Both water sources are considered fresh water with low salt concentrations. The IV-1 source consists of water from Luleå river with a Chloride concentration in the range of 0.2-270 mg/l and IV-4 is a brackish water from the archipelago of Luleå with a Chloride concentration of 18-950 mg/l. The salt concentrations vary due to climatic and seasonal conditions e.g. high or low water levels in the archipelago and water flow in the Luleå river. Both waters are filtrated before use. The water from IV-4 is pre-heated in winter by re-cycling of used cooling water.

Municipal drinking water is used as cooling water in closed system at the CC. Apart from that, municipal drinking water is used as emergency cooling water at different locations at the site. It is also used to replace IV-1 water for preparation of boiler water when humus concentration is too high. Excess water from the CP is cleaned in fix ammonia stripper and biological waste water treatment plant (biological nitrification and oxidation) before released to the water body Inre Hertsöfjärden together with used cooling water from the CP. At the BF and the BOF, the gas cleaning water is reused after removal of sludge. The sludge is removed by gravimetric settling. The BF sludge is additionally separated through settling in basins before the water is released to the internal water system Laxviken before it is released to the external water body Inre Hertsöfjärden. Since there can be production at the CP even though there is no steel production (during longer maintenance stops, particularly during summer) the water consumption must be individually measured. The CP consumption will be measured as $m^3$of water/ton of dry coke. For the rest of the plant the water consumption will be measured in m^3 water/ ton of crude steel. Mass flows of contaminants/substances with water are expressed as kg/ton of crude steel (CP excluded) and kg/ton of dry coke (for the CP). Figure 3 shows a water flow diagram for the overall SSAB site. No temperature variation is foreseen for each stream, apart from a temperature increase of 8°C of the stream of IV-1 to BF. Water from IV-1 is always filtered before usage: for PC1 application, it undergoes sand filtration and chemical addition; before application in CP it undergoes softening through ion exchange filter, pre-heating and boiler with consequent addition of chemicals for water to boilers, but no softening or chemical treatment for quenching and cooling of crushers is performed.

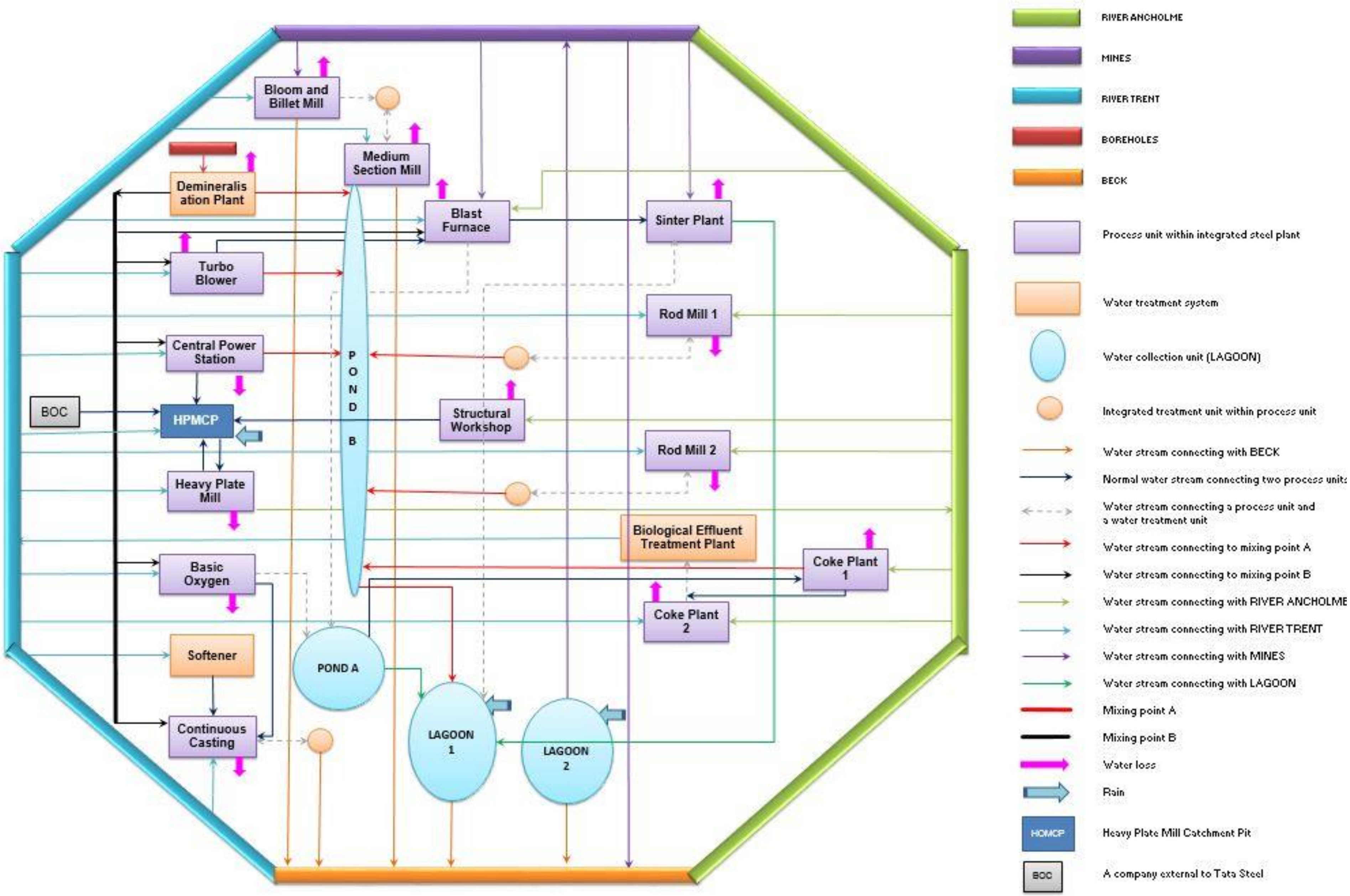


Figure 2. Tata Steel UK site overall water flow diagram

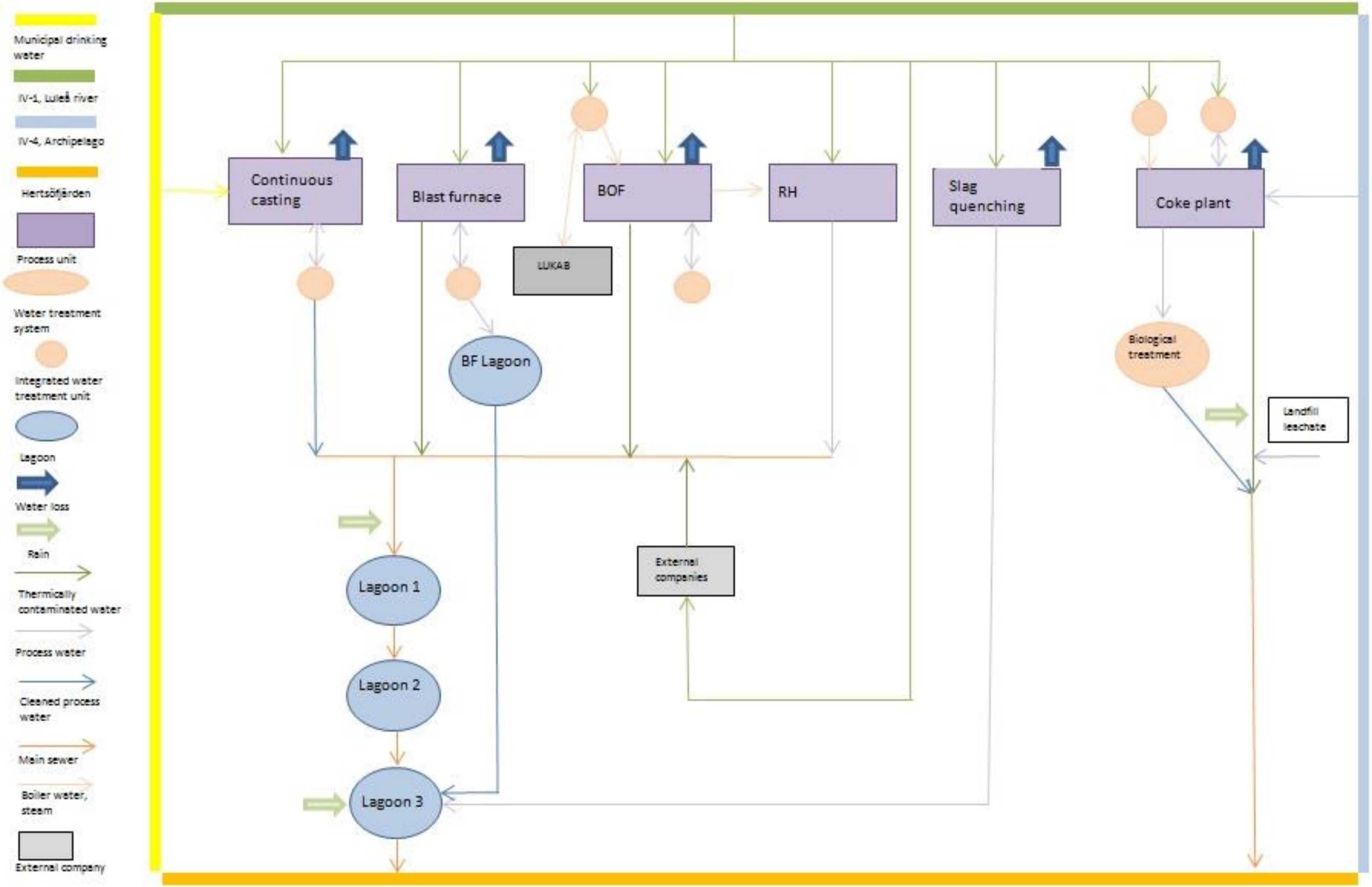


Figure 3. SSAB site overall water flow diagram

By-products and wastes flows

Many by-products and wastes results from the integrated steelmaking cycle: Table 1 provides a first classification and a summary of the main ones and of the processes that generate them.

	CP (quench)	CP (Battery)	CP (gas cleaning)	BP	BP (gas cleaning)	Desulphurization	BOF	BOF (gas cleaning)	Secondary Metallurgy	CC	Hot Rolling
Dust	★	★	★	★	★	★	★		★		
Slags				★		★	★		★		
Scales											★
Sludge	★		★		★			★		★	★
Tar			★								
Refractories		★		★			★		★	★	
Sulphur			★								
Light oil			★								★

Table 1: Summary of by-products and wastes of the integrated steelmaking cycle

In the following a brief analysis is given on by-products and wastes flows at ILVA and SSAB sites.

ILVA Figure 4 shows the by-products and wastes flows for the Taranto integrated steel plant. By-products and wastes at the Taranto Works are BOF and BF dusts, Hot rolling mill scales, BOF and BF slags, BOF and BF sludges. Their destinations are different depending on their classification as wastes or by-products according to the European Regulations (i.e. BREF). In particular BF dusts deriving from BF Gas dry cleaning and BF sludges deriving from wet of-gases cleaning (before the gases are sent to the Plant Energy of Taranto Energia) are by-products that form the mixture for the sinter plant. The amount of BF sludges that cannot be not used into sinter mixture are disposed as waste. BF slag deriving from granulation is sold to Cement Works, while BF slag that does not respect UNI ENV 197/1 standards is used in ILVA internal quarry as environmental recovery according to Italian law limitations. BOF dusts derive from the dedusting system that abates dust produced during charging or tapping operations. Dedusting systems are different and thus also the features of the dusts differ from each other: BOF dust constitutes a percentage of sinter mixture or briquette plant and it could be exceptionally disposed in landfill (internal or external to ILVA depending leaching test results). The Steel plant (BOF+CC) also produces slags that are magnetically separated within the Fe-plant to be used in ILVA internal quarry as recovery material according to Italian law limitations. Sludges produced by the BOF off-gases wet cleaning system are by-products that form the mixture for the sinter plant and, exceptionally, the amount that could be not used into sinter mix is disposed as waste. The HRMs produce scales which are rich in Fe oxides and can be used in sinter mix (fine scales) and sold as waste to Cement works (coarse scales).

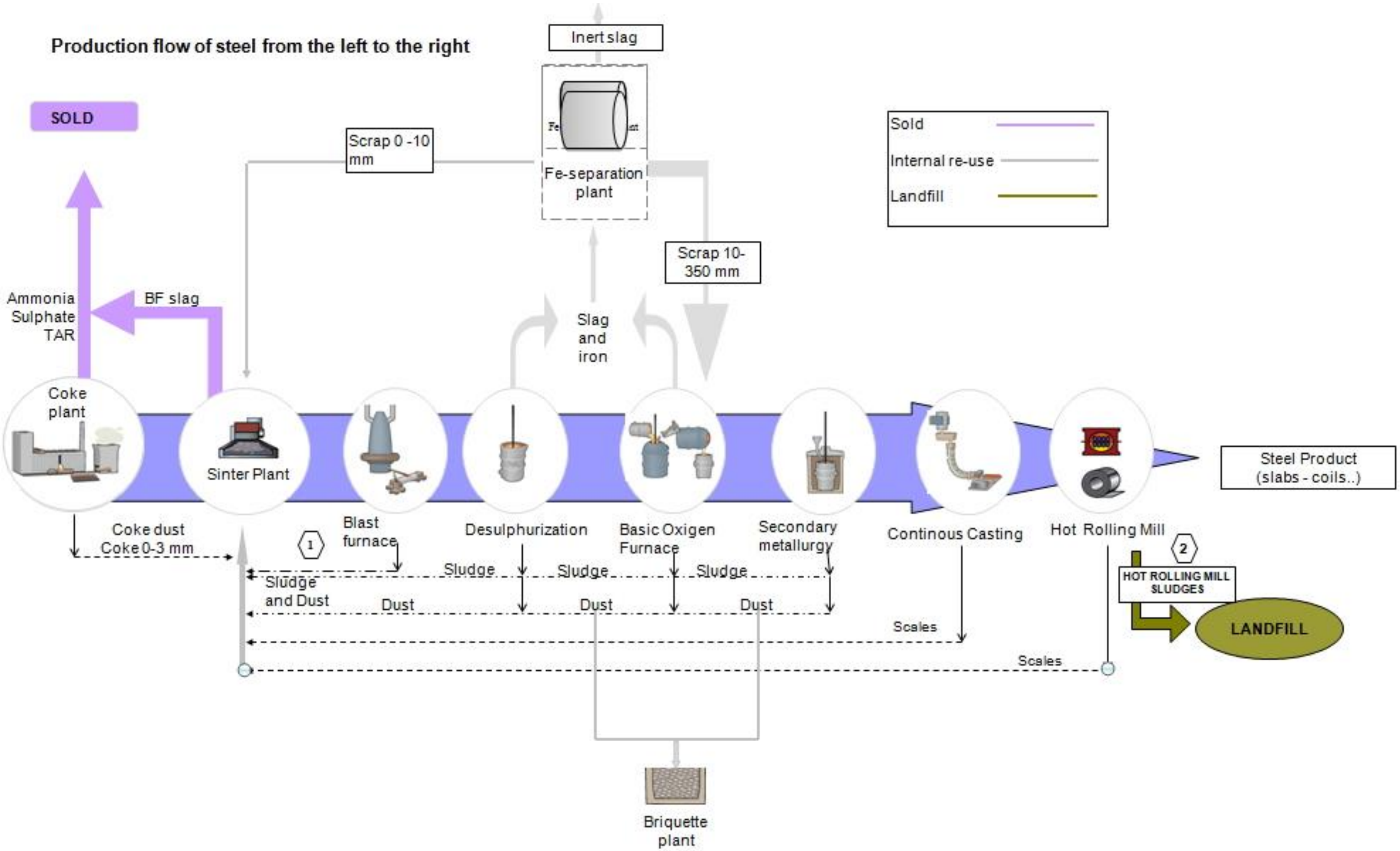


Figure 4. Schematic description of by-products and wastes flows at the ILVA Taranto Works. The materials are sold, internally recycled or landfilled.

SSAB Figure 5 shows the by-products and wastes flows for the integrated steel plant, where dusts, scales, slags, sludges etc. are recycled from different sub-processes (the thickness of the arrows does not represent the magnitude of the flow). BOF slag, 5-55 mm, is recovered within the BF, while the fine fraction are used as internal construction material or goes to landfill. Fine grained scrap and dusts are processed within the *briquette plant* before they are charged to the BF. Recyclable materials like desulphurization slag, BOF iron/slag residuals and steel ladle slag are magnetically separated within the *Fe-plant* to be distributed for different destinations. Materials that have no further use within the integrated steel plant are sold to be used for other applications. Some materials, e.g. materials with high alkali content, fine or wet fractions of dust, slag and sludge are or put on landfill as last resort.

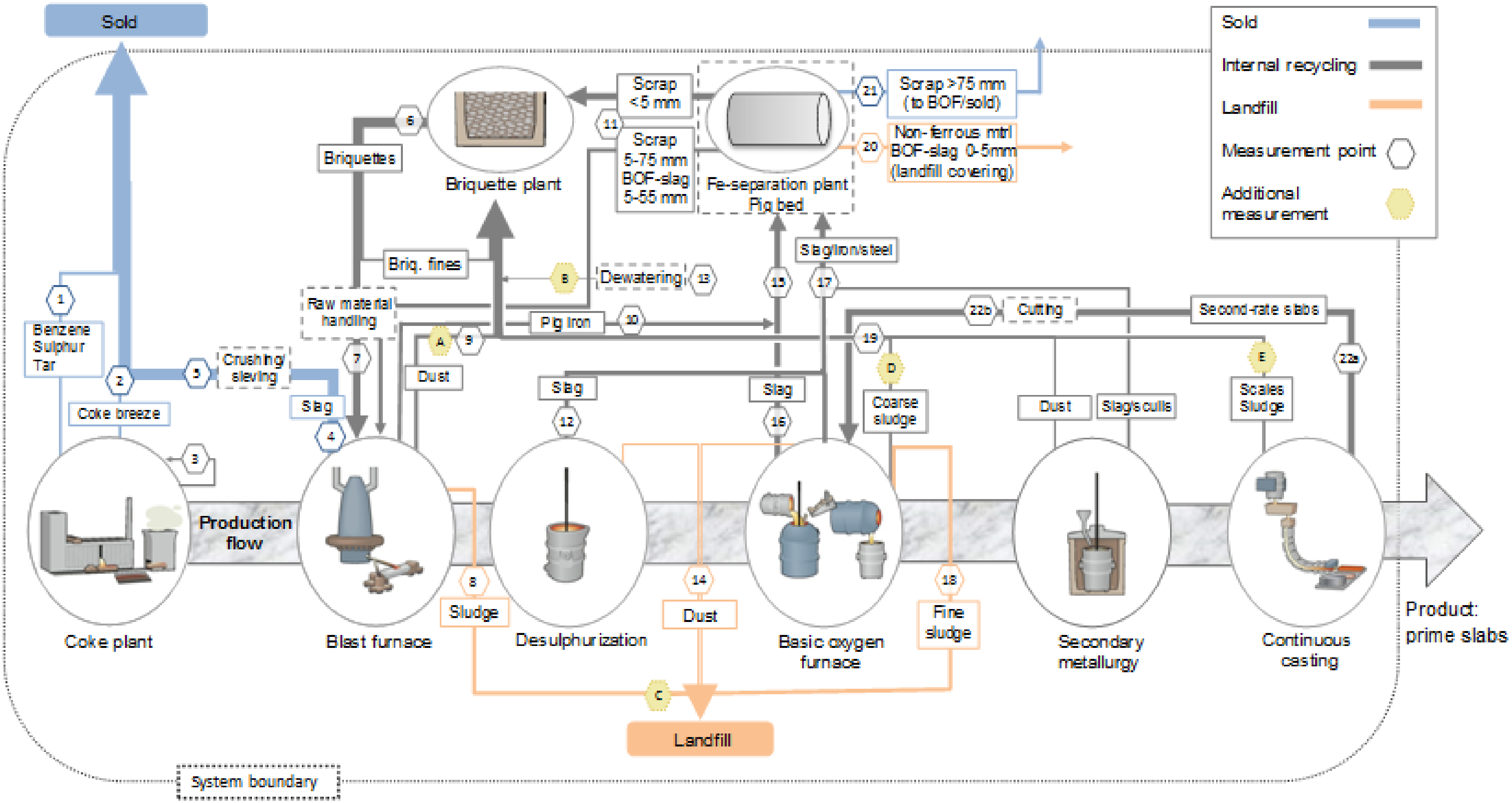


Figure 5. Schematic description of by-products and wastes flows at the SSAB EMEA in Luleå. The materials are sold, internal recycled or put on landfill.

As a result of the previous analysis, an inventory of the treatment processes was developed for each category of by-products. Obviously not all of them are implemented at both ILVA's and SSAB's facilities. The available and potential treatment processes as well as current and potential future destinations of by-products and wastes were summarized, in view of the selection of most meaningful reuse paths to investigate and explore through simulation and treatment processes to model. Thus finally a list of Key Processes and factors affecting water and material efficiency was produced, which constituted Deliverable D1.1 and are reported below.

In particular the main processes to be investigated for improvements in water usage efficiency are: BF, CP BOS and CC. BF and CPs could be key processes for improving water network efficiency. The possibility to use wastewater from one process to fed other processes that require lower quality water was deeply studied to improve water reuse. The list of key parameters and indices for water usage and consumption is reported in Table 2.

	Process Level	Site Level
Key parameters	• Water inlet points − Flowrate and contaminants • Water discharge points − flowrate and contaminants • Process loading	• Water distribution structure among processes • Flowrate for water source, sink and recycle streams • Contaminants in water source, sink and recycle streams
Key indices as constraints	• Water inlet points − flowrate and contaminants limits • Water discharge points − flowrate and contaminants limits	• Effluent discharge to the environment − flowrate and contaminants limits
Key indices as performance target	• Contaminants for certain process streams	• Total operating cost for the water network • Total amount (cost) of fresh water • Total amount of discharge

Table 2: Proposed key parameters and performance indicators at process and site levels for water

The main processes selected for investigation in order to improve wastes and by-products usage efficiency are: BF, Sinter Plant, BOF and HRMs. BF produce different by-products that have been evaluated in order to improve their efficient usage, and Sinter Plant and HRMs are key processes to evaluate the possibility of wastes recycling (not landfilled) after suitable chemical analyses. The list of key parameters and indices for material usage and consumption is reported in Table 3.

	Process Level		Site Level
Key parameters	• Oil content • water content • Zn content • Fe content • C content		• Kg of reused slag/ton of liquid steel • Kg of total landfilled waste/ton of liquid steel • % of recovered oil • total % of recovered by-products • total % of internally recovered by-products substituting primary raw material
Key indices as constraints	• Maximum allowable oil content • Maximum allowable water content • Maximum allowable Zn load to BF		• internal landfill capacity • required steel quality
Key indices as performance target	CP	Kg/ton of dry coke	• overall amount/value of wastes and by-products recovered as primary raw materials • overall amount of landfilled wastes
	BF	Kg/ton of HM	
	Steel Shop	Kg/ton of CS	
	HRM/HSM	Kg/ton of rolled material	

Table 3: Proposed key parameters and performance indicators at process and site levels for by products and wastes

Task 1.2: Analysis of practical and technical issues related to efficiency in dominant processes

In the light of the previously defined Key parameters and performance indicators, each industrial partner identified the main directions of investigation in its own facilities for improving the management and exploitation of both water (ILVA, TATA, SSAB) and by-products (ILVA, SSAB). Three priority levels were also defined where the level I corresponds to maximum priority. The resource management directions are part of Deliverable D1.2 and are reported in Tables 4 and 5.

Pr.	ILVA	SSAB	TATA Steel
I	Reduce freshwater consumption by: rationalization of fluxes and water network maximum exploitation of RO after pre-treatment Installation of new treatment plants	Increased recirculation of quenching water CC Alternative treatments of BF sludge water *e.g.* reuse, treatment	Gas wash and cooling water systems Reduce water demand and waste water in water systems (e.g. BOS, CC & BF) by improving water quality and process optimisation. This improves plant availability, increases energy efficiency and lowers maintenance costs.
II	Reduction of freshwater cost	Increased recirculation of cooling water CP Reuse of water for slag quenching Alternative primary cooling water CC	Water conservation by recovery and reuse of the main lagoon water by: Treatment of the low quality individual process effluents before entering the main lagoon to recover the lagoon water for reuse instead of discharging into river. Treatment of lower flowrates may be much more cost-effective than treating the high flowrate from the lagoon.
III		Alternative CP quenching water Reuse of BF cooling water Quality of raw water to Lulekraft Constant temperature in cooling water BF Alternative use of water from RH-VD	

Table 4: Practical objectives of investigation for water systems

Pr.	ILVA	SSAB
I	Increase the reuse of scale and sludge from the HRM after oil removal Increase reuse of BF sludge	Increased reuse of BOF sludge Drying/agglomeration for recycling in BF, DeS or BOF External application – selling or disposal Investigate the effects of BF dust injection – overall recycling in short and long time perspective Use ladle slag as raw material/slag former in processes such as BF, DeS and BOF and in agglomerates as a complement to cement
II	Recovery of FE units from HRM sludge after oil removal Recovery of oil from HRM sludge	Reuse of BF sludge Drying/agglomeration for recycling in BF, DeS or BOF External application – selling or disposal Recover secondary BOF dust via briquettes to BF, DeS or BOF
III	BOF slag still classified as waste, waiting for eventual reclassification as by-product. In this latter case, external re-use after eventual treatment (e.g. in agriculture) might be included in the present investigation.	Increase internal reuse of BOF slag and find new application for external use Increased/maintained briquette production by investigating the effects of new material compositions.

Table 5: Practical objectives of investigation for by-products

The partners also analyzed the practical and technical constraints that currently affect water networks in the steelworks and that could affect also the PI solutions. The list of the identified issues is part of Deliverable D1.2 and is reported in Table 6.

Practical/technical constraints	Comments
Lack of a unique water network	Users at the end of each system affected by inconsistent delivery pressures when upstream demand is high
Insufficient number of inter-connection points or pipelines	• Poor flexibility or water distribution • Makes it difficult to transport water. • Could be expensive to make new pipeline.
failures to water treatment or distribution systems due to ageing, leaks, blockages, corroded pipes /maintenance	• Serious interruptions to production • Increased need for maintenance
Water quality	E.g. concentration of salt or particles.
Not enough capacity on existing equipment	To low capacity of pumps, pipelines etc.
Distance between process units	Large energy consumption for pumping of water etc.
Existing supplies operating close to their physical limits.	• As water usage increases with increasing steel production, investment are needed to increase total flow rates.
Droughts / lack of buffer system/tanks	• the pumps operating during tidal windows have less time for abstracting the water required (the tidal windows decrease) • Decrease in water quality • Need to increase water reservoir
Lack of instrumentation	• lack of water flow monitors • lack of instrumentation for water quality in critical locations • continuous monitoring can help to reduce waste water, increase recovery and reduce water intake.
Complex regulation	The new PI-system could be difficult to regulate, control and supervise.
Increased emissions on other process units	I.e. sub-optimization. For example increased nitrogen emissions from BF due to coke quenching with biological waste water.
Increasing chemical treatment	More chemicals of same type needed
Need for new chemicals	Need for stronger chemicals that are not environmentally acceptable.

Table 6: Summary of the practical and technical constraints affecting water networks

A deep analysis of the practical and technical constraints that currently affect by-products and wastes reuse and recycling in the steelworks and that can affect also the PI solutions was pursued. The list of identified issues is part of Deliverable D1.2 and is reported in Table 7. Differently from what was done for waters, here a distinction is required among the different by-products and wastes that can be recycled.

Processes	Materials	Application area	Technical/practical constraints
CP	-Benzene -Sulphur -Tar -Coke breeze	Sold Sold Sold Sold	Particle size to small for BF, difficult to briquette, injection requires grinding, wearing
BF	-Briquettes -Dust -Pig iron -Slag -Sludge	Recycled Recycled via briquettes Injection to BF planned Recycled/sold Sold, stored Landfill	Particle size:5-85 mm, feeding system Briquette plant capacity, particle size ≤5 mm Negative impact for solidity of briquettes Wearing of equipment Particle size Air cooled High moisture cont., Zn, alkalis, small particles
Desulphurization	-Dust -Slag	Landfill Recycled/non-ferrous part to landfill	Alkalis, Zn, sulphur Separation technique
BOF	-Dust -Slag -Sludge -Dolomite lime	Landfill Limited recycling to BF (5-55 mm) /<5 mm to landfill Landfill Storage	Alkalis, Zn Particle size, phosphorus, vanadium Fine fraction: Zn, moisture, filter constraint Fine fraction
Secondary metallurgy	-Dust -Slag	Recycled Recycled/ non-ferrous part to landfill	No feeding system at LD or briquette plant
CC	-Dust -Scales -Second-rate slabs -Sludge	Recycled Recycled Recycled Recycled	
Hot Rolling	-Oily scales -Sludges	Recycled/landfilled (depending on the oil content) Landfilled	Oil content % (to minimize to improve recycling) Oil content (%) (to minimise for eventual recycling)

Table 7: Summary of the practical and technical constraints affecting by-products and wastes reuse/recycling

Task 1.3: Resources and by-products non-technical constraints
An analysis of the non-technical constraints that could affect the PI-based solutions was developed and the identified issues are listed in Table 8.

Non-technical constraint	Comment
Environmental legislation	Environmental legislation, environmental permit, e.g. dust, noise, amount and quality of water that can be released to recipient water body. Lack of general EU regulations related to the recycling of by-products outside the steelmaking cycle (for instance the use of steelmaking slag as fertiliser in agriculture is allowed only in some EU countries)
Possible changes in water abstraction licences	There is a major concern especially for the most valuable sources, i.e. the ones providing high quality water: the need increases to invest on treatment techniques capable to provide high (and stable) quality water.
Uncontrolled water usage by the individual plants	Insufficient flow monitoring data are available to managers to control the water consumption in individual plants
Bad-will	For example bad smell from quenching of coke with biological waste water.
Impaired work environment	For example cooling of slags with process water containing unhealthy chemical compounds.
Impaired security in processes	Particles in cooling water could lead to clogging and overheating e.g. in CC.
Personnel resources	The amount of extra maintenance and measurements could be too high. There may be a limit in personal resources to perform the maintenance and the measurements.
Climate/seasonal variations	Large distances, variation in quality of cooling water over the year, e.g. temperature, particles and salt concentrations.
Permit from authority	Big changes in processes demands new environmental permit or at least a notice to authority, which can take long time or even stop a project.
Increased consumption costs	For example if municipal drinking water is used to a larger extent.
Increased maintenance costs	The present crisis situation can limit the possibility major improvements such as renewing parts of the water network, better treatment for reuse/recycling, and maintenance/repair of the system

Table 8: Summary of the non-technical constraints affecting resource efficiency

Task 1.4: Inventory of parameters related to the water, energy, material and waste flows

Water (and related energy) flows
An analysis was conducted at each industrial partners aimed at pointing out those parameters related to water streams and water treatment processes which need to be considered in the modelling work and therefore also for the data collection.
Three lists of measurement points were produced for ILVA, TATA Steel and SSAB (they were included in the mid-term report). Also a list of relevant contaminants was produced, which is reported in Table 9. This table also reports the judgment, which was given by each involved industrial plant on the variable relevance and availability, which also depend on the particular process and/or water stream. This is an obvious consequence of the fact that not all these parameters are relevant for all the water treatment processes. Some of these parameters are currently not measured at the steelworks, at least in standard operating practice.

Contaminant Name	Description	Comments	ILVA	SSAB	TATA
TSS	*Total Suspended Solids (incl. Heavy metals)*	This will be further specified by the different components 10 - 17			
TOC	*Total organic carbon*	Suggested as a substitute for COD and HC. In certain situation a complement instead of substitute.			
THC[a]	*Total HydroCarbons, Includes oils (separate phase from water)*	When physical treatments are concerned, it only indicates "oils" as a separate phase from water. In case of chemical-physical or biological treatments also concentration has to be taken into account and possibly composition			
H_2S[a]	*Hydrogen Sulphides* (possibly also sulphites and sulphates)	Uncertain what is included. Is it just acids? We are generally not interested in the sulphur content. Possibly at certain places, not for all measuring points			
NO_2^- / N [a]	*Nitrite ion / nitrous acid*	e.g. biological plant			
NO_3^- / N [a]	*Nitrate ion / nitric acid*	e.g. biological plant			
NH_3, NH_4^+ / N [a]	*Ammonia nitrogen*	Great focus lately on ammonia discharge. This is of interest generally.			
Tox	*Other toxic compounds and biological processes inhibitors (e.g. CN, SCN^-, PAH, phenols)*				
Cl	*Total chlorine concentration (free active chlorine)*				
Zn	*Zinc*	both filtered and unfiltered			
V	*Vanadium*	both filtered and unfiltered			
Pb	*Lead*				
Ni	*Nickel*				
Cr tot	*Total chromium*				
Fe	*Iron*				
Sn	*Tin*				
SiO_2	*Silica*				

No information available	
Available and relevant	
not available/not relevant	
Need ad-hoc measurements/analyses	

Table 9 Selected Contaminants in the modelling of water treatment processes ([a] Variables that are included at some measuring points)

A second list was produced including the main process variables, which is reported in Table 10.

Variable	UoM	Description	Comments
T	°C	*Temperature*	
M	kg/h	*Total water mass flowrate*	
pH		*pH of the water stream*	
C	mg/L	*Concentration of the i-th contaminant species in the water stream*	
ρ_p	kg/m^3	*Density of suspended solid particles*	Useful for some treatments (e.g. sedimentation), but not generally. The amount of suspended solids before and after treatment is of interest and can be calculated as C*M
p	mm	*Diameter of suspended particles*	Maybe for some specific treatment options, but not generally (see above)
m_c	kg/h	*Mass flowrate of the i-th contaminant species*	
μ	µS/cm	*Conductivity*	Measure of salts dissolved in water
LSI		*Langelier Saturation Index (pH-pH$_s$)*	Implicitly also alkalinity, total dissolved solids and the calcium hardness will be measured.
Alkalinity			Needed if Langlier saturation index is to be evaluated. Not needed at all measuring points.
Hardness	mg/L as $CaCO_3$	*calcium hardness*	Needed if Langlier saturation index is to be evaluated. Not needed at all measuring points.
TDS	mg/L	*total dissolved solids*	Needed if Langlier saturation index is to be evaluated. Not needed at all measuring points.
TSS	mg/L	*Total suspended solids*	
Cl-	mg/L	*Cloride*	

Table 10: Main process variables considered for input and output flows of water treatment processes

By-products and wastes flows

An analysis was conducted at each industrial partners aimed at pointing out the most relevant parameters related to by-products and wastes fluxes and treatment processes.
Two lists of measurement points were produced for ILVA and SSAB (they were included in the mid-term report), which are also reported on the flow diagrams depicted in Figures 4 and 5.
The compilation of lists analogous to the ones reported in Tables 9 and 10 is more complex due to the variety of the different by-products and wastes to consider and related treatment processes. A list of contaminants related to each by-product or waste is reported in Table 11.
A second list was produced including the main process variables to be considered in the modelling of processes implementing by-products treatments and reuse for the input and output flows, which is reported in Table 12.

Chemical contaminants/components of interest																
	Process															
	Sinter		*Coke Oven*		*BF*		*BOF*		*CC*		*HRM*		*Desulphurisation*		*Secondary Metallurgy*	
Form	D-SD		D-SD		D-SD		D-SD		D-SC-SD		SC-SD		D-SG		D-SD-SG	
Component	*ILVA*	*SSAB*	*ILVA*	*SSAB*	*ILVA*	*SSAB*	*ILVA*	*SSAB*	*ILVA*	*SSAB*	*ILVA*	*SSAB*	*ILVA*	*SSAB*	*ILVA*	*SSAB*
Moisture																
Oil																
CaO					+SG		+SG(+desulphurisation SG								Only SG	
Total Cl					+SG (granulation)								OnlyD	Only D		
Total Cr					+SG (granulation)				noD +SG	noD +SG					Only SG	
Cr_2O_3							only SG (+desulphurisation SG)	only SG (+desulphurisation SG)								
Total Fe					+SG(+desulphurisation SG)		+SG(+desulphurisation SG)									
Metal Fe							+SG(+desulphurisation SG)	+SG(+desulphurisation SG)							Only SG	Only SG
FeO					Only SG	Only SG	Only SG	Only SG							Only SG	Only SG
Fe_2O_3							Only SG	Only SG								
P_2O_5 (Total P)							+SG(+desulphurisation SG)								Only SG	
Total Pb/ Total Cd					+SG (granulation)	+SG (granulation)							Only D			
V					Only SG		Only SG									

NOTES
SSAB has no sinter plant, slag granulation and HRM.
D: Dust SD: Sludge SG: Slag SC: Scale

Available and relevant
Not Available/not relevant
Need ad-hoc measurements/analyses
No information available

Table 11 Selected Contaminants for by products and wastes

Variable	UoM	Description
T	°C	*Temperature*
pH		*pH of the material*
Grain size distribution (slag)	Mm	*Granulometry*
Particle size distribution (dust)	Mm	*Granulometry*
Bulk density	g/cm^3	
Moisture	wt-%	*Index of the water content, relevant especially if dewatering operations are required*
Relevant chemicals		
Total Fe	wt-%	*Total Iron content, important discriminant for the internal recovery*
C content	wt-%	*Total carbon content*
Oil	mg/kg	*Total oil content, important discriminant for internal and external recovery, cited among the KPis*
other chemicals from the contaminants tables		*See Table 18*

Table 12: Main process variables considered for input and output flows of processes implementing by-products treatment and recovery

Task 1.5: Benchmarking of current industrial practices and technologies

Benchmarking documents on water and by-products were produced and can be found in Appendix A.

Task 1.6: Analysis of suitability of existing simulation tools to the purpose of the project

Various relevant simulation tools available in the market (both generic and specific softwares) which are suitable to be adopted in the project were reviewed. General-purpose software programs were considered, which had been developed by external software houses, as well as specific ones, that had been developed by the research partners. A comprehensive review of all the software programs listed in see Table 13 was provided.

No.	*Generic*		*No.*	*Specific*	
	Software	Developer		Software	Developer
G.1	ASPEN Plus	AspenTech	S.1	WATER	PIL
G.2	HYSYS	AspenTech	S.2	Remind	MEFOS/PRISMA
G.3	PRO/II	Invensys	S.3	MASMOD/TOTMOD	MEFOS/PRISMA
G.4	UniSim	Honeywell			
G.5	SuperPro Designer	Intelligen, Inc.			
G.6	GAMS	GAMS Development Corporation			
G.7	Matlab	Matworks			

Table 13: List of the considered softwares: the prefix "G" represents generic softwares while prefix "S" represents specific ones

A comparative study of the selected software was carried out. Finally for chemical water treatment processes, due to the large variety of the treatment processes investigated within the project, Aspen Plus and Aspen Hysys were finally preferred as they are more generic and flexible. On the other hand, when process integration of the total site water network and water reuse strategies are to be considered, WATER was preferred due to the more holistic and high level approach and tailor-made process models were produced for those treatments which were not included in the original model libraries. On the other hand, for by-products and waste management, the reMIND optimization framework was preferred, which embeds MASMOD and TOTMOD to calculate mass balances on specific processes.

2.2.2 WP 2: Water management

Task 2.1: Data and process knowledge collection on water and related energy

The extraction of relevant data was carried out. For the processes of interest, in fact, the relevant variables (e.g. those required for process modelling) were identified. The first round of data collection and analysis was far more time consuming than expected, but afterwards, due to the realization of data measurement systems that became available within the facilities of some industrial partners, the foreseen duration of this task was extended until the end of the project. Such extra work was actually beneficial for the project overall, as it allowed to collect a considerable amount of fresh data that were used for models and simulations validation. In particular at ILVA the installation of a new (which was not planned at the beginning of the project) system of measurement, allowed the acquisition of an extensive set of process data and variables. As far as the collection of process knowledge is concerned, technical and process constraints were pointed out for each industrial partners' site. At ILVA a table of internal process constraints was compiled (see Appendix B) in order to determine potentials of internal water re-use, as a basis for the integrated optimization studies to be carried out in WP 4. Such table contains in fact the maximum allowed concentration of contaminants in the water entering each process in order to make it usable. The collection of this information required an intense exchange of information and several discussions with plant personnel in order to identify nominal operating conditions and possible margins for improvement.At SSAB process knowledge regarding the water systems was collected mainly by investigations of the process information systems, technical drawings and discussions with operating personal. It has ended up in: (I) Flow diagrams; (II) Lists of measurement points including the kind of measurements performed at each point; (II) Process constraints. Flow diagrams provide an overview of the system including available measurement points for different kinds of measurements, as exemplified in Figures 6 and 7.

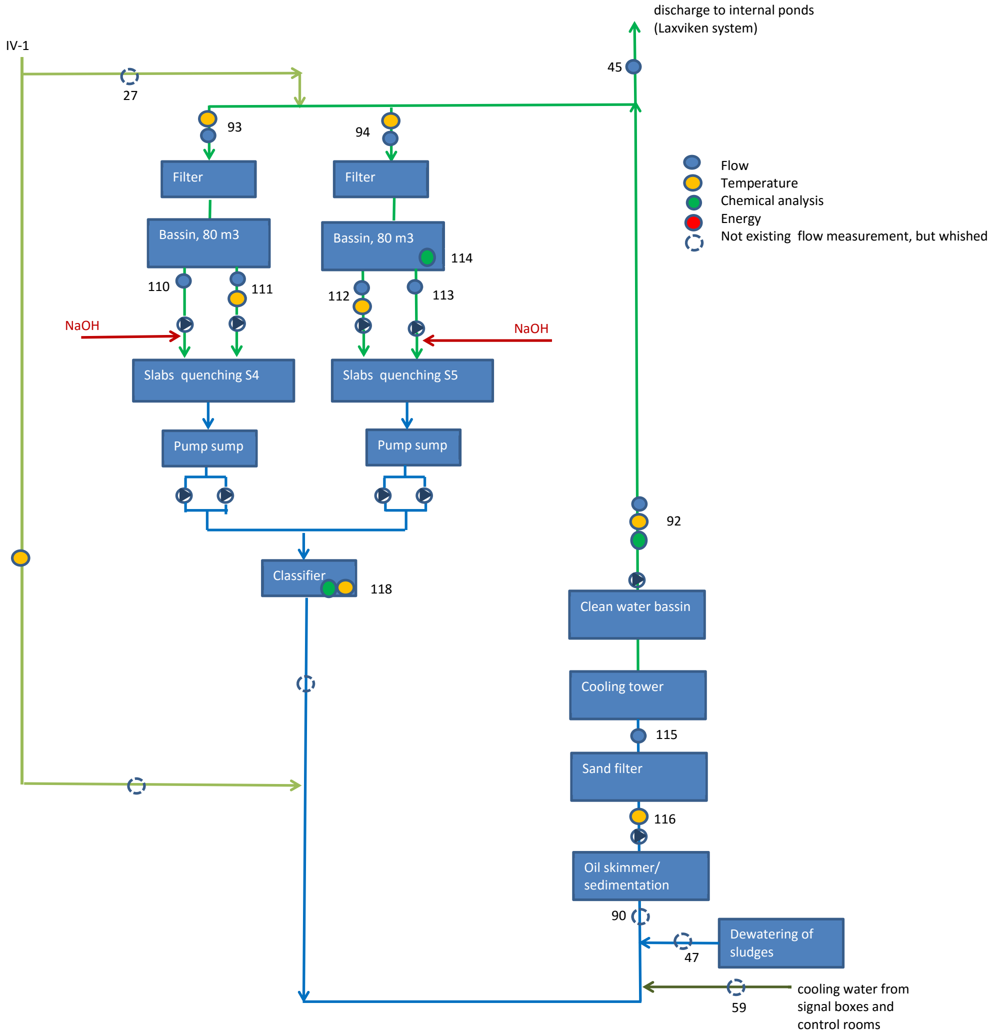


Figure 6. Example of flow diagram with added measuring points for the recirculating of quenching water system at the CC at SSAB.

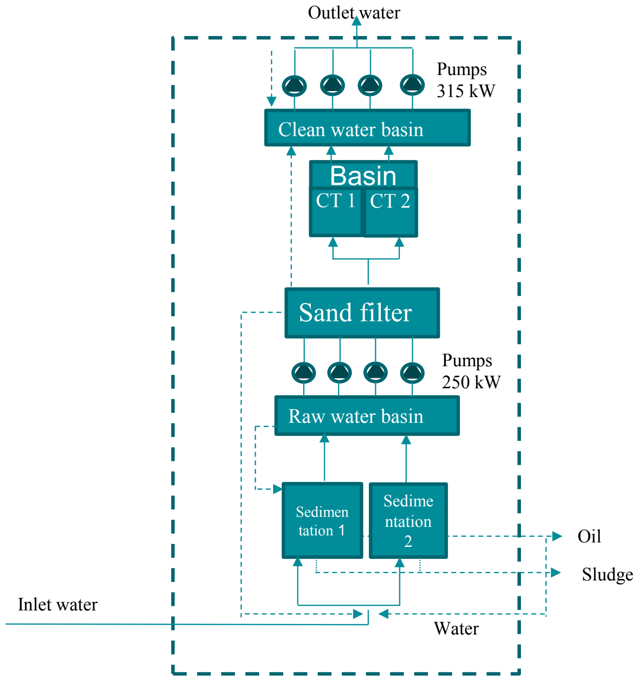
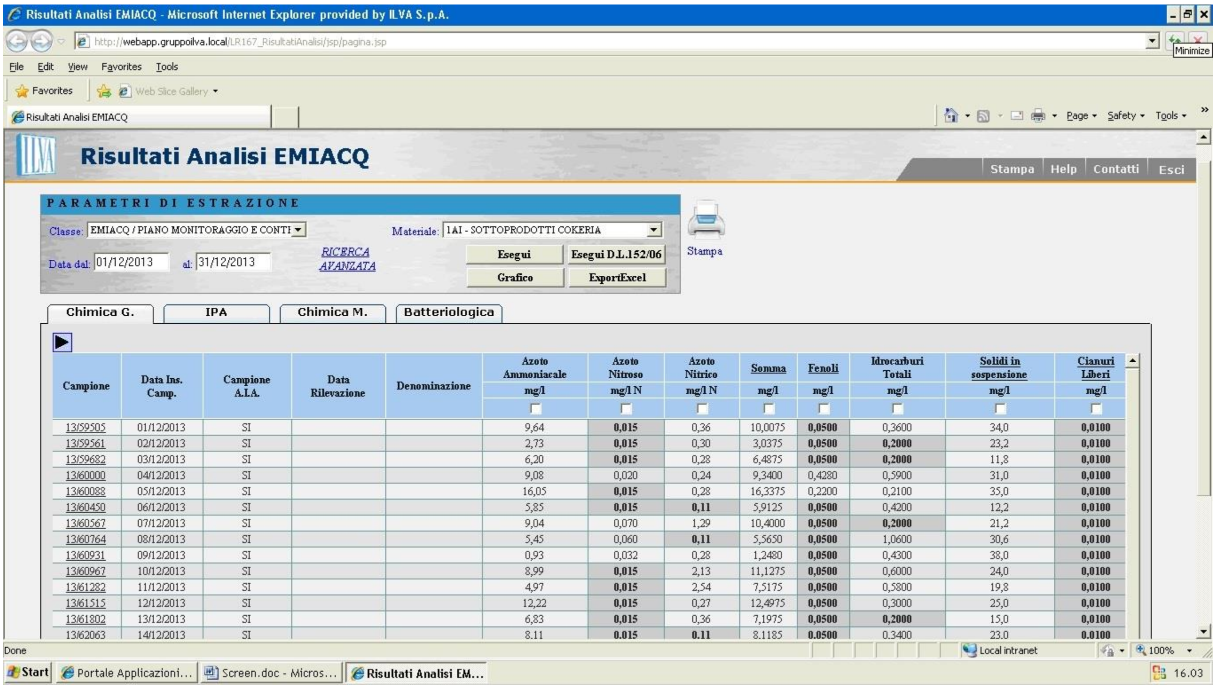


Figure 7: Outline of the water treatment of CC quenching water.

The measurements include water flow, temperature, energy consumption, chemical consumption, chemical composition of the water and for specific pumps information if they are in operation or not. Lack of measurements was identified. Additional flow measurements were installed at some places, *e.g*. at the outlets of the steel work, in order to be able to make overall flow balances. Due to practical limitations it was impossible to install flow meters at some points. Estimations were made at these places.
Technical and process constraints were identified. The main constraints for the BF gas cleaning system are devoted to a temperature upper limit and risk of carbonate precipitation/clogging and for the CC recirculation system mainly to temperature and the infrastructure of the system. Due to good quality of the make-up water (fresh water) there has been little focus on other demands regarding the chemical content of the water. If the recirculation ratio is possible to increase additional constraints might be identified.

Task 2.2: Data preparation, analysis, interpretation & reconciliation

In order to carry out mass, energy and contaminant balances, PIL, SSSA and MEFOS developed an approach that was applied to a case study on each of the three industrial partners' sites. A description of such cases is provided in Appendix E. the example used in this case is the BG Gas Wash (GW) circuit. The case study demonstrates strategies to join available data with reasonable estimates and assumptions. Similar strategy was adopted for data reconciliation and simulation of other water circuits and lagoons. As discussed towards the end of the case study, these simulations are further used to systematically plan and prioritise future measurement campaigns.
At ILVA the new data acquisition system allowed to measure on a continuous basis (hourly data are available) the flowrate, temperature and pH of every discharge point. Laboratory analyses carried out on a daily basis are also available, divided by process or treatment plant, through a web portal that interactively allows to export the data in different formats. It is also possible to display the trend of a single contaminant over an arbitrary time horizon, as exemplarily depicted in Figures 8 and 9.



Campione	Data Ins. Camp.	Campione A.I.A.	Data Rilevazione	Denominazione	Azoto Ammoniacale mg/l	Azoto Nitroso mg/l N	Azoto Nitrico mg/l N	Somma mg/l	Fenoli mg/l	Idrocarburi Totali mg/l	Solidi in sospensione mg/l	Cianuri Liberi mg/l
13/59505	01/12/2013	SI			9,64	0,015	0,36	10,0075	0,0500	0,3600	34,0	0,0100
13/59561	02/12/2013	SI			2,73	0,015	0,30	3,0375	0,0500	0,2000	23,2	0,0100
13/59682	03/12/2013	SI			6,20	0,015	0,28	6,4875	0,0500	0,2000	11,8	0,0100
13/60000	04/12/2013	SI			9,08	0,020	0,24	9,3400	0,4280	0,5900	31,0	0,0100
13/60088	05/12/2013	SI			16,05	0,015	0,28	16,3375	0,2200	0,2100	35,0	0,0100
13/60450	06/12/2013	SI			5,85	0,015	0,11	5,9125	0,0500	0,4200	12,2	0,0100
13/60567	07/12/2013	SI			9,04	0,070	1,29	10,4000	0,0500	0,2000	21,2	0,0100
13/60764	08/12/2013	SI			5,45	0,060	0,11	5,5650	0,0500	1,0600	30,6	0,0100
13/60931	09/12/2013	SI			0,93	0,032	0,28	1,2480	0,0500	0,4300	38,0	0,0100
13/60967	10/12/2013	SI			8,99	0,015	2,13	11,1275	0,0500	0,6000	24,0	0,0100
13/61282	11/12/2013	SI			4,97	0,015	2,54	7,5175	0,0500	0,5800	19,8	0,0100
13/61515	12/12/2013	SI			12,22	0,015	0,27	12,4975	0,0500	0,3000	25,0	0,0100
13/61802	13/12/2013	SI			6,83	0,015	0,36	7,1975	0,0500	0,2000	15,0	0,0100
13/62063	14/12/2013	SI			8.11	0.015	0.11	8.1185	0.0500	0.3400	23.0	0.0100

Figure 8. Sample window showing coke ovens wastewater discharge characteristics

The system automatically points out measurements that are below the sensitivity range of the instrument: in case a value lower than the lower bound of the instrument is measured, the system automatically registers the lower limit. Moreover, automatic alerts are generated (the responsible personnel receive automated email messages) in case outliers are individuated, e.g. if a value of flowrate, T or pH is outside a predefined range, or if a contaminant value overcomes a pre-defined threshold (e.g. 80% of the emission limit) in daily laboratory analyses.

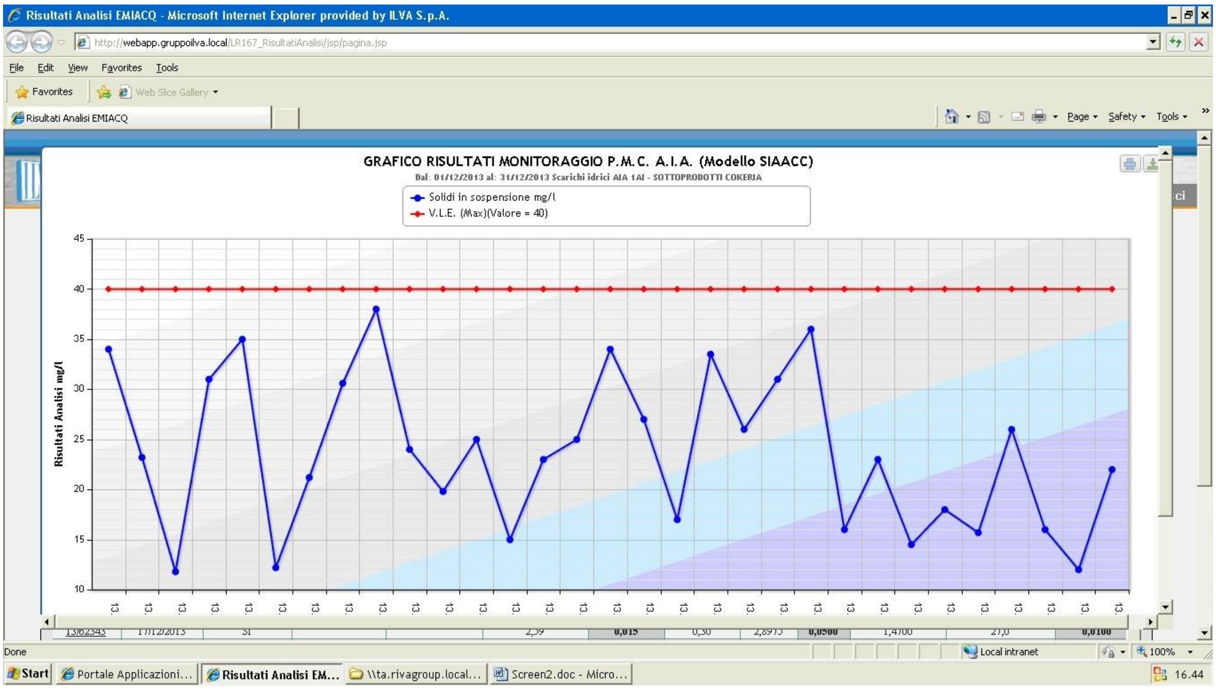


Figure 9. Sample window showing coke ovens wastewater discharge characteristics (focus on the TSS trend)

At Tata Steel data collection was pursued in the areas outlined in Figure 10. The first phase of the process data collection mainly concerned individual processes: a combination of historical plant data, spot measurements and estimations based on plant data available from other steel plants were used to achieve heat and mass balance of the entire site water network.

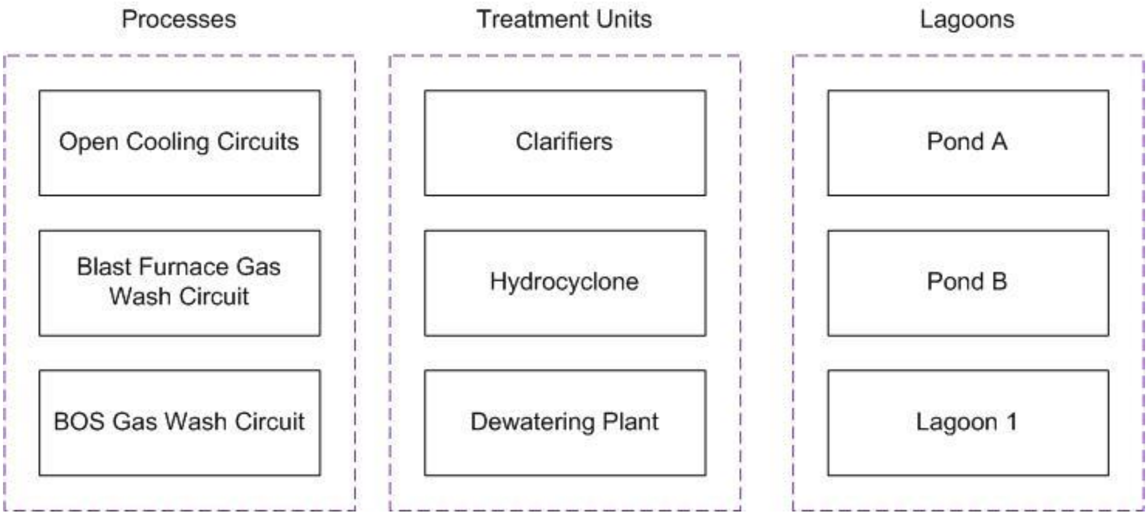


Figure 10 Tata Steel data collection overview

Details of the further data collection efforts are summarised below.

Lagoons 4 sets of water samples were taken for all individual water sources going into the lagoons (see Figure 11). These data sets were associated through a reconciliation approach and the final heat and mass balance for the lagoon system were calculated. Some exemplar results of this operation can be found in Table 14 for some key contaminants. Solubility and contaminant concentration of individual metals were also measured to predict metal contaminant levels (e.g. Fe, Zn, Pb, Ni) in the discharge water.

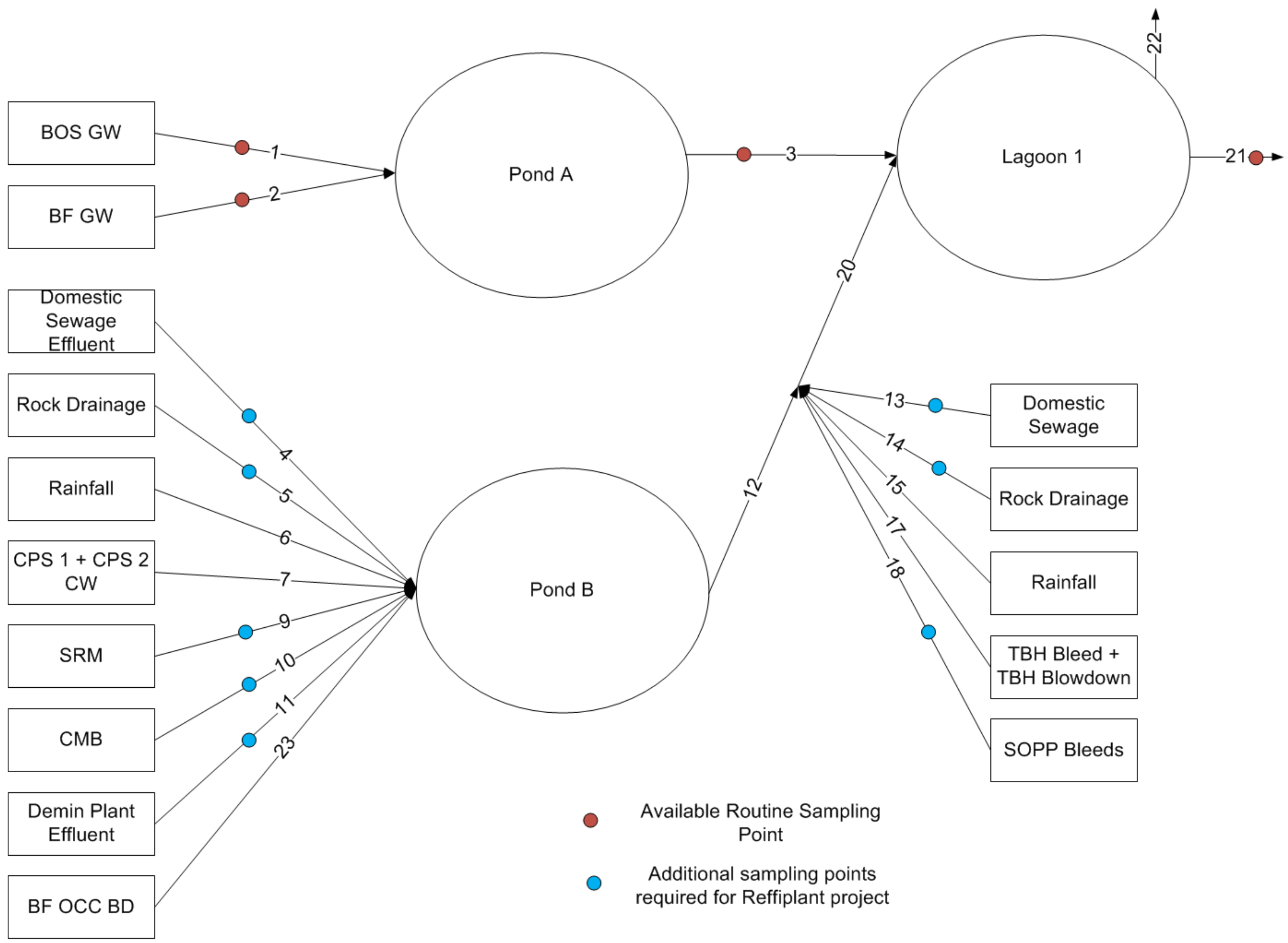


Figure 11: Standard and additional data points within Tata Steel water networks

Process		Stream	Flowrate m³/hr	TSS mg/l	TDS mg/l	Chloride mg/l	Ammonia mg/l
Pond A	1	BOS Gas Wash to Pond A	13	7	785	122	0,0
	2	BF Gas Wash to Pond A	35,4	79	2685	661	71,5
		Pond A discharge (from mass balance)	48,4	60	2175	516	52,3
	3	Pond A discharge to Lagoon 1 (actual)	48,4	32	2200	535	25,4
		% contaminant removal in Pond A		47%	-1%	-4%	51%
Pond B	4	Domestic Sewage Effluent to Pond B	12	18	1813	303	0,000
	5	Rock Drainage to Pond B	123	12	1773	218	0,722
	6	Rainfall to Pond B	15	12	1773	218	0,722
	7	CPS Tower 1 to Pond B	16,4	10	1287	190	0,044
	9	SRM to Pond B	5,5	29	1013	197	0,000
	10	CMB to Pond B (confidential)	5,5	34	1110	248	0,131
	11	Demin. Plant Eff. to Pond B	71	24	6718	35	0,039
	11	BF OCC	0	22	1182	178	0,031
		Pond B discharge (from mass balance)	248,4	16	3125	168	0,418
	12	Pond B discharge (actual)	248,4	13	1680	234	0,405
		% contaminant removal in Pond B		18%	46%	-40%	3%
Other Streams flowing to Pond B Discharge to Lagoon 1	13	Domestic Sewage Effluent to Pond B discharge	3,3	18	1813	303	0,000
	14	Rock Drainage to Pond B discharge	139	46	1773	227	0,280
	15	Rainfall to Pond B discharge	10,6	46	1773	227	0,280
	17	TBH Blowdown to Pond B discharge	8,2	7	960	240	0,000
	18	OPP Bleeds to Pond B discharge	2,7	419	1140	244	0,045
		Lagoon 1 discharge (from mass balance)	460,6	28	1750	264	2,98
Lagoon 1		Lagoon 1 discharge (Actual)	460,6	18	1813	303	2,95
		% contaminant removal in Lagoon1		38%	-4%	-14%	1%
		Water reuse	44	18	1813	303	3,0
	21	Lagoon 1 discharge to Beck	417	18	1813	303	3,0

Table 14: average sampled data and results of mass balance

PSD data for HCs: 3 sets of measurements were taken for total suspended solids and their particle size distribution along various inlet and outlet streams around clarifiers, HCs and dewatering plant. PSD measurements were also taken for mines water, BOS Gas Wash, Pond A and Lagoon 1 discharge streams. The fact that the duration of data collection was extended allowed the application of the models developed within WP 3 in order to perform the data reconciliation. An example of these data sets and associated data reconciliation through the models for the gas washing, the recycled water from agitator tanks and clarifiers inlets can be found in the Table 15. Noticeably large variations in water quality were observed; thus it was decided to take at least three sets of spot measurements to predict average contaminant levels at any given point of time within the system.

	From gas flumes	Recycle from agitator tanks		Clar 1 or 2 Inlet		Clar 3 Inlet	
		Actual	Model	Actual	Model	Actual	Model
Flow (m³/h)	2000	27	27	675,7	675,7	710,2	710,2
TSS (mg/L)	1272	10387	10387	1393	1393	1719	1719
Cont Mass Load (g/h)	2544	280	280	941	941	1221	1221
Particle Size (µm)	contaminant mass load in each interval (g/h)						
0,5	11,55	0,93	2,85	4,16	4,80	5,00	7,46
1	183,55	17,26	44,29	66,94	75,94	82,48	117,49
3	331,16	27,38	70,51	119,51	133,89	145,12	201,24
5	739,33	55,94	114,10	265,09	284,48	320,33	398,36
10	382,50	62,11	29,36	148,20	137,29	212,91	168,93
15	372,23	103,53	15,99	158,59	129,41	260,89	147,41
30	170,71	10,20	2,36	60,30	57,69	71,29	60,47
50	115,78	1,84	0,64	39,21	38,81	41,33	39,57
75	79,07	0,89	0,21	26,65	26,43	27,99	26,68
100	113,72	0,35	0,18	38,03	37,97	38,42	38,18
150	38,77	0,01	0,03	12,93	12,93	12,93	12,97
200	5,64	0,00	0,00	1,88	1,88	1,88	1,88
300	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table 15: Tata Steel Data and associated model-based reconciliation for gas washing, recycled water from agitator tanks and clarifiers inlets

Zn and Pb content around the inlets and outlets of the HC systems: Zn build-up affects the BF lining leading to its premature failure. Similarly Zn and Pb have other environmental concerns associated with them, thus their content needs to be monitored/predicted in the light of increase in sludge recycling via the sinter plant. Zn and Pb measurements helped to predict their separation performance across various particle separation devices such as clarifiers, HCs and filters. The resulting correlations helped to optimize the sludge recovery potential. Similarly high Cl content in the sludge or the water supplied to the sinter plant may lead to increase in dioxins and particulate emissions. Thus Cl concentration was monitored/predicted for the sinter plant feed in this regard.

Magnetic filter (MF) trial data were collected concerning relevant variables, such as flowrate, suspended solids concentration, metal concentration around inlets and outlets of the filter.

HPM data were collected to analyze the water reuse case study (see Appendix I Section 19.1), such as flowrate data for the last 3 months as well sizes of pipes and equipment and other relevant plant information. In particular the following data sets were collected to be used for simulation and validation of results for the HPM-Ancholme water reuse case study:

1) Pump Information

The following documents were collected for all three sets of pumps (River pumps, Storm pumps and Reservoir pumps) in this regard:

a. Performance curves of pumps
b. Yates test results
c. Pump drive logs for power consumption
d. Pump ON/OFF logs and corresponding pressure logsT

Yates test is a thermodynamic method of differential temperature measurement which is used to determine the performance of pumps. This together with power consumption and discharge pressure information, helps to determine the pump efficiency and the corresponding operating point on performance curves. With such data, the information shown in Table 16 was extracted for each pump services.

	River Pumps	Storm Pumps	Reservoir Pumps
Flowrate, m^3/h	154	138	214
Discharge Pressure, bar	10	6	11.9
Pump Efficiency, %	51%	69.9%	62.7%
Power Consumption, kW	96	33	118

Table 16: HPM- Ancholme Case Study - Pump Information

Apart from that, the pump ON/OFF logs were used for validating the simulation results for base case. Based on the pump logs available for the month of April 2015, each of the three pumps were in operation for the % of time shown in Table 17.

	River Pumps	Storm Pumps	Reservoir Pumps
% of time ON (actual)	10%	30.6%	59.4%
% of time ON (predicted by base case simul.)	10.2%	29.5%	60.3%

Table 17: Validation of simulation against pump ON/OFF logs

2) Reservoir Information

The following documents were collected with regards to the Catchment pit and Ancholme Reservoir:

a. Reservoir drawings for their dimensions
b. DCS screenshots for Low & High liquid levels (LLL & HLL) setpoints
c. Level fluctuation logs

The reservoir dimensions were used to calculate the cross-sectional area which was used to calculate level changes due to flow rates in and out of the reservoir, while liquid level setpoints (LLL & HLL) were used to determine when to switch among the pumps. Results are shown in Table 18.

	HPM Catchment Pit	Ancholme Reservoir
Cross-sectional area, m^2	1143	3738
Low Liquid Level (LLL), m	4	2.5
High Liquid Level (HLL), m	4.5	3.85

Table 18: HPM- Ancholme Case Study – Reservoir Information

3) Pressure Information

Pressure was measured at two different locations (see Figure I27) namely:

a. Near Coke Oven 1 supply point

b. Near Ancholme supply line common to both river and storm pumps

Pressure logs monitoring both of these pressure points were collected in order to understand the time lag between pressure transmission from one point to another. As illustrated in Figure 12, the pressure changes due to switching of pumps are observed at both points, however there is a time lag of 6 minutes on an average in pressure transmission from one point to another.

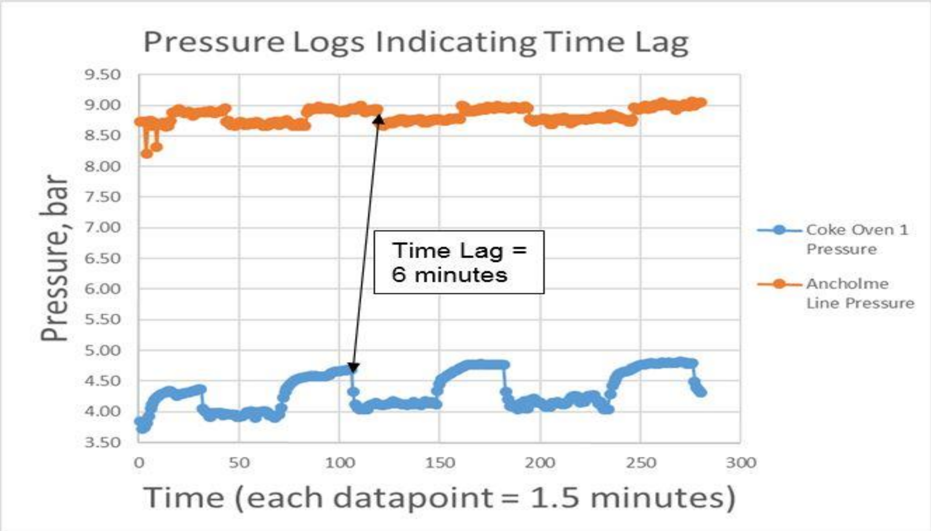


Figure 12 - Pressure Logs (07Apr15) illustrating time lag in pressure transmission

SSAB Data were collected at the Lulea site for the two objectives indicated at first priority in Table 3, (optimization of recirculation of quenching water at the CC and optimization of the recirculation of BF gas cleaning water). Tables 19, 20 and 21 summarise some statistics regarding the hourly collected data. In addition to these data, also water composition data were collected once a week during a month period at specific measurement points for the two mentioned recirculation system (see Table 22). Furthermore additional measurement points for the outgoing flows which were installed in November 2013 allowed the collection of new data which were analyzed and exploited in order to validate the overall water balance which was developed in WP4. Daily average values were collected for measurement points identified during mapping and system definition for those that are logged in SSAB data handling systems. Missing data were calculated using mass balance calculations or qualified approximations from experienced personnel at SSAB.

Continuous casting and water treatment at SSAB EMEA Luleå September hourly data 2013					
Continuous caster					
Id-nr	*Unit*	*Max*	*Average*	*Min*	*Description*
17403	pH	10,1	9,2	8,5	Spray water continuous caster nr 5
17414	l/min	869	427,1	0,0	Flow process water from caster appr. 1/4 of recirculated spray water
17507	l/min	8572	8019	0	Spray water flow continuous caster nr 5
17508	°C	33,3	29,0	23,1	Temp. Spray water incoming continuous caster nr 5
17546	m3/h	619	590,1	0,0	Incoming water to continuous casting nr 5 from water treatment
23702	t/h	296	154,9	0,0	Steel flow continuous caster nr 4
23703	t/h	210	153,0	0,0	Steel flow continuous caster nr 5
27505	m3/h	1200	532,5	0,0	Incoming water from water treatment to continuous caster nr 4
27534	°C	32,8	28,5	22,3	Temp. Spray water continuous caster nr 4
27537	°C	33,1	28,8	22,5	Temp. Spray water in tank continuous caster nr 4
Water treatment plant					
Id-nr	*Unit*	*Max*	*Average*	*Min*	*Description*
20803	pH	7,2	6,7	6,2	Ingoing fresh water (IV1)
20901	°C	39,4	33,3	16,9	Ingoing temp. water treatment
20902	M	2,86	1,8	1,4	Level in raw water basin
20903	pH	8,67	7,9	7,1	water treatment
20912	m^3/h	2800	2084	1455	Water flow through filters
20917	°C	33,8	29,1	17,2	Temp. Cooling tower 1
20918	°C	32,4	27,8	15,9	Temp. Cooling tower 2
20920	M	2,87	2,5	1,2	Level clean water basin
20922	%	85,3	68,4	20,2	Frequency from pump engines from clean water basin
20924	m^3/h	1825	1403	933	Outgoing flow from water treatment
20925	bar	5,91	5,5	4,6	Outgoing water pressure water treatment
20926	°C	33	28,1	15,9	Temp. Outgoing water from water treatment
20928	m^3/h	1200	529	0	Spray water flow continuous caster nr 4
20929	m^3/h	n/a	n/a	n/a	Spray water flow continuous caster nr 5
20932	m^3/h	856	265	0	Discharge water
20935	°C	25,1	14,6	1,8	Outdoor temperature
20959	0/1	1	0,788	0	On/off water pump M1 mains operation from raw water basin
20960	0/1	1	0,789	0	On/off water pump M2 mains operation from raw water basin
20961	0/1	0	0	0	On/off water pump M3 mains operation from raw water basin
20962	0/1	1	0,802	0	On/off water pump M4 mains operation from raw water basin
20963	0/1	1	1	0	On/off water pump M1 frequency drift from raw water basin
20964	0/1	1	0,997	0	On/off water pump M2 frequency drift from raw water basin
20965	0/1	0	0	0	On/off water pump M3 frequency drift from raw water basin
20966	0/1	0	0	0	On/off water pump M4 frequency drift raw water basin
20987	0/1	0	0	0	On/off water pump M12 mains operation from clean water basin
20988	0/1	1	0,977	0	On/off water pump M13 mains operation from clean water basin
20989	0/1	1	0,999	0	On/off water pump M14 mains operation from clean water basin
20990	0/1	0	0,000	0	On/off water pump M15 mains operation from clean water basin
20991	0/1	1	0,978	0	On/off water pump M12 frequency drift from clean water basin
20992	0/1	1	1	0	On/off water pump M13 frequency drift from clean water basin
20993	0/1	0	0	0	On/off water pump M14 frequency drift from clean water basin
20994	0/1	0	0	0	On/off water pump M15 frequency drift clean water basin

Energy consumption water pumps in water treatment plant					
Calc.	kW	500	453	250	Power pumps raw water basin
Calc.	kW	846	700	688	Power pumps clean water basin

Table 19 Statistics regarding hourly collected data at SSAB.

Gas cleaning hot metal production BF 3 at SSAB Luleå hourly data September 2013					
Id-nr	*Unit*	*Max*	*Average*	*Min*	*Description*
5215	kNm^3/h	368	350,3	211,1	Flow top blast furnace gas
5301	°C	240	121,6	74,2	Temperature top gas
5305	°C	44,1	38,9	33,9	Temperature top gas after scrubber
5312	°C	37,6	35,2	32,3	Temperature ingoing water to scrubber
5314	m^3/h	351	332,8	286,9	Water ingoing scrubber upper flow
5315	m^3/h	399	337,3	329,3	Water ingoing scrubber lower flow
5316	m^3/h	702	670,1	652,7	5314+5315 (sum of ingoing water to scrubber)
5320	m^3/h	399	381,4	367,0	Internal recirculating water in scrubber
5335	°C	54,5	47,6	36,1	Temperature outgoing water from scrubber to sedimentation
5366	m^3/h	30,7	24,8	8,5	Flow blast furnace sludge from sedimentation to basin
5374	°C	49,3	45,4	28,9	Temperature water ingoing cooling tower
5390	°C	38,5	36,0	11,9	Temperature water outgoing cooling tower
5397	m^3/h	48,4	34,7	10,4	Flow water outgoing cooling tower

Table 20 Statistics regarding collected hourly data at gas cleaning for BF3 at SSAB

Industrial water at SSAB Luleå hourly data September 2013					
Id-nr	*Unit*	*Max*	*Average*	*Min*	*Description*
6101	m3/h	1868	1804	1767	Total inlet water IV 1 - inlet point 1
6102	°C	15,7	13,6	9,4	Temperature inlet water

Table 21 Statistics regarding hourly data on water consumptions at SSAB

Variable	Intake	CC quenching	BF gas cleaning	Comment
Temp, pH, susp, cond	X	X	X	Basic analyses
Hardness, alkalinity, Ca	X	X	X	Risk of precipitation
TOC	X	X	X	Typical contaminants
Na, F	X	X		Possible contaminants from casting powder
Cl	X	X	X	Risk of corrosion
NH_4-N, NO_2-N, NO_3-N	X	X	X	Typical contaminants
Cyanide, phenols	X		X	Typical contaminants
Zn	X	X	X	Typical contaminant

Table 22 Chemical ad-hoc analyses performed at SSAB.

Data analysis on the BF gas cleaning system

The BF gas cleaning system at SSAB in Luleå includes a wet gas scrubber, which washes out particles and certain water soluble chemical components from the gas. Figure 13 shows a schematic picture of the gas cleaning system. Most of the gas cleaning water is recirculated, but some of it is removed from the system together with the sludge flow from the clarifier. The sludge is stored in dewatering basins and the water is ultimately discharged at discharge point Laxviken.

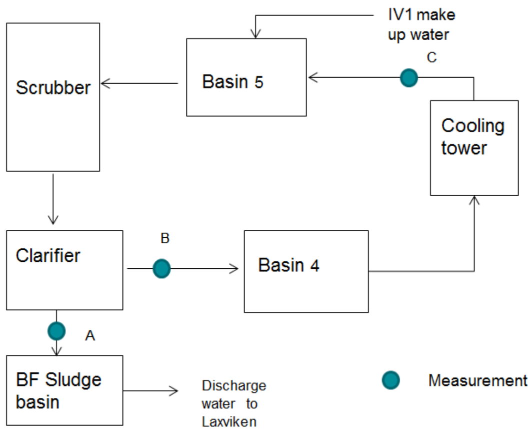
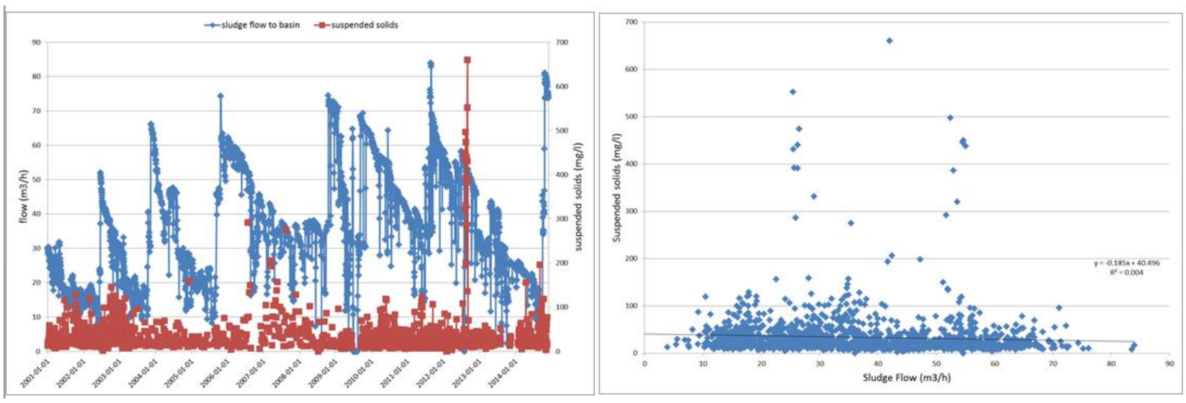


Figure 13: Schematic sketch of the BF gas cleaning system of SSAB

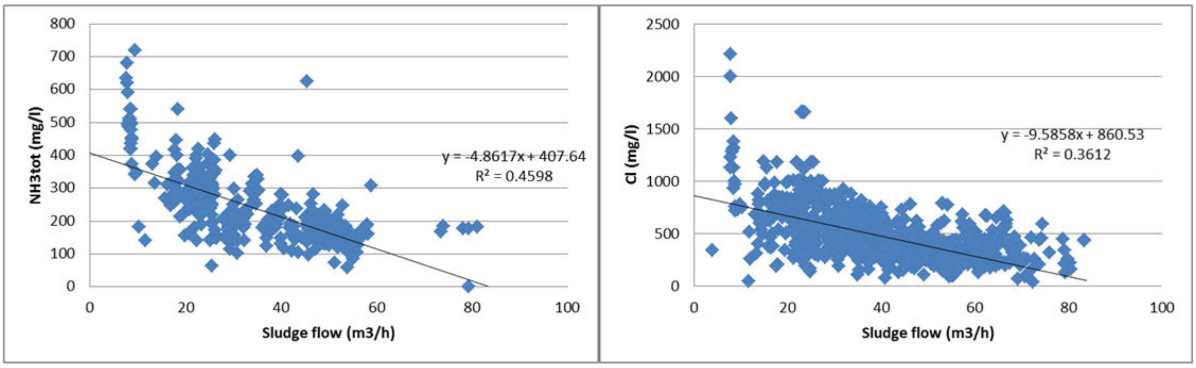
MEFOS made a statistical data mining in order to explore correlations regarding the degree of recirculation of the gas cleaning water and the concentration of various components in the recirculated water. The purpose of the analysis was to investigate if there is a build up of any chemical compound during recirculation, or if it is possible to recirculate more of the water in order to minimize the amount of process water that is leaving the system.
The correlation between the concentrations of different compounds, such as TSS, ammonia (NH_{3tot}), chloride (Cl^-), Calcium (Ca), Zinc (Zn), Iron (Fe_{tot}) and cyanide (CN^-), in the recirculated water (flow B and/or C) and the sludge flow from the clarifier (flow A) was investigated. The piping that transports the sludge phase to the sludge basin is clogged due to increased fouling over time. When the flow to the sludge basin is lower, the amount of recirculated water is larger. When the flow is too low, the pipeline is rinsed and the flow is restored. This happens typically every two years and gives rise to the natural variation in flow (amount of recirculation).
As a first step, the correlation between the amount of suspended solids in the water out from the clarifier (point A in Figure 13) and the sludge flow from clarifier (point C in Figure 3) was investigated. Figure 14 shows the measurements of suspended solids plotted against time together with the sludge flow and suspended solids as a function of the sludge flow. The periodic variations in sludge flow are due to the fouling and rinsing of pipeline described above. It is not possible to find any correlation between the two variables over the long period of time from 2001 to 2014.



a) b)

Figure 14: a) Suspended solids in the recirculated water from clarifier and sludge flow from clarifier, for all available data from 2001 until 2014. b) Suspended solids as a function of sludge flow from clarifier.

To further investigate a possible correlation, the data were divided into 6 shorter periods of time, starting at the time for a rinsing of the pipeline and ending at the next. The same methodology was applied for these periods of time, but no correlation was found for suspended solids and sludge flow.
The same methodology was applied in order to investigate correlations for NH_{3tot}, Cl^-, Ca, Zn, Fe_{tot} and CN^- with sludge flow from clarifier. However, the available data only ranges from 2012 and forward. A correlation between ammonia nitrogen and sludge flow was found (see Figure 15).



a) b)

Figure 15: a) NH_{3tot} vs. sludge flow to basin. b) Cl^- vs. sludge flow to basin

As ammonia is typically found as ammonium chloride, it is expected that a similar correlation exists for the Cl^- concentration. Figure 15 shows that this correlation exists, but it is somehow weaker.
The same correlations could not be found for Ca, Zn, Fe_{tot}, and CN. Since these compounds are typically found in high concentrations in the BF sludge, and there is no correlation between the sludge flow and the total suspended particles, the result is expected.

Data analysis on the CC spray-on water

At SSAB Luleå there are two CC machines, S4 and S5, which are connected to the same cooling circuit. During one day, ad-hoc measurements were performed by MEFOS and SSAB for steam evaporated during the cooling on S5 and the water leaving the sump. In Figure 16 a schematic sketch for the water cooling system on an individual CC machine is shown with markings for installed measurement equipment and additional measurements used during the testing.
The water leaves the sump via two pumps. One pump is constantly operating and the other pump is controlled by the depth of water in the sump. The already installed measurements are placed on the pipe for the spray-on water, after the bypass water, and on the pipe for the depth controlled pump. The additional measurements were performed on the steam evaporated from the cooling and on the flow from the continuously operated pump. The steam flow was measured with a pitot pipe and the flow was measured with an ultrasound flow meter.
The amount of steam evaporated was in average 16 t/h. Comparing this with the production rate of steel the specific evaporation of spray water is 335 kg/t of steel. This represents 2.6% of the spray-on water on volume basis. By assuming that the same amount of water is needed on both S4 and S5 for cooling, a simple mass balance was done which identified the unknown flow of make-up water into the cooling circuit. Additional measurements were carried out after the testing on the bypass water flow, which verified the assumption that equal amount of cooling water, was used on both S4 and S5 per ton of steel.

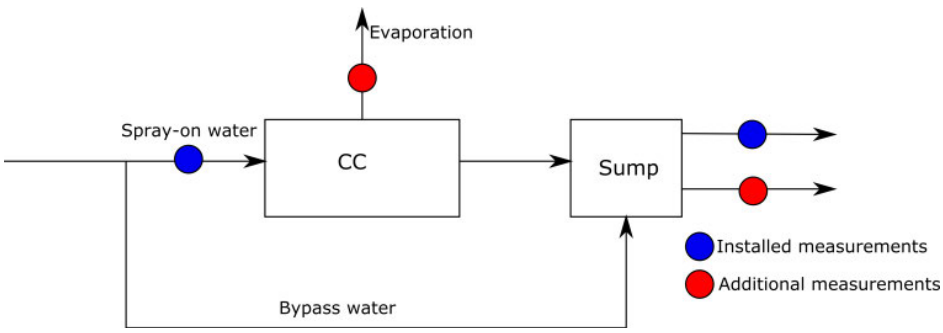


Figure 16: Placements for measurements during measurement campaign

Data analysis on the IV1 water intake

At SSAB site, there are two primary intakes, IV1 (from Luleå River) and IV4 (from Luleå Archipelago), and two major discharge points, Laxviken and KV-diket. A small flow leaves the system at discharge point Svartöviken and through evaporation. The variation in incoming IV1 water over the last three years, 2012-2014 is shown in Figure 17, while the average values for the last three years are shown in Table 23. The flow varies between the years, and between the different seasons. The values for 2014 show that during summer, there is a larger need for cooling water.

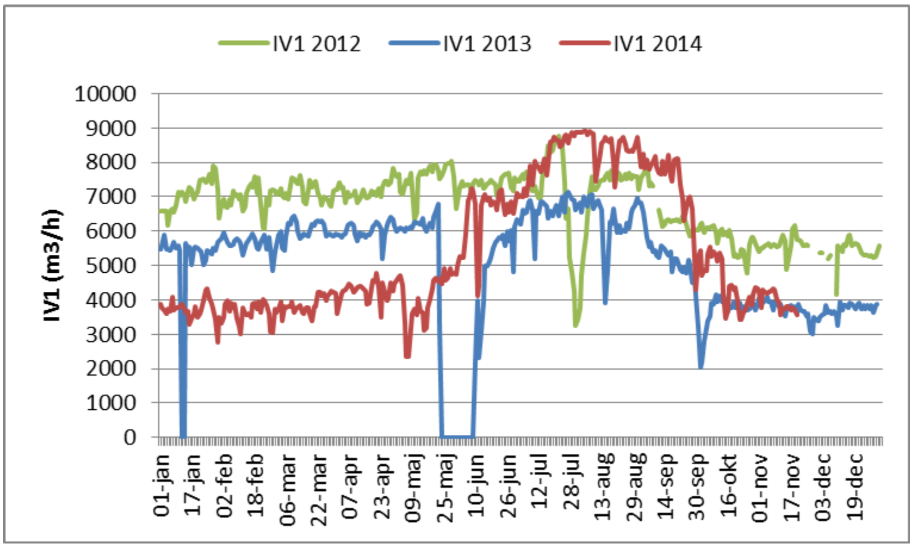


Figure 17: IV1 flow 2012, 2013 and 2014 (until 22nd of November).

Year	**2012**	**2013**	**2014**
IV 1 (m^3/h)	6768	5015	5369
IV 1 (m^3/t HM)	31	22	22

Table 23: Average water consumption IV1 for 2012-2014

A comparison between the incoming IV1 water and the discharge to Laxviken was done.
As stated before, the main part of the used IV1 water is discharged at Laxviken. The exceptions are evaporation and a few minor indirect cooling streams that are discharged at Svartöviken or KV-diket. The few additions to Laxviken that are not IV1, are small flows i.e. storm water. The discharge into Laxviken should therefore be smaller than the intake of IV1. It is evident from Figure 18, that this is the case for most of the year of 2014, although during the period from mid October until January, the situation appears to be opposite. This difference between incoming and discharge is not feasible and needs to be further investigated in order to establish if the measurements are reliable.
The average discharge water to Laxviken is 4990 m^3/h and the average IV1 intake is 5370 m^3/h. The average difference between the inlet and the discharge is 400 m^3/h for 2014, which corresponds well to estimated evaporation etc.

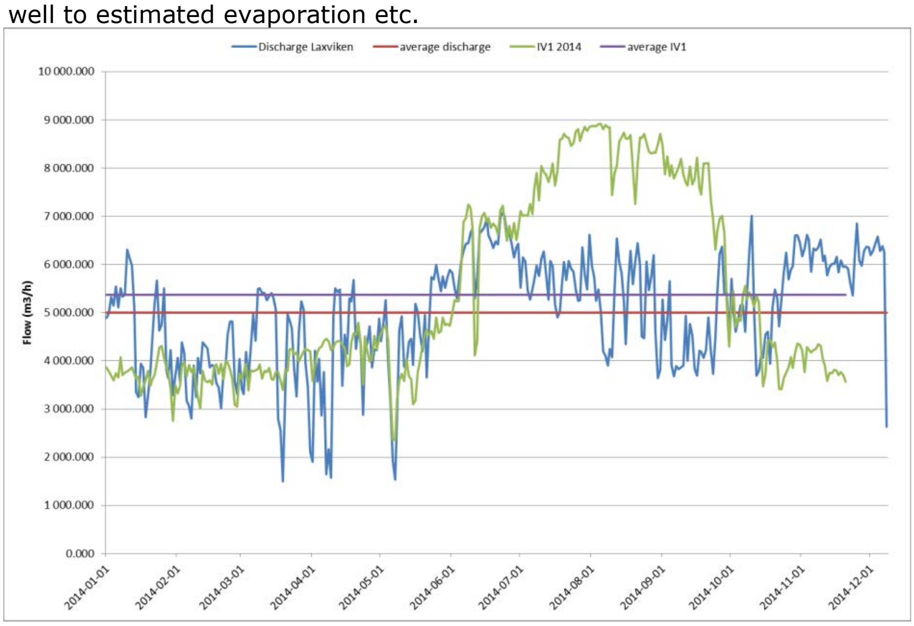


Figure 18: Laxviken discharge point and IV1 intake for the period 1/1/2014-22/11-2014.

Task 2.3: Modelling and simulation of water treatment processes

An analysis of the industrial partner's sites was conducted in order to identify the main water treatment processes to model. The most relevant water treatment processes were then modelled, in order to realise a models library to be exploited for simulation purposes in WP4.
To this aim, a general model template was realised in order to allow a unified development of the models. The template, illustrated in Figure 19, can be treated as a "black box", communicating with the incoming and outgoing water streams only the most relevant information (e.g. relevant parameters necessary for the optimisation of the treatment model).

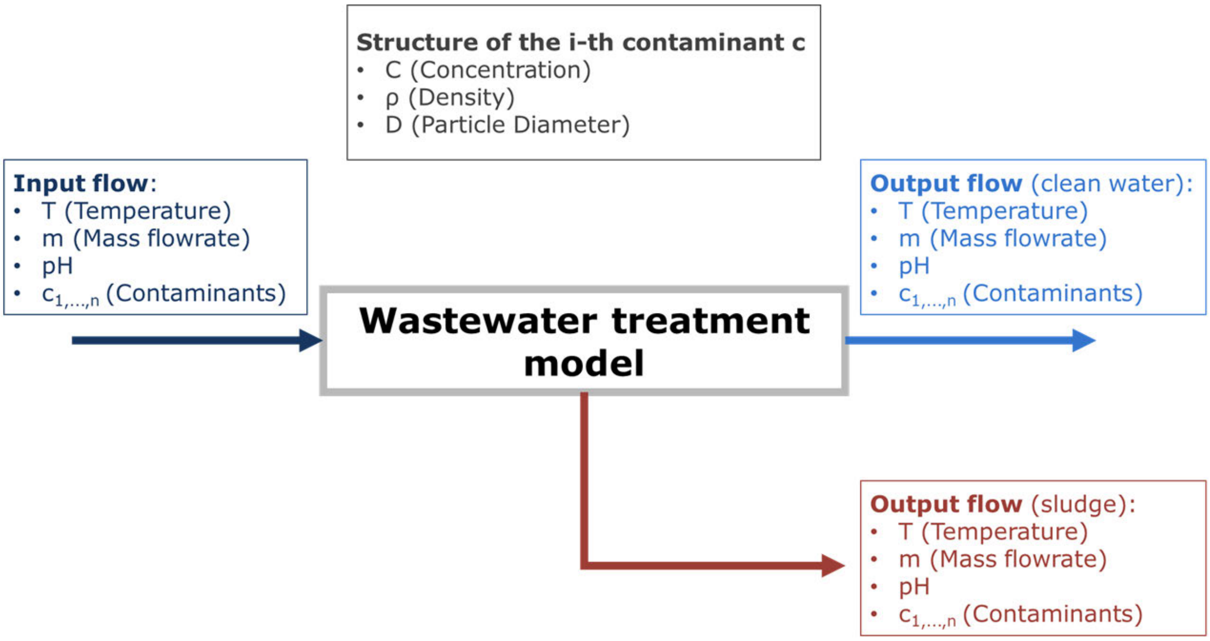


Figure 19 Structure array description of a general water treatment unit.

The treatment block can embed different models that read as input the values of the incoming parameters (water temperature, flowrate, pH, contaminants properties such as concentration, density, particle diameter) and use them both as variables and boundary conditions to return the output flow conditions (sludge and treated flows). Mass and energy balances should be calculated within the model block itself, which return as output the values of the *n* output water streams parameters to be fed to the subsequent water using operation or treatment.
This library of models, which is described in detail in Appendix C, includes a clarifier, an ammonia stripping column, a Reverse Osmosis (RO) block, a cooling tower, an activated sludge, gas scrubbers, HC, pumps and pipes. The developed models can be divided in two levels of complexity:

- Level 1 – Simple unit models: These models are based on simple mass and energy balance equations. Here less sensitive variables such as ambient conditions are fixed as parameters; while simple correlations are added by curve fitting results obtained from rigorous models for a desired operating range. The resulting model shall be suitable for optimisation studies.
- Level 2 – Detailed models in rating model: These models are derived from detailed design calculations used for designing the subject equipment. The equations are restructured to perform rating mode calculations wherein equipment performance can be predicted for a given design. Here the equipment characteristic is incorporated by means of semi-empirical correlations wherein equation parameters obtained are specific to the equipment under consideration. Thus multiple data points will be required to develop these equipment specific semi-empirical correlations.

Such library also represented a basis for the simulation models developed within WP4.

Simulations of solutions for water efficiency

Besides the development of the water treatment unit operation model library, a simulation-based analysis was carried out in order to increase the water usage efficiency at SSAB. In particular 2 focus areas were identified at SSAB for the water system efficiency as mentioned in task 1.2 and presented in Table 4. These are the recirculation system of quenching water at the CC and the gas cleaning system of the BF. Within task 2.1 and 2.2 knowledge was gathered over the water treatment system at the CC. Theoretical, practical and equipment constraints were considered to simulate the heat and mass balances of the inlet, circulated and discharge water from the system. Figure 20 shows the main water flows in the system.

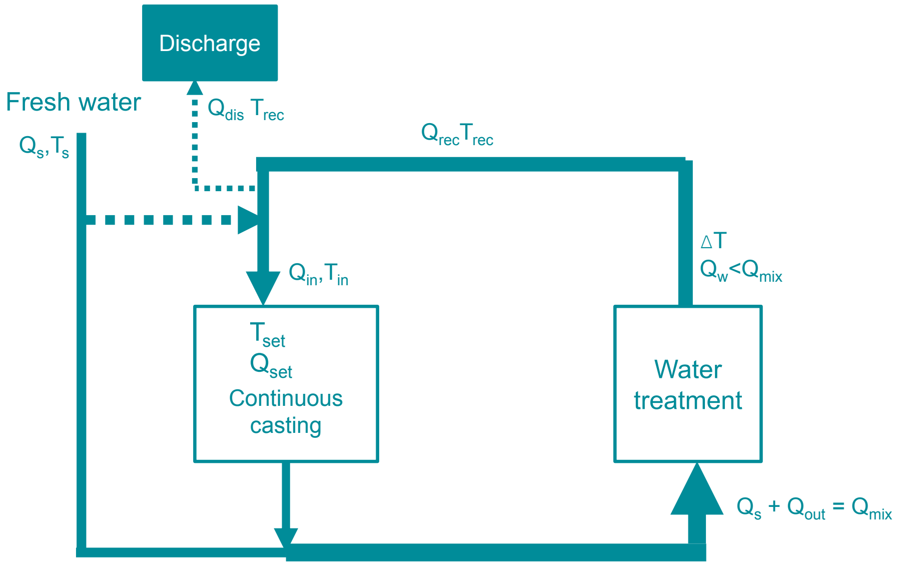


Figure 20. Water flow of the system of recirculation of quenching water at the CC.

Especially of interest was the water treatment plant, where the inlet is a mix between fresh water and waste water from quenching of slabs in the continuous caster. The water treatment consists of oil skimming, sedimentation, sand filtration and cooling. After treatment it is either recirculated back to the continuous casting or discharged to internal lagoons with discharge to the sea. The detailed outline of the water treatment plant is shown in Figure 7.
A water heat- and mass balance model with constraints and parameters from the sampled data and information from Task 2.1 and 2.2 was constructed. Due to missing data for some parts of the system, qualified assumptions were made to be able to simulate the whole system. The objective of the modelling of the system is to optimise the recirculation of quenching water. The most important parameter for the inlet water to continuous casting is stable temperature. In current situation water is cooled by means of mixing with fresh water and by cooling in towers in the water treatment plant. The objectives in the model are to target the temperature into continuous casting T_{in} and to minimise the discharge and inlet water (Q_s, Q_{dis}). Since mixing with fresh water is one method to decrease the temperature of inlet water the amount of water added will be dependent on fresh water temperature. The two in solid lines in Figure 21 show the simulation results from the recirculating water Q_{rec} and discharge Q_{dis} as a function of fresh water temperature T_s. In this case the water flow and water temperature in and out from the CC plant were fixed. In reality this flow varies along with casting programs and production levels. The quenching water flow varies greatly between different qualities of produced steel.

Task 2.4: Identification of potential solutions/technologies for water and energy efficiency

Both process knowledge collection and modelling and simulation work allowed each industrial partner to identify a list of potential solutions and technologies for water and energy efficiency at their own site. Three lists were compiled as a basis for the work in WP4, constitute Deliverable 2.1 and are reported in Appendix D.

Concerning SSAB, a simulation for evaluating the saving potential regarding the recirculation of quenching water at the CC was developed to verify whether a change of the point where the inlet fresh water is added to the recirculating system can decrease the water consumption, the discharge amounts and the energy consumption. After considerations of process data, equipment and infrastructure, potential solutions at the CC water system were investigated to the aim of minimising the usage of water and evaluating the related effects on the energy consumptions. The model developed in Task 2.3 was used to simulate the effect of adding fresh water after water treatment instead of before as is the current case. A redistribution of fresh water mixing can lead to lower pumping energy, more accurate mix of fresh water to process water (stable ingoing water temperature to CC) and less discharge. Figure 21 shows the results of the simulations as a function of fresh water temperature: it is clear that moving the point of water mixing decreases the water usage in the system.

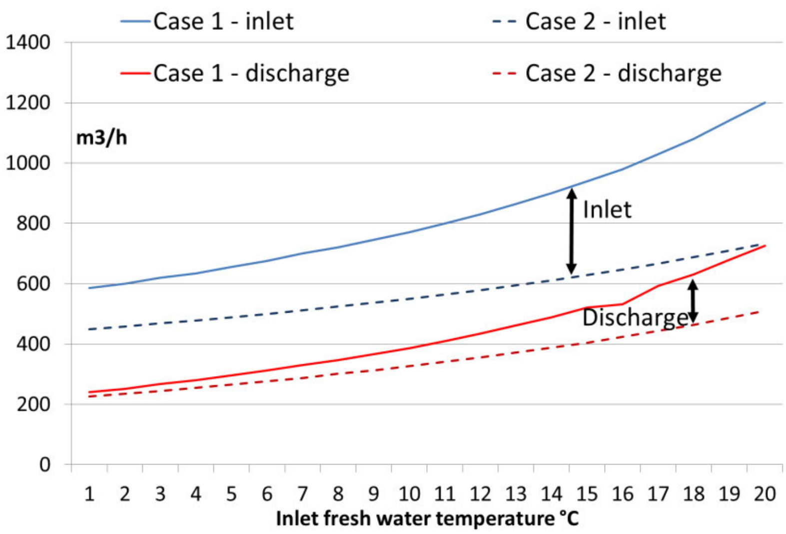


Figure 21. Fresh water consumption and amount of discharge for two different cases of operation of the recirculation system for CC quenching water.

From statistical data it was found that the number of pumps used for pumping water from raw water basin through sand filters had a relation to the water flow (see Figure 21) over the water treatment plant. When flow was higher than 1890 m^3/h a second pump was needed. This pump used frequency operation. The installed effect of the pumps is 250 kW each. Water pumps to transport treated water back to CC were during the sample period 2x315 kW in full operation. This made it hard to find a relation with water flow and pump energy. Further investigations have to be made. Figure 22 shows simulated energy saving potential from raw water pumps for various fresh water temperatures for the case when fresh water addition is redistributed to after water treatment plant:

Below 15°C there are no savings, but as the fresh water further increases the energy saving is rapid. This is a consequence of the fact that in the base case only one pump is needed up to 14°C but as the fresh water is getting warmer more water is needed to be able to reach the temperature requirements of the continuous casting. When water additions is moved to after water treatment plant the water flow through the plant is below 1890 m^3/h and only one pump is operated.

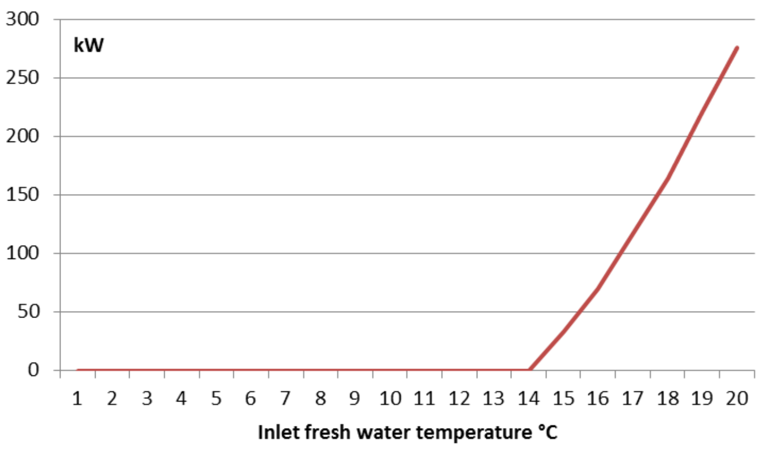


Figure 22: Simulated energy savings from raw water pumps for various fresh water temperatures

Other potential solutions to improve water efficiency at SSAB's site were pointed out by exploiting the process knowledge and the data collected in Task 2.1, which are listed in Table D1 of Appendix D.

Tata Steel to point out its own most promising potential solutions, which are listed in Table D2 of Appendix D. In particular a deep simulation analysis focused mostly on the BF off-gas washing circuits (see Appendix E) pointed out the need to introduce new treatment plants in order to increase water efficiency and waste water re-use.

Potential solutions were also pointed out at the ILVA site (Table D3 of Appendix D). In particular the analysis of the internal process constraints at ILVA highlighted the possibility to improve water reuse by feeding as input to some process the wastewater from another process potentially without any treatment, as the features and quality of the steams, on one hand, and the requirements of the processes, on the other hand, allow this connection. Also some potentials for exploitation of blow down streams after salts removal through RO or micro-filtration were pointed out. These case studies were deeply investigated in WP4.
As far as the ammonia stripping process is concerned, the developed column model allowed to carry out a few sensitivity analyses in order to evaluate the impact of possible variations in the inlet steam and sodium hydroxide flowrates. Such analyses aim to observe the general trend of the ammonia stripping process varying the NaOH and the steam flows with the precise intent to obtain guidelines to reduce these flowrates, respecting contaminants limit law. The pH of the outlet stream is relevant in terms of trend, rather than its absolute values. Two case studies were realised: a first one, representing nominal operating conditions, and a second one, which is related to the current, reduced capacity conditions. Numerical results are reported in Tables C2 and C3 of Appendix C.

Case A – Nominal OCs
Figures 23 and 24 illustrate the results of the sensitivity analyses. Such analyses show that an increase in the NaOH flowrate can lead to a reduction the NH_3 concentration in liquid outlet stream but the value of pH becomes bigger and it could be a problem relating with the regulatory limit at the discharge point. Furthermore it is evident how the steam flowrate cannot be reduced under the value of about $1,1 \cdot 10^4$ kg/hr without increasing NaOH because the ammonia in the outlet water reaches unfeasible values. The change in pH is justified by the more diluted conditions when the steam flow increases, even if the NH_3 appears reduced.

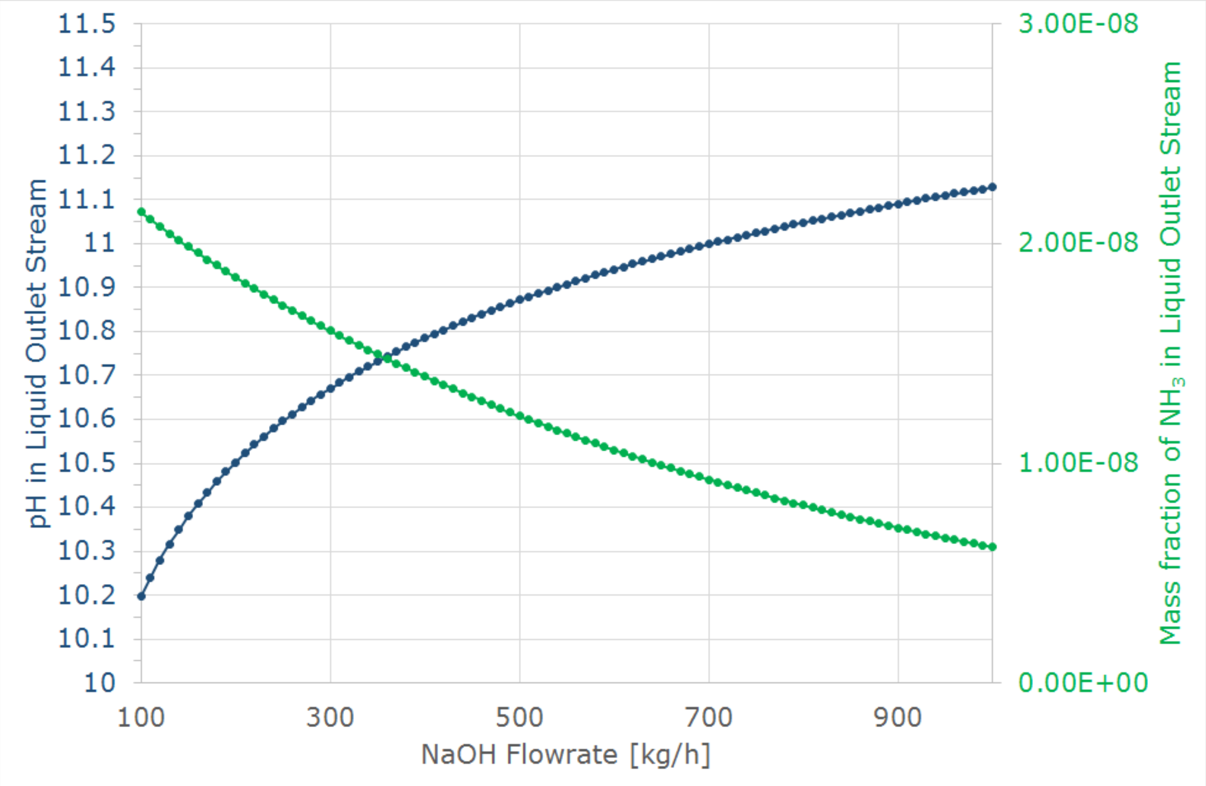


Figure 23. Trends of liquid outlet pH and NH_3 concentration with changes in NaOH flowrate

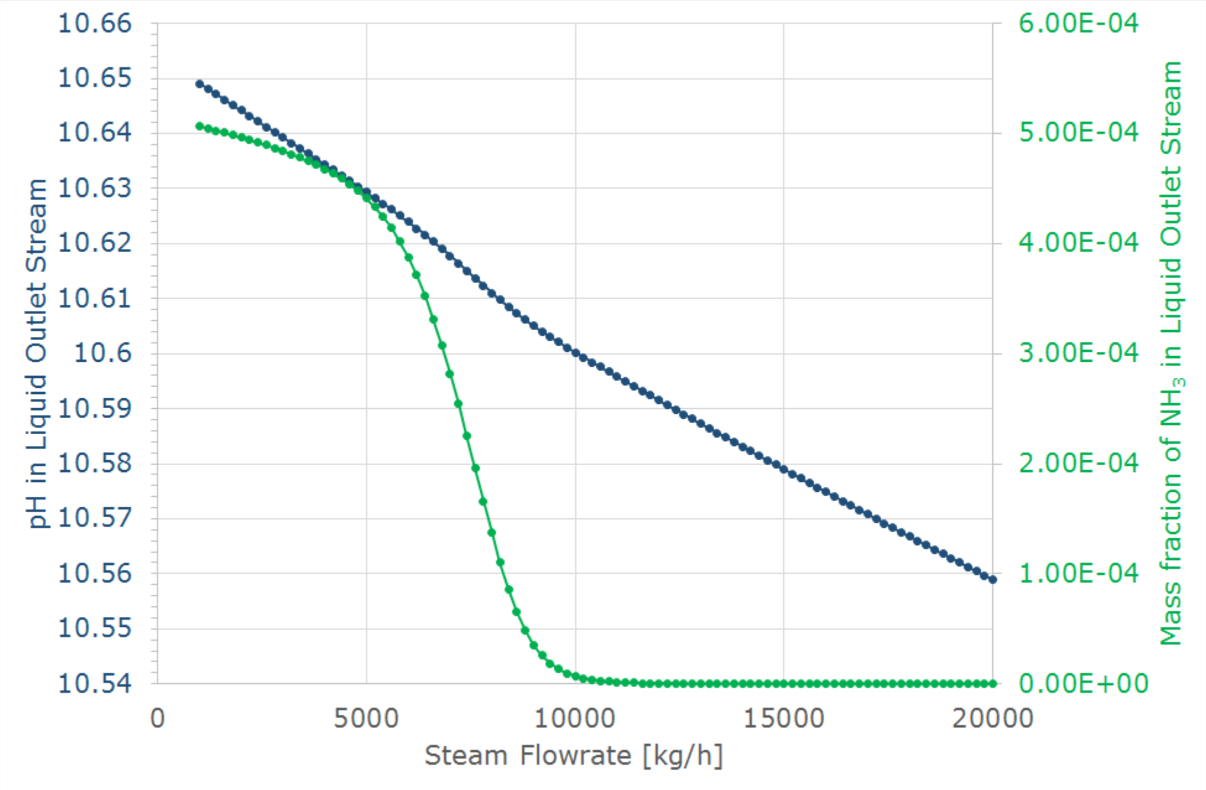


Figure 24. Trends of liquid pH and NH_3 concentration with changes in steam flowrate

Case B – Actual (off-design) OCs

Similar observations can be done for the second case study that represents the current operative conditions. Figures 25 and 26 show the main simulation results.

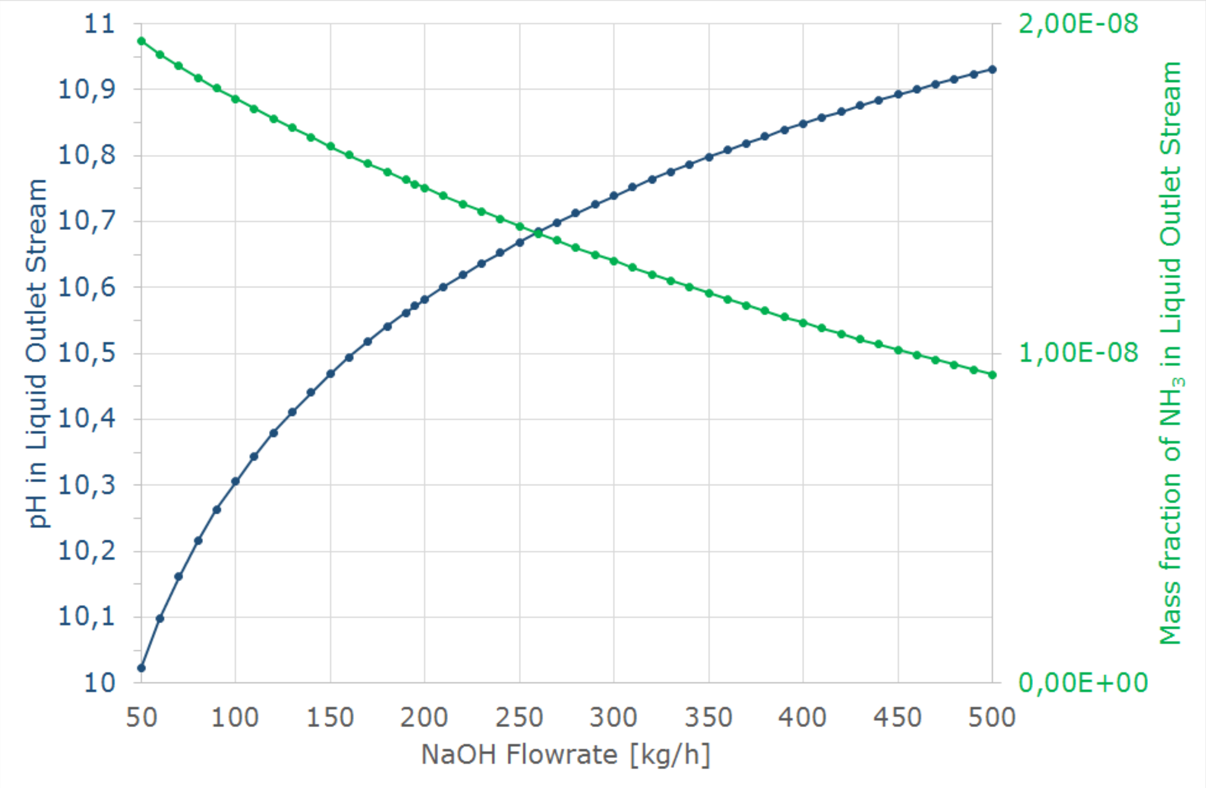


Figure 25. Trends of liquid outlet pH and NH_3 concentration with changes in NaOH flowrate

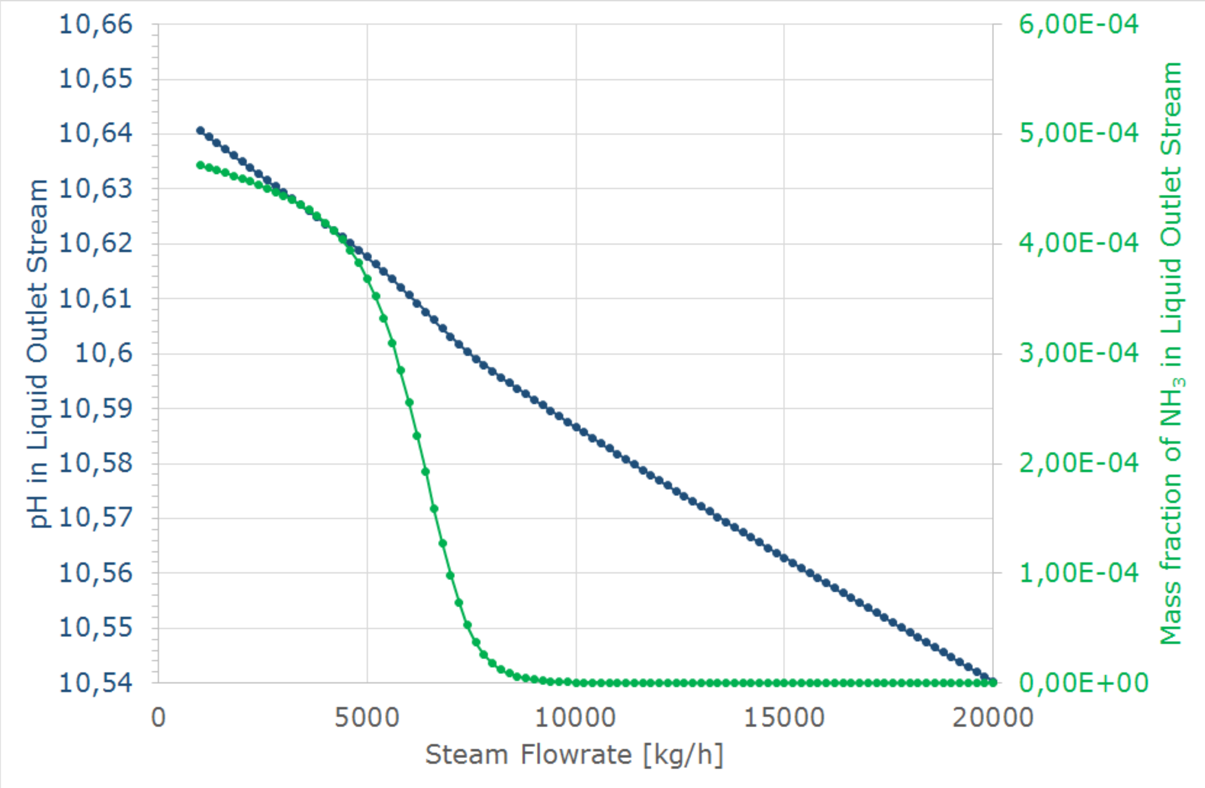


Figure 26. Trends of liquid outlet pH and NH_3 concentration with changes in steam flowrate

The conditions give values of NH_3 concentration in liquid outlet stream of $1{\cdot}10^{-8}$ which are under the law limit specification and it is not necessary to increase the NaOH inlet flowrate. On the other hand, the steam flowrate cannot be reduced under the value of about $1{\cdot}10^{4}$ kg/hr.
Finally the above described investigation demonstrate that there is the possibility to reduce NaOH consumption in ILVA's ammonia stripping plant while the steam flowrate has low leeway. Given that the mass fraction of NH_3 in the outlet water stream is significantly under the law limit specification, it is possible to optimize the use of steam and soda.

Conclusions drawn from the simulations
The ammonia stripping final waste water treatment has the objective to produce a treated water to discharge, which concentration of contaminants need to be under Italian law limit for discharge. In order to obtain a more detailed description of the real process a simulation model was carried out. This model was used to predict some effects in changing operative conditions of the unit and consequentially to acquire a specific knowledge of the process.
The main simulation results show that the concentration of ammonia in the treated water is generously under the value admitted for discharge. This fact highlights the fact, unknown from industrial partner, that there is the possibility to decrease the caustic soda amount (constant steam flowrate) or steam flowrate (low leeway) until value of about 1,1·104 kg/hr (constant NaOH flowrate) without crossing the limit value. Details are show in Appendix C and in Figures 23-26.

2.2.3 WP 3: Waste minimization

Task 3.1: Data and process knowledge collection related to material and waste flows
ILVA data collection related to by-products and waste flows was mainly performed with respect to the by-products or waste destination.
The mill scales are sold to cement plants or reused in sinter production: thus they must be compliant with some specifications which are imposed by the customers or by the regulation.
In the case of mill scale sold to cement plants, they are classified as waste identified by the CER code n° 100210 and they must respect the limits of oil content of about 0.25 %wt required by the buyers. Moreover, according to the Annex II of the Italian Ministerial Decree 05/02/98, the recovery of non-dangerous waste (such as mill scale) in cement industry is allowed only if they hold fixed chemical characteristics: iron oxides have to be about 95 %wt, other oxides (e.g. SiO2,

CaO, MgO, etc.) about 5 % and PCB have not to be present. To this aim, the amount of previous listed compounds are analysed and Table 24 lists the mean composition and amount of ILVA mill scale sold to cement industry. It is clear that buyers and legislation prescription are observed.

Species	UOM	Value
FeO	%wt*	59.75
Fe_2O_3	%wt*	34.55
Other Oxides	%wt*	5.53
Mineral oils (C12 - C40)	%wt.*	0.17
PCB	mg/kg	<0.1
Amount	kg/ton of steel slab	2.74

*percentage by weight of dry matter

Table 24 Average composition and amount of ILVA mill scale sold to cement industry

On the other hand, the mill scale used as by-products in the mixture fed to the sinter plant process is practically oil-free. Indeed, the main goal of this process is the recycling of iron-rich steelmaking by-products in order to produce a good quality agglomerate for the pig iron production by avoiding the production of harmful emissions such as dioxins. For this reason, it is important the reuse of by-products that have a negligible contaminants content (below to the legal limits), such as oil and chloride, that are both source of dioxins due to the high temperature of the sintering process, or phosphorous that affects the quality of the agglomerate. In the case of ILVA, oil and chloride content must respect the Integrated Environmental Authorization (AIA); in particular, the oil content has to be lower than 0.1 %wt and chlorides are monitored in terms of "control value" and have to be the lowest possible value in order to respect dioxins limits on chimney. Table 25 lists the analysed parameters and provides the average composition and amount of oil-free mill scale reused in sinter production: the iron and phosporous contents comply the regulation limits related to the sinter plant and the chloride and mineral oils respect the AIA prescriptions.

Species	UOM	Value
Fe tot.	%wt.*	71.06
Mn	%wt.*	0.31
P	%wt.*	0.01
Zn	%wt.*	0.001
Cr	%wt.*	0.03
Pb	%wt.*	0.001
Cl- (chlorides)	%wt.*	0.03
Mineral oils (C12 - C40)	%wt.*	0.07
Others	%wt.*	28.488
Amount	kg/ton of steel slab	15.04

*percentage by weight of dry matter

Table 25 Average Composition and amount of ILVA mill scale for internal reuse in sinter plant

Sludges coming from BF or Steelshop are usually by-products and are used in the mixture fed to the sinter plant process after some specific chemical analyses.
In the case of a reduction of the BF production, there is also a reduction of by-products demand from the Sinter plant. The sludges are therefore not fully reused and, become non-dangerous wastes and are disposed in the landfill according to the Italian legislation (D.M. 27/09/2010). In particular, leaching tests are performed in order to verify if the sludge respects the landfill specifications: Table 26 shows typical leaching test results for BOF and BF sludges and compares them with the leaching tests limits for disposal in non-dangerous waste landfill according to Ministerial Decree 27/09/2010. It is evident that the leaching test results for BOF and BF sludge are well below to the legislation limits for disposal in not dangerous waste landfill or are below the detection limits of the instrument.

Species	BOF sludge	BF sludge	Legislation Limits (L/S = 10 L/kg) *[mg/L]*
As	< 0,01	< 0,01	0.2
Ba	< 0,01	0.02	10
Cd	< 0,01	< 0,01	0.1
Cr tot	< 0,01	< 0,01	1
Cu	< 0,01	< 0,01	5
Hg	< 0,0001	< 0,0001	0.02
Mo	0.021	<0.01	1
Ni	< 0,01	< 0,01	1
Pb	< 0,01	< 0,01	1
Sb	< 0,01	< 0,01	0.07
Se	< 0,01	< 0,01	0.05
Zn	< 0,01	< 0,01	5
Cl- (chlorides)	119	86	2500
F- (fluorides)	2.9	2.7	15
SO_4^{2-} (sulphates)	105	148	5000
DOC	< 5	< 5	100
TDS	327	574	10000
pH	10.7	9.6	**≥6**

Table 26 Leaching tests results for BOF and BF sludge and limits for non-dangerous waste landfill (D.M. 27/09/2010).

SSAB used the year 2012 as basis for the data collection, as it was the most recent whole year at the time when the collection started. The collection of data from SSAB was performed mainly with respect to;

- the production and flow of raw materials and products for processes (BF, DeS, BOF)
- analytical data for raw materials and products, including slag, sludge and dust
- specially selected trace element analyses, for example Zn

Data from the year 2012 were used as a basis for PI-simulation. However, 2012 might not be an ideal representative year due the actions to recirculate maximum of stored scrap to the BF and a high proportion of recirculated scrap to LD. This is the reason why the duration of the data collection was extended until the end of the project.
During 2014, based on earlier modelling/simulation work performed by MEFOS, (see WP4) a short full scale trial was also conducted, in order to acquire data for a deeper process knowledge and test preliminary results with on-site applications before further modelling and extended full scale trial. The main results are reported in Appendix I Section 19.2.

Task 3.2: Data preparation, analysis, interpretation & reconciliation

In the SSAB case, heat-mass-balance modelling (BF, HM desulphurization and BOF) some preparations and surveys were necessary to be performed e.g. detailed BF Zn distribution model – metal/slag/dust/sludge. The BF Zn distribution model is based on the mass balance for 2012. Input and output Zn data is given in Table 25. As the total amounts of produced dust and sludge only are some 2.5% of the total raw material input, while more than 80% of the output Zn is found in dust and sludge, it can be concluded that most of the Zn in dust and sludge originates from vaporization of Zn in the lower part of the BF, followed by condensation in the gas phase in the upper part of the BF.

BF input Zn			BF output Zn		
Material	Zn, g/tHM	% of input	Material	Zn, g/tHM	% of output
Ore pellet	19,7	19,7	Hot metal	4,8	4,8
Briquette	70,6	70,5	Slag	13,3	13,3
Scrap	0,2	0,2	BF dust	41,8	41,7
Limestone	0,2	0,2	BF sludge	40,2	40,2
BOF slag	4,2	4,2			
Coke/coal	5,2	5,2			
TOTAL	100,1		TOTAL	100,1	

Table 25: Zn-balance for SSAB BF No 3

According to the priorities expressed by SSAB and ILVA, the focus of the analysis was put on possibilities for a more efficient recovery and treatment of some by-products or waste flows.
The treatment of by-products allows in fact reduction of the volume of waste for disposal, the amount of hazardous waste and the recovery of some raw material for internal or external reuse.

HRM oily scales constitute a top offender in the ILVA priorities list. With the aim of improving separation of oil, dry matter and water from such by-product, several oily sludge and millscale treatment processes were evaluated by ILVA. The processes proposed by technology suppliers are listed in following Table 26 where the oil content of the scales before and after the treatment and hence the separation efficiency are reported.

PROCESS	Inlet Oil	Outlet Oil
Thermtech pyrolysis	15%	0.2%
Paul Wurth	20%	0.005%
Harsco – Equinox Technology	0.8-3.8%	<0.05%
R1 process by S.E.A.*	1.37-28.9%	0.11-2.9%
Non-thermal processes: washing with water and with or without degreasing agent (in collaboration with Drewo)*	0.05-2.49%	0.01-2.21%

Table 26: Oily sludge and millscale treatments (* R1 process and washing process were evaluated and tested by ILVA on a lab scale).

Task 3.3: Identification of potential solutions/technologies for waste recycling

One of the prior objective of ILVA is the recovery of oily scale after oil removal. Therefore, two processes were deeply investigated to this aim, namely the R1 process and non-thermal washing. Such processes are described here: their feasibility was assessed primarily in a set of lab-scale tests, then models of these processes were developed in order to assess their viability on a larger scale.

ILVA R1 Process by S.E.A. (a local SME).

R1 Process by S.E.A. allows a sustainable recovery and recycling of raw materials and also the reduction of waste designed to disposal. R1 is not a waste treatment process.

The process is based on the distillation and pyrolysis of oily materials by the use of thermic energy in an inert atmosphere. A possible flowsheet of the process is shown in Figure 27.

The plant to apply R1 technology consists of a reactor (an electric furnace) where the sludge/scale is subject to thermal process, a condenser system to separate and recover vapours, off gases and condensable phase, an off-gases treatment system and a decanter system to separate oily phase from water phase.

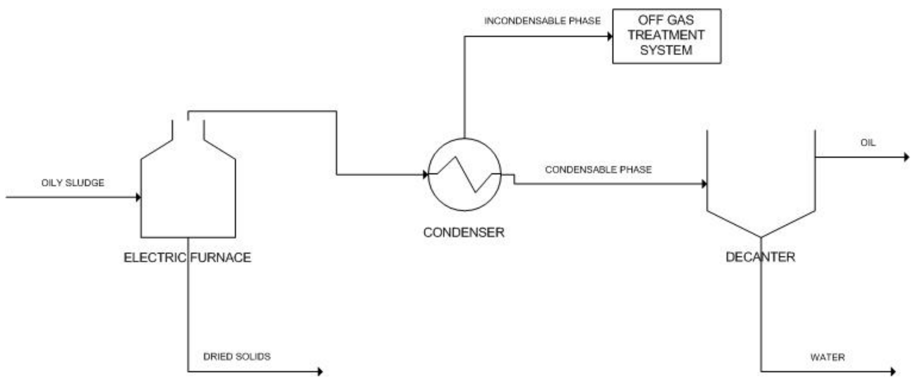


Figure 27. R1 process flowsheet

The R1 products are incondensable gases, condensable ones consisting of water, oil, solvents, etc. and dry solids consisting of inorganic matter and elemental carbon.

All these product can have a specific destination:

- The recovered "oil" can be reprocessed or sold.
- The water can be internal reused.
- The solid dry matter (reduced by weight from 10 to 80 % and volume) can be disposed as non-dangerous waste, sold or reused in the process if its properties are suitable.

Examples of constraints for the re-use of the solid fraction are: to reuse millscale in sinter production, the oil content must be unless 0,1% (AIA prescription); moreover, to sell millscale to cement plants the oil content must be about 0.25%.

The process has some advantages like the absence of combustion (e.g. no flame, no emissions deriving from incomplete combustion) and a thermal efficiency greater than 90%.

An experimental campaign was made by S.E.A and ILVA to collect data and to demonstrate the efficiency of R1 technology.

The pilot plant experiment consisted in the following steps:
First, nitrogen is fluxed through the furnace to obtain an inert atmosphere. Then the heating process starts from 25°C to 550-610°C; in this phase gas and liquid formation occur. The process is completed when there is no liquid formation anymore(after 6-11 h). At this time the thermal process is stopped and a cooling phase starts to bring back the temperature of the reactor to room temperature and allow to discharge dried residue.
Five samples were tested:

- A1 – sludge from last water treatment;
- A2 – sludge of hot rolling mill with lime;
- A3 – centrifuged sludge of hot rolling mill;
- A4 – sludge semi-liquid of plate mill;
- A5 – oily mill scale.

The relevant experimental data and results are listed in Table 27.
The results show that only a good compromise between time and temperature of treatment allow to achieve the oil content target of about 0,1 % to allow the internal reuse of dry residue.

SAMPLE	A1	A2	A3	A4	A5
OPERATING CONDITIONS					
Temperature [°C]	560	590	600	550-590 (2 thermal phases)	610
Time [h]	7	6	9	11	11
OIL CONTENT					
Oil input [% in initial sample]	13.27	13.67	9.46	28.9	1.37
Oil output [% in output residue]	2.9	0.36	0.36	1.48	0.11
RECOVERED PRODUCT					
Hydrocarbon recovered [% wt of total sample]	6.2	6.3	10.3	8.2	4.3
H_2O recovered [% wt of total sample]	26.5	20.8	2.6	55.5	7.8
Dry residue [% wt of total sample]	63.8	62.5	79.5	21.4	87.9
Incondensable and Loss [% wt of total sample]	3.4	10.4	7.7	14.9	-
Oil removal efficiency [%]	46	45	>99.9	23.7	>99.9

Table 27: Experimental data and results of R1 process

Scale Washing Process
Washing is a simple kind of oily millscale treatment to separate solids from oily phase. ILVA, in collaboration with Drewo, carried out an experimental campaign to validate this hypothesis of treatment. The process consists of a washing treatment of oily scale from various sources (park, sheet mill and plate mill) with water with or without degreaser in a rotating machine.
The various oily scales are characterized by different content of oil and particle size distribution: for example park scale has a smaller particle size than plate mill scale.
The following variables were considered in experimentation: washing phase number and duration of each of them, water temperature, amount and type of degreaser.
The used degreaser (Drewo product) consists in a aqueous mixture of tetra potassium pyrophosphate, sodium silicate, caustic potash and acid 1-idrossietiliden-1,1-diphosphonic in aqueous solution; its pH is about 12-14.
In the experimental campaign three cases were analysed:

- Three stage wash at room temperature: first and third stages with only water and second stage with a degreaser aqueous solution (5% wt).
- Three stage wash at 50°C: first and third stage with only water and second stage with a degreaser aqueous solution (5% wt).
- Three stage wash at 50°C with only water.

The length of a single stage is about 10-15 minutes. Figure 28 shows the 3 stage washing process.
The experimental campaign shows that it is possible to achieve an oil removal efficiency of about 65-90%. However, oil removal is strongly dependent from oil initial content: in oil reach park scale the removal efficiency is about 17-18%. The temperature does not appreciably affect the efficiency of the process. Experimental data give uncertain degreaser effect but it is plausible to consider that degreaser enhances oil removal. Furthermore, the finest fraction of solids and its oil content is dragged by water and so at the end of the process this fraction is lost: the park scale is finer than sheet mill scale and plate mill scale and so it have a greater number of lost solids.

Figure 28. Washing Process Stages

Other by products recovery solutions

Another solution to improve by-products reuse concern BOF sludge recovery, which is a prior objective for SSAB. The fine grained BOF sludge of SSAB is today landfilled. As the sludge contains about 50 % Fe it would be worthwhile to use it as raw material in some process e.g. the BF. The possibility to use the BOF sludge as a raw material could be achieved if the sludge is dried and agglomerated either as pellet or briquette. Although the Zn content is rather low it could be a limitation for recycling to BF. Another material sent to landfill is steel Ladle Slag (LS) which could be used as slag former or as complementary binding agent in agglomerates. SSAB has no sinter plant so fine grained material as BF flue dust and fine scrap are recycled via cold bonded briquettes. The briquette plant has reached its maximum production volume but if the BF dust could be recycled via injection to the BF there would be some capacity to increase the total recycling since other material could be briquetted. These three potential solutions for waste recycling all answer to the earlier identified KPI. The overall amount of wastes and by-products recovered as primary raw materials will increase and the overall amount of landfilled wastes will decrease if any of the solutions above are realized.

Moreover, other the potential solutions to increase re-use of by products from the production cycles were pointed out by the industrial partner from both the process knowledge collected in the previous tasks and the investigations and experiments that are currently ongoing within two projects funded by the EU through the RFCS, which are entitled, respectively, "*Impact of long-term application of blast furnace and steel slags as liming materials on soil fertility, crop yields and plant health*" (Ref SLAGFERTILISER Contract No. RFSR-CT-2011-00037) and *"Removal of Phosphorus from BOF-slag,"* (Ref PSP-BOF Contract No. RFSR-CT-2013-00032). Within these two projects the use of BF and BOF slag for soil fertilisation, liming and remediation is investigated. Therefore, to the aim of REFFIPLANT, this can be represented just as an addition of a further "sink" to consider when exploring different re-use paths, provided that some preliminary pre-processing step (e.g. sieving) are performed. On the other hand, in particular within PSP-BOF, some processing steps are investigated that should allow separation of BOF slag in two fractions, one rich in Fe and low in P for internal recycling (e.g. witin the sinter plant) and one rich in P and poor in Fe for external uses. Therefore, if some results will become available within the project duration, some at least simplified models could be develped to take also this possibility into account.
Table F1 in Appendix F shows a summary of the potential solutions for both ILVA and SSAB that could increase the recirculation of by products and wastes and their effect on the Key factors and performance indexes that have been pointed out in WP1.

Task 3.4: Integration of waste treatment processes for waste minimization

Models were developed by SSSA in order to investigate and evaluate some waste treatment processes, which are of relevant for ILVA, exploiting the simulation software Aspen Plus®. Such models, that represent the processes described in Task 3.3, were used to evaluate the potential scalability and re-applicability of the proposed solution in the industry. A detailed description of such models is reported in Appendix G.

The case studies of interest for SSAB involved simulation with the excel-based TOTMOD model (BF, HM desulphurisation and BOF). Figure 29 shows the results from modelling the recycling of BOF fine sludge (mixed with small size DeS scrap) in the form of a pellet, as well as steel ladle to BF. With the given generation of BOF sludge and 100% yield of pellet into the BF, the maximum amount of BOF sludge pellet was calculated to some 22 kg/tHM. The available amount of steel LS is some 10 kg/t_{HM}. The 0 line represent the reference case.

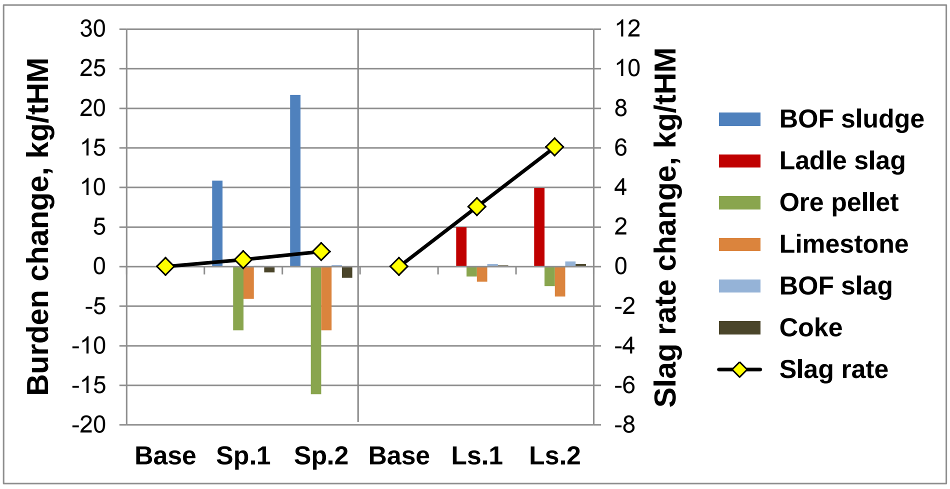


Figure 29. Effect of recycling BOF sludge pellet (left in the diagram);
Sp.1 – recycling of 50% of produced BOF fine sludge,
Sp.2 – recycling of 100% of produced BOF fine sludge.
Effect of recycling steel ladle slag (right in diagram);
Ls.1 – recycling of 50% of produced steel ladle slag,
Ls.2 – recycling of 100% of produced steel ladle slag.

The results indicate important gains in reduced need for iron ore pellet and limestone in the case of recycling of BOF sludge, with only minor increase in BF slag rate. Some slight reduction in coke rate is obtained. When steel ladle slag is recycled the effect on iron ore pellet and limestone is less due to lower Fe and CaO contents in ladle slag compared to BOF sludge pellet. More "ballast" (mainly SiO_2, MgO and Al_2O_3) in the ladle slag also mean a larger increase in BF slag rate, balancing out some positive effects of less iron ore pellet and limestone on the coke rate. Both BOF sludge and steel ladle slag recycling to BF show potential to decrease the yearly amount of material that goes to landfill but the potential is larger for BOF sludge (see Figure 30).

A case study of BF flue dust injection back into the BF was also carried out. The results are depicted in Figure 31.

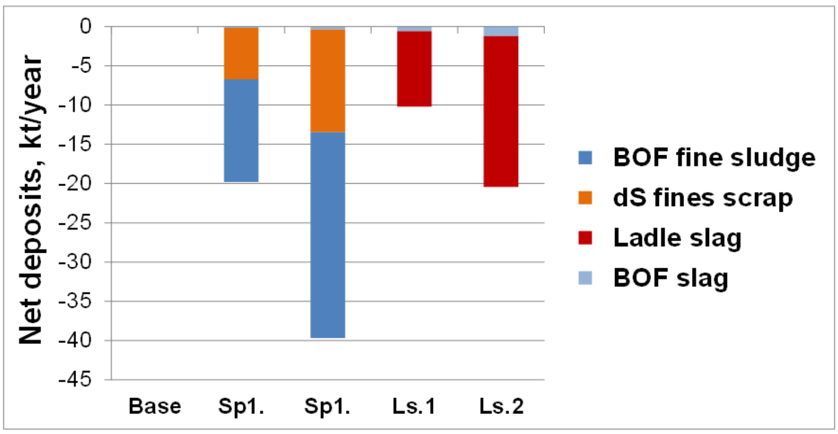


Figure 30 BOF sludge & ladle slag to BF - effect on landfill/storage volumes

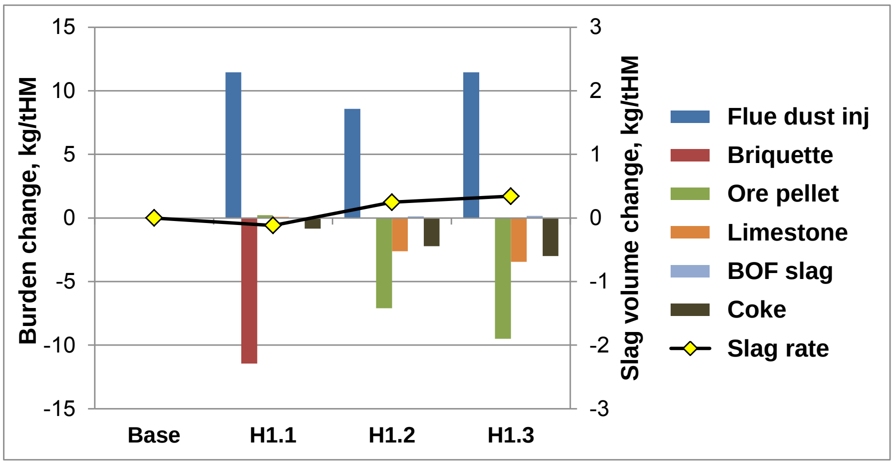


Figure 31 Effect of injecting BF flue dust back into the BF;
The 0 line represent the reference case
Case H.1 – Injecting 2/3 of all flue dust – no replacement in briquette
Case H.2 – Injecting 1/2 of all flue dust – fully replacement by scrap mix[1]
Case H.3 – Injecting 2/3 of all flue dust – fully replacement by scrap mix

Conclusions drawn from the simulations

As far as the recycling of by products at ILVA are concerned, two processes were evaluated in order to treat oily materials (sludge and millscale) and to recover them to be sold or reused. A few experiments at laboratory scale had been already carried out: simulation models were developed to obtain more detailed results and extend the investigation with some sensitivity analyses.
For the R1 Process (distillation and pyrolysis of oily materials), the experiments and the Aspen Plus simulation show that, when applied for treating oily sludge or scale, it allows to obtain an oil removal efficiency of about 100% at the imposed operative conditions. The simulation shows that a total separation between solid and liquid (vapour fraction=1) is possible with a suitable temperature in the reactor (of about 340-400°C) in dependence of the initial oil content: the more is the initial oil content the more is the temperature of total vaporization. The R1 process allows to recover almost pure oil, water and scale that can be sold or reused; the sludge volume is also reduced.
As far as the Washing Process of oily millscale is concerned, the experiments campaign and the Aspen Plus simulation show that the process allows to obtain an high oil removal (of about 80-90%) and a suitable oil content in treated scale to reuse it in sinter production. The simulation shows that the oil removal is affected by the washing water mass used in the process: the higher is the washing water the higher is the oil removal but then the oil removal efficiency asymptotically stabilizes. The higher the initial oil content, the higher the oil removal efficiency. Other simulation results show that the degreaser mass flow only slightly affects the oil removal (probably because the degreaser type is not appropriate) and the temperature (from 25°C to 70°C) does not appreciably affect the oil removal efficiency. The use of more stages of different residence time and different amount of water and degreaser in each stage and the remove of dirty water in every stage is suggested to improve the efficiency of the oil removal from millscale. It is also worth to remark that a good mixing must be ensured in order to increase oil removal.

The conclusions drawn from the case studies of interest for SSAB concerning recyclying of wastes into the BF are as follows:

- Recycling BOF fine sludge into the BF – major cost savings:
  - Reduced need for iron ore pellet and limestone
  - Limited effect on BF slag and coke rate
  - "All" plant input Zn to BF sludge (Zn increased from 0,5 to 0,7% in BF sludge), but very small reduction in total Zn to landfill (less ore pellet)
  - Slightly higher Mn, P, S and V in hot metal
  - Landfill reduction potential: 40 000 t/year (sludge + dS scrap)
- Recycling steel LS to the BF – minor (or no) cost savings:
  - Large portion of oxidic material gives increased slag rate

[1] "scrap mix" consists of several materials (mainly steel scrap fines, dS scrap fines, BOF coarse sludge, mill scale and recycled briquettefines) which are pre-mixed and stored before used in the production of the BF briquette.

- Small reduction in limestone and iron ore pellet
- Large increase in HM Mn content and higher Al_2O_3 in BF slag
- Landfill reduction potential: 20 000 t/year (if all BF slag is sold)

- Recycling BF flue dust into the BF:
  - Major cost savings (cheaper to inject than to briquette)
  - Reduced need for iron ore pellet, coke and limestone - IF injected flue dust is replaced in briquette by, e.g. "scrap mix"
  - Limited effect on BF slag rate, HM quality and Zn balance
  - Landfill reduction potential: 20 000 t/year

2.2.4 WP 4: Integrated process optimization

Task 4.1: Development of holistic models suitable for multi-objective optimization

Optimization studies on water networks

SSSA and PIL developed some holistic models aiming at the simplified representation of common unit operations of resources usage to predict the main properties of products flows. These models are inserted in a general-purpose tool for preliminary study of simulation and optimization of industrial water networks (WATER software for water resource) that is implemented by PIL.

Starting from process knowledge and literature state-of-the-art, a simplification of the detailed design procedures was carried out and some Excel-based holistic models of different treatments and processes were developed, related to the wastes and water cycles in iron and steelmaking industry. The models needed to be as simple as possible, without the loss of physical and process information. A holistic models library was added up in common with all the research partners, which represents Deliverable 4.1 and includes the main treatments and processes representations involved in the industrial case studies to analyse (see Appendix H). In particular, the following spreadsheet-based linear/non-linear unit models were developed:

a. Clarifier (based on PSD data and particle settling velocities)
b. Activated sludge
c. Belt and sand filters
d. Venturi scrubber
e. Reverse Osmosis
f. Oil separator
g. Flotation unit
h. HC
i. Lagoons
j. Pumps & Pipes

A superstructure approach was chosen in order to carry out the integrated water network optimisation studies (Figure 32). The unique feature of this approach is that all feasible connections, including water re-use, water regeneration and re-use, water regeneration recycling, local recycling around process and treatment units and pre-treatment of feed-water streams can be considered.

The mathematical model of water network consists of mass balance equations for water and contaminants for every unit in the network. Mixing rules are developed to propagate data from mixer and splitter nodes within the model. The model is suitable for variety of studies in both new designs and retrofits. These could be fixed topology studies (no cost solutions), re-use studies involving re-piping opportunities (low cost solutions), or regeneration and reuse studies involving distributed treatments (medium cost solutions).

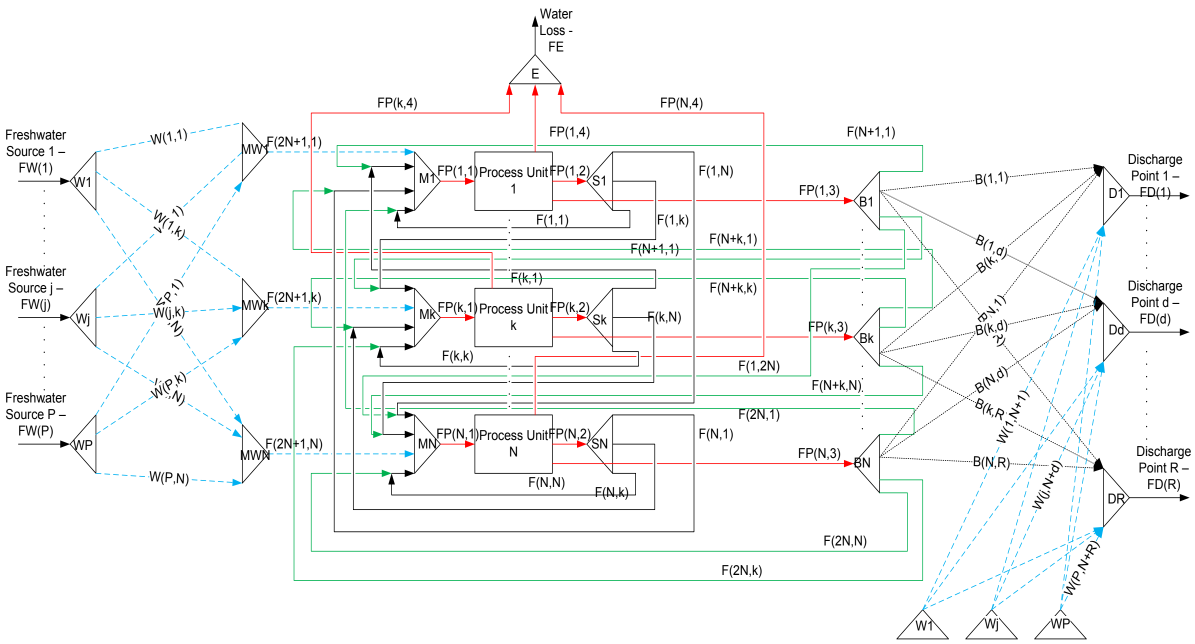


Figure 32 Network Model Superstructure

MEFOS and SSAB developed a model for the water network at SSAB plant in Luleå. It is a mass and heat balance in Excel based on the mapping that had been previously done within the project. In order to validate the model, measurements for 2014 (until November 22nd) were exploited for the tests. This is due to the new measurement points that were established during November 2013 as a part of this project.

The model compares available measured values for sources and sinks, to calculated consumption. It can also be used in order to calculate how the water consumption and the flow or quality of the discharge water (temperature and chemical composition) will be affected by a change in the system. The temperature effect at the Laxviken outlet is e.g. one of the effects that are considered in the case study of the CC spray on water. The overall water balance is used for case studies in Task 4.3.

The total amount of water used in the different processes; IV1, IV4 and municipal drinking water (sanitary use not included) is 7765 m^3/h if the measured incoming IV 1 water flow is used and 8532 m^3/h if the sum of all applications is used (storm water, landfill leachate etc adds another 50 m^3/h of water to the total intake, but they are the same for both cases). Measured flow for IV4 is used in both cases (if measured IV1 flow is measured and if IV1 flow is calculated. The sum of all applications is based on both measured data and approximations stated in WP2. In order to get better calculated values, more accurate approximations and/or extra measurements will be needed.

IV1 and IV4 dominate as water sources, and the usage of municipal drinking water in the processes is limited. Even though the Municipal drinking water consumption for process use is very limited, due to the higher cost rate it contributes to 16% of the total cost for process water.

The water that is used in the different processes has been divided into 4 types of application:

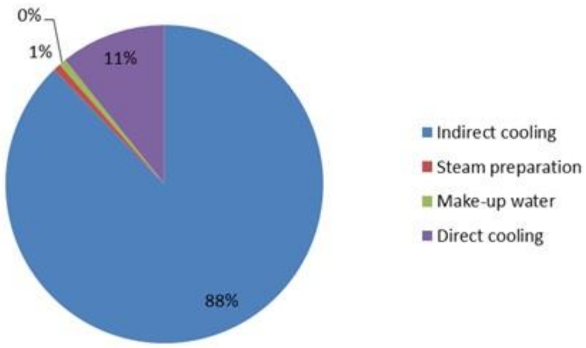
- indirect cooling in heat exchangers
- direct cooling (coke and slag quenching and cooling of slabs)
- steam preparation
- make up water

The distribution between the different applications is shown in Figure 33.a, which clearly shows that indirect cooling is by far the largest type of consumption. The different discharge points are: Laxviken, KV-diket, Svartöviken and Evaporation: Figure 33.b shows the distribution among them. The measured and calculated (sum of all applications) flows and temperatures for the different discharge points are summarized in Table 28.

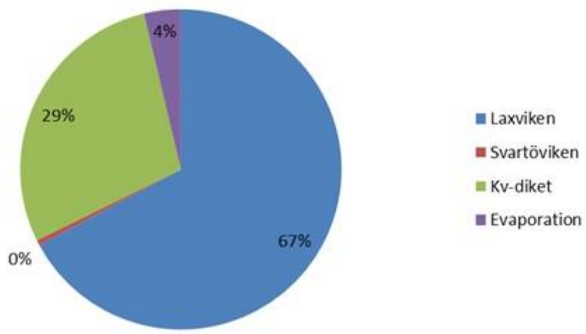
Discharge	Flow (m^3/h)	Calculated flow (m^3/h)	Temperature (°C)	Calculated Temp. (°C)
Laxvinen	4991	5688	16.5	18.8
Svartöviken	28	43	n.a.	6.3
Kv-diket	2400	2421	17.9	17.6
Evaporation		314		
Total	7733	8467		

Table 28: Mean measured and calculated flows and temperatures for different discharge points.

IV 1 is the largest source of water at SSAB Luleå. The distribution of IV1 water is depicted in Figure 34. The largest consumers of this freshwater are Cooling of BF, Oxygen Plant, indirect cooling CC (spray on water for casting of slabs) and indirect cooling of CC. There are some minor consumors eg coke quenching, make up water, raw material handling, steam preparation, but since they are each smaller than 1% of the total flow they are shown as "other" in Figure 34.



(a)



(b)

Figure 33: (a) Different applications for Process water (closed circuits not included); (b) Distribution among the different ways of discharge, Laxviken, Svartöviken, KV-diket, evaporation.

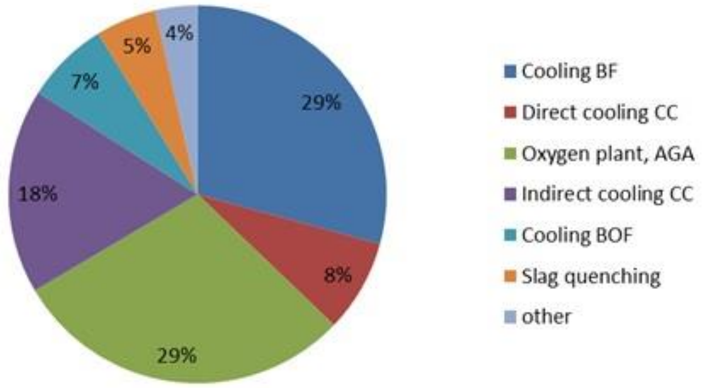


Figure 34: Distribution of IV1 water

The calculated water consumption (sum of all applications) for IV1 is 6136 m^3/h, compared to the measured flow of this stream which is only 5369 m^3/h. This is a difference of 14 %. The measured flow for the discharge at Laxviken is 4991 m^3/h. This results is reasonable and realistic if compared to the measured incoming flow, taking into account the evaporation which is calculated to around 300 m^3/h and the small amounts of water that leave SSAB at other discharge point. All available outgoing flows to Laxviken add upp to 5688 m^3/h. This is an error of 14% compared to measured flow. The temperature of the outgoing flow at Laxviken was calculated to 18.8 °C. That is an error of 14% compared to the measured temperature of 16.5 °C. An error of 14% is not satisfactory and more work on validation of data and the model is needed.

IV4 Almost all of the IV4 water is used for indirect cooling in heat exchanger. The flow is discharged at discharge point KV-diket together with water from the biological waste water plant. The calculated discharge corresponds well to the measured outgoing flow.

Optimization studies on material flows

The optimisation method used in the modelling work for recycling of secondary materials at both ILVA and SSAB steel production plant is mixed-integer linear programming (MILP) by using the Java-based software reMIND. Figure 35 depicts the structure of the reMIND model developed by MEFOS. The model is based on a global mass- and energy balance for the production chain and individual sub-balances for the main processes. The developed model makes it possible to perform total analysis assessing effects from changes in operations regarding the included processes. On the other hand, Figure 36 shows the structure of the reMIND model developed by SSSA. In this case, the model, also based on mass balance, is a sort of expansion of the "Recycling of material" block of the SSAB model. It represents the different routes of the main steelworks by-products and wastes: reuse after or without a treatment, sale or disposal.

Analysis using reMIND can be made as multi-objective/multi-criteria analysis and can be made with different time steps. A MILP problem consists of an objective function, variables and constraints. The objective function includes different variables which can be minimised or maximised depending on what is desired. Typical objectives are minimised landfill or disposal, cost, CO_2 and energy.
The two developed system optimisation models were used by MEFOS and SSSA to investigate recycling strategies for secondary materials to improve the in-plant material efficiency for SSAB and ILVA, respectively. The MEFOS model generally consists of the steel production routes with the consumption of resources, generation of secondary materials and the material recycling possibilities. Optimisation is made regarding the different recycling options of dusts, sludges and slag, minimising the landfilled amounts, while constraining the energy consumption. On the other hand, the SSSA model is simpler, neglects the upstream production process and considers only the by-products and wastes amount as well as the downstream recovery processes. In the developed model only some by-products, treatments and reuse options were included, as they are related to the case studies of interest for the project. However, the model is flexible and expandable: it can be upgraded and customized according to the requirements and following the same approach.
SSSA developed some Excel-based holistic models to carry out investigations on the possibility to recycle of some by-products streams of ILVA (see Task 4.3) and to generate data to be used in reMIND optimization study. Material treatment units were modelled starting from process and empirical data and literature information.
The holistic models was grouped in a library, which was added up in common with all the research partners and includes the main treatments and processes representations involved in the industrial case studies to analyze (see Appendix H). In particular, the following spreadsheet-based linear/non-linear unit models were developed:

a. Cooling stage;
b. Grindind and sieving stage;
c. Magnetic separator stage.

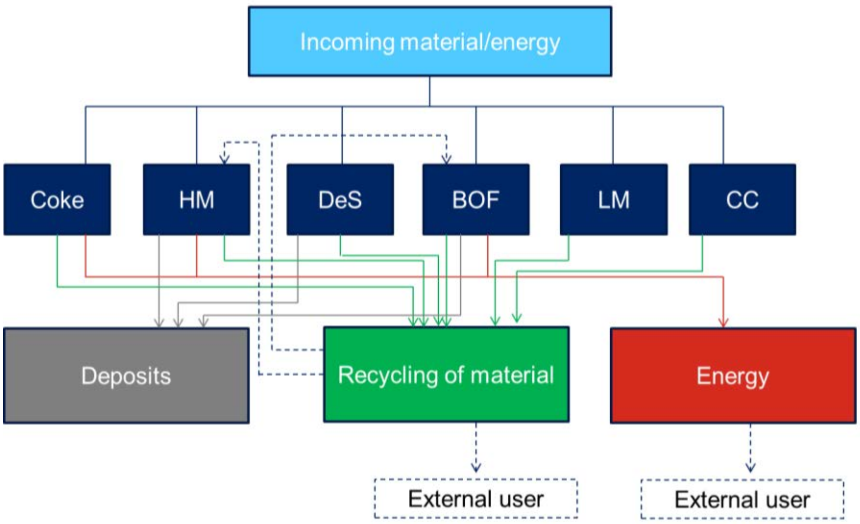


Figure 35: Illustration of nodes and flows in the MEFOS reMIND model.

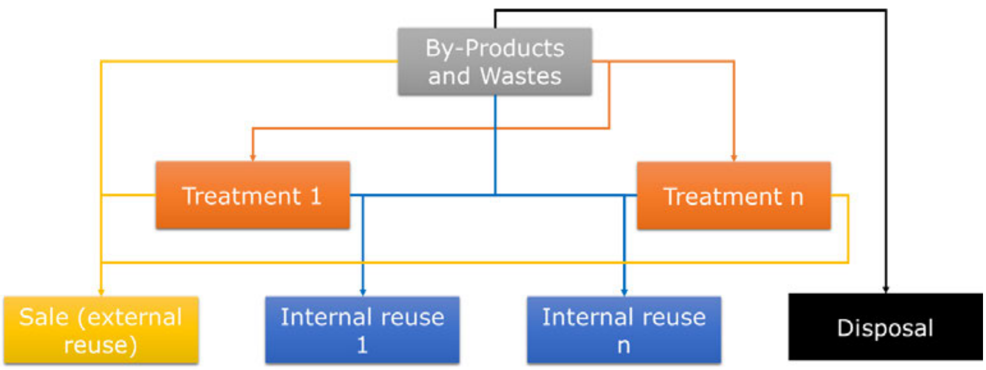


Figure 36: Illustration of nodes and flows in the SSSA reMIND model

Task 4.2: Implementation of Multi-Objective Optimisation (MOO) techniques

Real world optimization problems are often characterized by the need to simultaneously combine and optimize of many different objectives in order to achieve a final solution. Therefore what is called a MOO problem consists in finding one (or more) optimal trade-off among several possibly conflicting objective functions [1]. More precisely in [2] MOO is defined as the problem of *"finding a vector of decision variables which satisfies constraints and optimizes a vector function whose elements represent the objective functions. These functions form a mathematical description of performance criteria which are usually in conflict with each other. Hence, the term optimize means finding such a solution which would give the values of all the objective functions acceptable to the designer"*. From the mathematical point of view a generic MOO problem can be defined as follows:

$$\begin{aligned} &\text{min} && \mathrm{f}(\mathrm{x}) = [f_1(\mathrm{x}), f_2(\mathrm{x}), \ldots, f_k(\mathrm{x})] \\ &\text{subject to} && h(\mathrm{x}) = [h_1(\mathrm{x}), h_2(\mathrm{x}), \ldots, h_m(\mathrm{x})] \le 0 \\ &\text{with} && \mathrm{x} = (x_1, x_2, \ldots, x_n) \in X \qquad X \subset \Re^n \end{aligned}$$

where x is the variable vector, $f(x)$ is the *objective vector*, i.e. the vector having as elements the different objective functions, $h(x)$ if the constraint vector and X is space of feasible solutions. As it has been stated before, for nontrivial MOO problems there is not a unique optimal solution. In fact the vector function $f(x)$ forms a mathematical description of the performance criteria which can also conflict against each other and the utopian solution $f^*(x)=[f_1^*,f_2^*,\ldots f_k^*]$ where f_i^* denotes the minimum of the i-th individual objective is feasible only for trivial problems as it can be reached if all the functions $f_i(x)$ have their minimum in the same point, which is a very rare condition, especially as the dimensionality of the problem increases.

A widely used approach to MOO problems search not a unique solution but for a set of solution meeting a trade-off optimality criterion firstly introduced by Edgeworth in 1881 [3] and subsequently generalized by Pareto in 1896 [4]. This set forms, in the objectives space, the so-called *Pareto front* (or *Pareto set*). All the solutions belonging to the *Pareto set* have the property to be *non-dominated*, which in practice means that no other solution exists, which can improve at least one of the objectives without degrading the other ones. From the mathematical point of view, a solution *a* dominates *b* if and only if for each objective function f_i, $f_i(a) \le f_i(b)$ and for at least one objective function this inequality is strict: This can be formally stated as follows:

$$a \succ b \Leftrightarrow f_i(a) \le f_i(b) \forall i \quad \wedge \quad \exists j : f_i(a) < f_i(b)$$

In many real word applications Genetic Algorithms (GAs) are exploited in order to carry out the optimization as they allow a flexible problem formulation and an effective generation of a set of different trade-off solutions even when coping with very complex problem and highly nonlinear constraints. This was also the original choice made in this project at the proposal stage and in fact some GA-based MOO algorithms were evaluated, such as the Niched Parted Genetic Algorithm (NPGA) [5], the Non-dominated Sorting Genetic Algorithm 2 (NSGA2) [6] and the Strength Pareto Evolutionary Algorithm 2 (SPEA2) [1]. A general purpose software in the C++ programming language was also developed by SSSA.

However, GAs present also the drawback of a considerable computational complexity and do not fit well the simulation approach that has been followed in the development of the WATER Int software. Therefore, finally, an alternative approach was attempted and a MOO module was developed within the WATER software wherein two optimization objectives can be selected at a time. One of the optimization objectives needs to be cost-based (e.g. minimize capital cost, minimize operating cost, or minimize total cost) while the other needs to be flow based (e.g. minimize freshwater flowrate, minimize treatment flowrate, or minimize discharge flowrate).

A series of optimization runs is internally executed with different target value boundaries for flow based optimization objective function. In each of these runs, data set of constraint value and corresponding optimum for cost based objective functions is obtained. These obtained data sets is plotted together and essentially represents the 'Pareto front' for a given problem. The proposed approach of decomposing a MOO problem into a series of constrained optimization problems is depicted in the Figure 37.

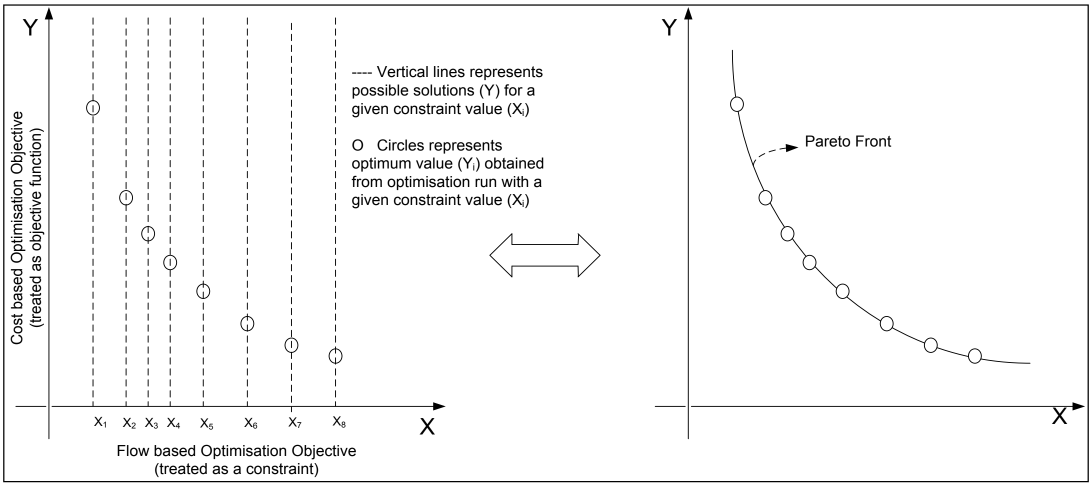


Figure 37 Proposed approach for MOO implementation in WATER software

Please note that these constrained optimisation runs cannot be performed in reverse order i.e. fix cost based objective function and optimise flowrates. This is primarily due to the way the WATER software framework is being set-up in terms of its calculation sequence.
The MOO module discussed above was implemented within the WATER software with source water flowrate as one of the two objective functions. The user needs to select the other cost based objective function and also provide the range of values over which the source water flow rate shall be varied. A snapshot of MOO setup panel within WATER is provided in Figure 38.

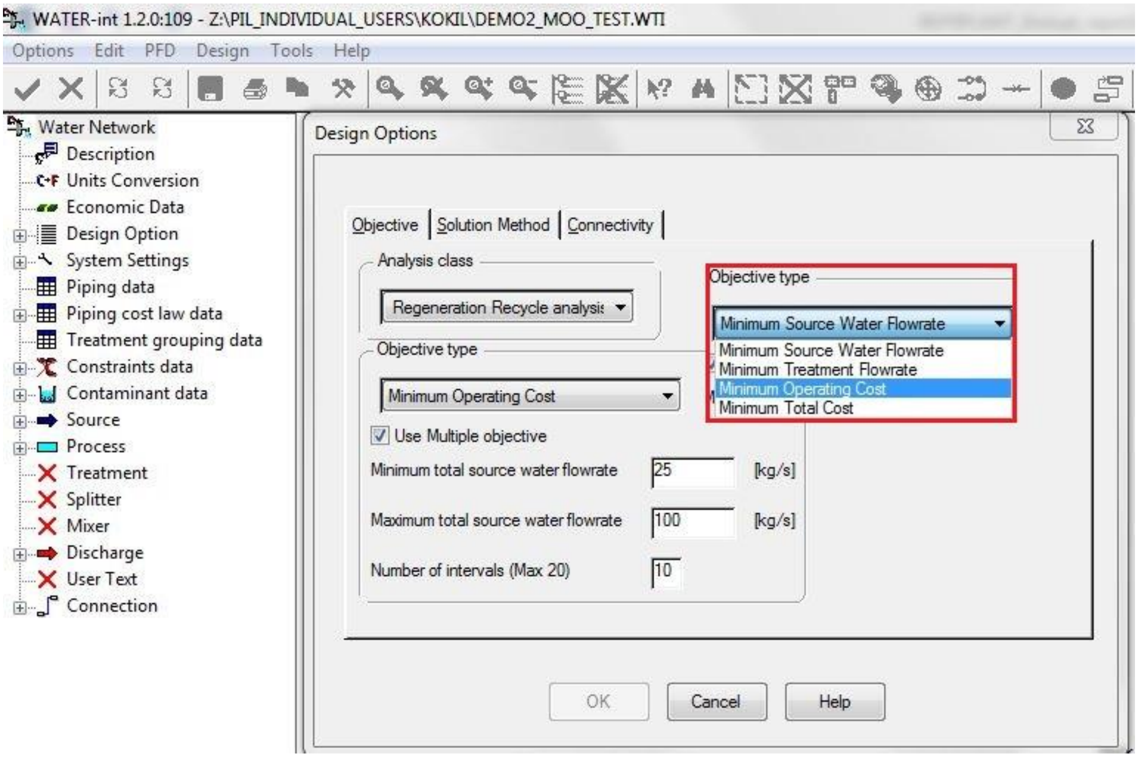


Figure 38 Snapshot of MOO setup panel within WATER

Based on the above setup details, WATER runs the program a number of times equal to number of specified intervals and collects data for all converged optimisation runs. Please note that if the problem is infeasible for a given constraint on source water flowrate, then that data set are ignored. All feasible data sets will be plotted together and curve fitting will be performed on these obtained points. The resultant curve in essence will represent the Pareto front. The graphical interface of WATER for Pareto front graph is illustrated in Figure 39. Other examples of the Pareto front graphs obtained for Tata Steel case studies are illustrated in Appendix I.

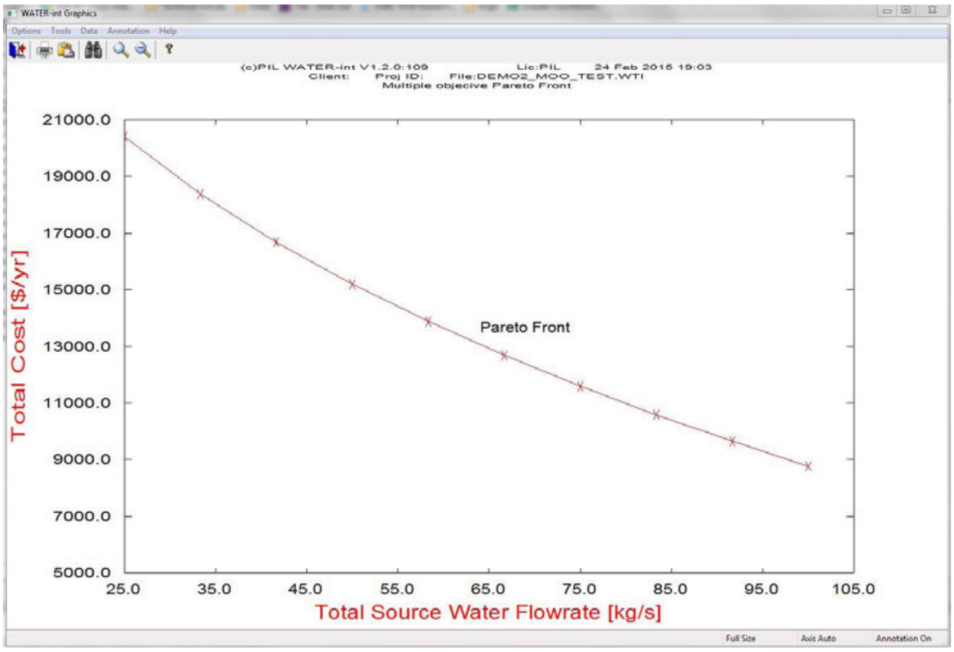


Figure 39 Snapshot of Pareto Front graphical interface within WATER

Task 4.3: Investigation of case studies and selection of solutions/technologies

Cases-study related to water efficiency

Potential solutions for improving water efficiency at ILVA system were investigated and reported in Mid-Term Report. According to ILVA priorities, a subset of options was selected from the table of solutions, in order to investigate in detail through process modelling and simulations the potential feasibility and convenience:

- reuse of blowdown water from CC No 1 for the off-gas cleaning of the BOF No 1;
- reuse of blowdown water from 41/2/3 AI for the off-gas cleaning of the BOF No 2;
- reuse of blowdown water from 33 AI for the TUL1 pipe mill cooling;
- reuse of RIV2 blowdown water from 52 AI for the TUL2 pipe mill cooling;
- reuse of RIV3 blowdown water for the TUL2 pipe mill cooling;
- alternative use of process water streams for off gas cleaning.

Unfortunately, due to the current reduced productivity of ILVA plant, the pipe mill No 2 (TUL2) is currently not constantly operating, thus the analysis of the related solutions were not deepened as no possibility was foreseen in the short term of any experimental activity in this plant.
The solutions that were simulated by SSSA are (further details are provided in Appendix I, which also represents Deliverable D4.2):

1. reuse of blowdown water from CC No 1 (CCO1) for the off-gas cleaning of the Basic Oxygen Furnace No 1 (BOF1);
2. reuse of CCs No 2/3/4 blowdown (CCO2/3/4) in Basic Oxygen Furnace No 2 (BOF2);
3. reuse of pipe coating No 1 blowdown (RIV1) in pipe mill No 1 (TUL1);
4. alternative use of process water streams for off gas cleaning (contaminants reduction and water reuse of coke-making area wastewater).

SSSA approach to the simulation of water reuse options was the same for each case study.
Starting from lab data of water quality (e.g. ions content, calcium hardness, total hardness, pH value, electrical conductivity) main chemical compounds like salts and oxides were selected, which are frequently present in water streams. Calculation of species concentrations was carried out to match real data about ionic content. All the data related to salts and chemical species and the specific concentration in water streams obtained in this way are inputs for the simulations, which were developed using Aspen Plus® commercial software and WATER software (for the last one). The reason for this choice was that WATER allows obtaining suggestions about the possibility of water reuse, also considering not existing networks, on the basis of the only water properties, without taking into account whole system behaviour but selecting some promising options for further investigations. Aspen Plus® allows the user to carry out a more detailed simulation, involving all the chemical and physical processes linked with the selected plants, testing different operating conditions.

In collaboration with ILVA technical staff, Pipe and Instrumentation Diagrams (P&ID), data about normal operating conditions of the unit operations involved in each case study and literature information related to the lack of real data (such as, e.g., equipment efficiency and particle size distribution of steelmaking sludges) were gathered.
A preliminary global mass balance on the plant area to analyse was fundamental in order to evaluate intermediate losses and flowrates which are not measured. Some hypotheses on unknown flowrates were done according to the normal rate of the fluid in pipes and to the real pipes sizes.
In the simulation flowsheet each unit is considered on the basis of the context unique or composed by different sub-units to obtain an output with features as close as possible to real data. Some changes in simulated operating conditions became necessary for these reasons.
After the validation of the complete model of plant area, which has to agree with real process information, it was possible to model the change in charge stream, focusing on the differences in the outputs of interest.
According to simulation results in terms of potential benefits, the most promising solutions appear to be the first case study of reuse of CCO1 water blowdown in BOF1 gas washing water network, the third one of reuse of water blowdown coming from RIV1 in TUL1 water system and the last one of production of high quality water from coke-making area water blowdown to be used as input to other plants instead of Sinni river fresh water. Results for the second case study shows some benefits in using CCO2/3/4 blowdown for BOF2 area but actually the differences in current quality of wastewater with respect to past year one suggest such solution to be no more promising.
The low current productivity, connected with the uncostant operation, does not allow evaluating the possibility of on-site application for TUL1 case study. On the other hand, tests can be carried out for the first and the fourth options, respectively related to BOF1 and coke-making areas. ILVA position and interest focused on the last case, also due to the fact that the proposed treatment for wastewater results in obtaining high quality water, which can be used in any field of plant application.
As far as the analysis of the case studies related to Tata Steel water network is concerned, PIL followed a three step systematic work process in order to identify the improvement opportunities and carry out further optimisation work. The details of the work process are illustrated in the guidelines described in detail in Appendix L.
Based on this approach, the following 11 case studies were identified at the Tata Steel site at the end of Stage 2.
Reuse Solutions:

12. Lagoon Water Segregation
13. Pond A water reuse in Sinter Plant
14. HPM overflow water reuse in Coke Oven 1 and BF OCC via Ancholme water supplies
15. Reuse of Pond A & BF GW water to bowsering tanks
16. TBH blowdown maximisation to BF GW circuit
17. Pond B water reuse in open circuit cooling cycles

Regeneration Reuse Solutions:

18. HC rearrangement to achieve recycled water quality improvements by better capturing of metals and suspended solids
19. Strategic addition of filters to achieve recycled water quality improvements by better capturing of metals and suspended solids.

Regeneration Recycling Solutions:

20. Lagoon 1 water reuse in BF GW circuit followed by Ammonia treatment of its blowdown. Ammonia treatment options considered in this regard are as follows:
    a. Chlorination
    b. Breakpoint Chlorination
    c. Air stripping of ammonia
21. Lagoon 1 water reuse in BF GW circuit followed by RO treatment of BF GW circuit water
22. Demin plant effluent brine concentration

Out of these case studies #3, 8, 9 & 10 were carried forward for stage 3 optimisation. These case studies are merged together under the following 4 headings:

v. Lagoon 1 water reuse in BF GW Circuit
vi. Pond A water reuse in BF GW Circuit
vii. Recycling of the BF GW HCe overflow water with suitable treatment
viii. Heavy Plate Mill (HPM) − Ancholme Water Reuse

Note that many of the left out solutions have the potential to be economically attractive for future operating scenarios such as increased production capacity and stricter environmental legislations.
Details of the above mentioned four case studies can be found in Appendix I as a part of Deliverable D4.2.

Potential solutions for improving water efficiency at SSAB plant in Luleå system concerned

- the spray-on water used at the CC
- the BF gas recycling system

The spray-on water for the CC is cooled with a Cooling Tower (CT). However, the cooling tower is old and not functioning properly and a lot of the cooling is done by dilution with make up water. The old CT should be replaced with new cooling equipment, either a new CT or a Heat Exchanger (HEX). Investigations on the CC cooling system were performed in order to understand how installation of new cooling equipment would affect the system, with respect to make up water, total usage of cooling water and discharge temperature from the Laxviken pond system. From the measurement campaign that was carried out, the water flows in the system could be determined.

The BF gas treatment system at SSAB Luleå plant was studied and modelled in WP 2. The correlations between the recirculation of the gas treatment water and the concentrations of various compound was studied and investigated in more detail in a plant trial (WP 5). The model was further developed based on the results from the plant trials and was used for a case study in order to investigate the effects of increased recirculation, with and without treatment of the recirculated water.

Details of these cases study can be found in Appendix I which also represents Deliverable D4.2.

Cases-study related to by-products and wastes

For ILVA wastes- and by-product-related issues, some potential solutions had been reported, which include:

- the distillation and pyrolysis for sludge/scale recovery;
- a mill scale washing process for not oily scale recovery;
- an increased internal (e.g. to produce pellets for the sinter plant) or external (e.g as fertilizer) reuse of BOF slag;
- optimization of the reuse of by-products or wastes.

Some of the presented options had been evaluated and simulated in WP3 by SSSA. Unfortunately, Italian law dispositions do not allow a manufacturing industry to treat its own wastes without a special permission. For this reason, the results on the first two cases study can be useful from a European point of view but cannot be tested in Italy without the aforementioned permission.

Simulation of the case study of reuse of BOF slag as fertilizing material [7] was carried out (see Appendix I which also represents Deliverable D4.2) using the holistic models developed by SSSA for material treatment units. The results are promising and show the potential benefits related to the reduction of waste amount and cost saving due to external use as fertilizer.

The last case study has a conclusive character, as it exploits the results obtained in the other cases in order to suggest improvements in the management of by-products and wastes by minimizing the costs and the amount of disposed material and by maximizing the quality of products (e.g. pellets). Furthermore this case has been also used to assess the suitability of the reMIND software in the study of by-products and wastes management optimization (Task 4.4).

SSAB developed an Excel-based model (TOTMOD) to carry out MEFOS process simulations on preliminary case studies. The method and developed model is based on the Microsoft® Office Excel spreadsheet model MASMOD. The developed model includes element distribution between slag and metal, and can be used for process simulation and analysis of various operating conditions as well as the influence of specific process parameters.

Task 4.4: Assessment of developed tools for total site analysis based on partners feedback

The Water-int™ software is based on linear optimisation framework and hence it does not consider complex ionic interactions between different contaminants. Instead it works on the basis of fixed or linearly varying separation factors which are back-calculated based on the regression of the available plant measurement values. The accuracy of such approach has been validated in the cases study of Tata Steel and is illustrated below by means of Pond A mixing example from the Tata Steel plant.

In this system, blowdown streams from GW systems of the BF GW and BOS GW are mixed together and allowed to settle in a lagoon (Pond A). Due to the large residence time in these lagoons, a considerable portion of suspended solids (TSS) are expected to be settled down at the bottom of Pond A which can be later recovered as sludge. Also due to complex ionic interactions between the two blowdown streams, some degree of separation is also observed for other contaminants such as TDS, chlorides (Cl) and ammoniacal nitrogen (NH_3).

Table 29 compares the Water-int™ prediction of Pond A outlet water quality against actual measurements. As illustrated in the table and the subsequent bar chart below, Water-int™ results are close enough (±15%) to be used for preliminary investigations of process integration opportunities. Figure 40 shows a comparison between the *Water-int*^{TM} simulation results and the actual measurements related to relevant contaminants.

		Units	BOS GW b/d (Measured)	BF GW b/d (Measured)	Pond A Outlet (Measured)	Pond A Outlet (Predicted)	% Difference
Data Set #1	NH_3	mg/l	0.138	76.7	25	27.9	12%
	Cl	mg/l	114	722	586	575.2	-2%
	TDS	mg/l	571	2760	2160	2160.0	0%
	TSS	mg/l	14.6	99	31.4	31.4	0%
Data Set #2	NH_3	mg/l	0.055	68.4	25.3	24.9	-2%
	Cl	mg/l	132	703	552	563.1	2%
	TDS	mg/l	1160	2780	2300	2259.2	-2%
	TSS	mg/l	6.75	116	32	36.2	13%
Data Set #3	NH_3	mg/l	0.03	64.1	25.7	23.3	-9%
	Cl	mg/l	102	662	527	527.0	0%
	TDS	mg/l	720	2670	2080	2113.5	2%
	TSS	mg/l	8.18	166	55.4	51.7	-7%
Data Set #4	NH_3	mg/l	0.03	56.6	20.6	20.6	0%
	Cl	mg/l	138	555	426	449.5	6%
	TDS	mg/l	687	2530	2220	2003.4	-10%
	TSS	mg/l	6.17	81.7	22.6	25.6	13%

Table 29: Validation of *Water-int*^{TM} results against actual plant measurements for Pond A

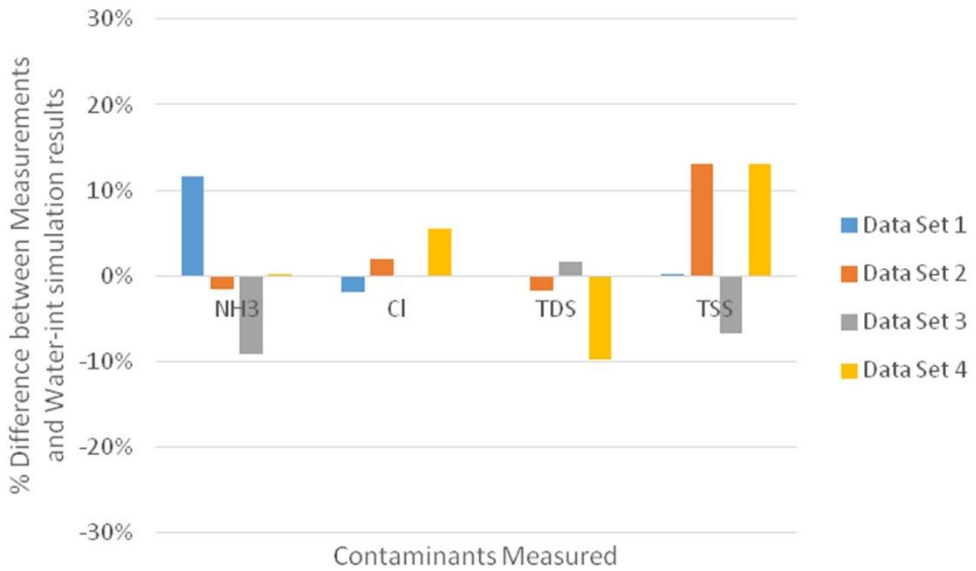


Figure 40: Comparison of *Water-int*^{TM} simulation results against actual measurements.

The Water-int^{TM} software was evaluated also in some case studies related to ILVA. In particular the investigation of pipe coating n°1 blowdown (RIV1) reuse in pipe mill n°1 water network (TUL1) carried out by Aspen Plus® (WP4) has been carried out also using Water-int^{TM} in order to compare the two obtained simulation results. Same data used in Aspen Plus ® simulation but with poorer chemical information was used in Water-int^{TM} modelling. The developed model is shown in Figure 41.

The results of the two simulation systems were compared and similar outcomes were obtained, as depicted in Figure 42. Both simulations show that RIV 1 blowdown reuse allows a reduction of freshwater intake with only small variations of the water stream parameters. The differences between the results of the two models are due to the fact that Water-int^{TM} does not consider chemical compounds interaction. However, the good and similar results obtained with the two different simulation frameworks attest that Water-int^{TM} is suitable for preliminary and simplified PI analyses.

Furthermore, Water-int^{TM} has been also used in the investigation of optimal configuration of water treatments to allow the reuse of coke-making area wastewater in ILVA facility, as explained in Appendix I. The good results obtained by ILVA in on-site trials (WP5) following the indications obtained through the Water-int^{TM} simulation attest that this software is also suitable for preliminary optimization studies.

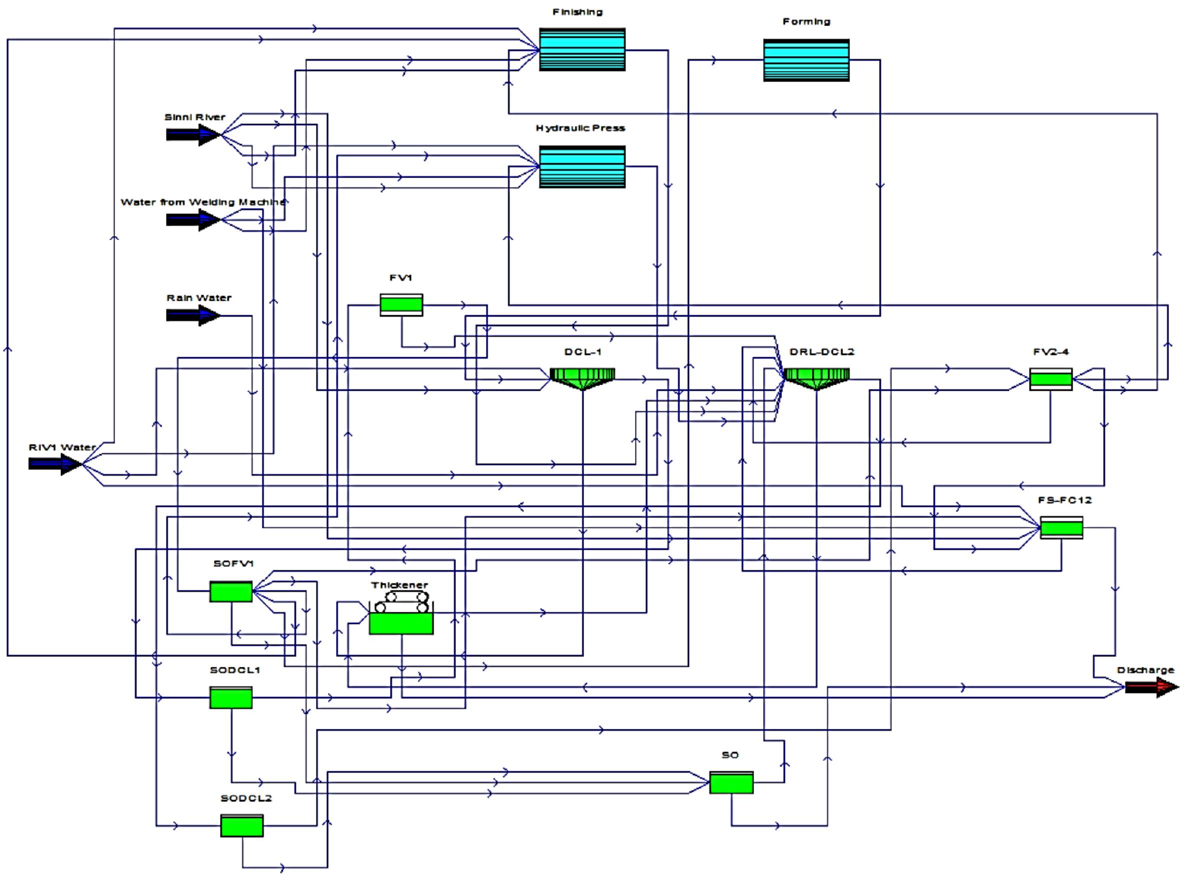
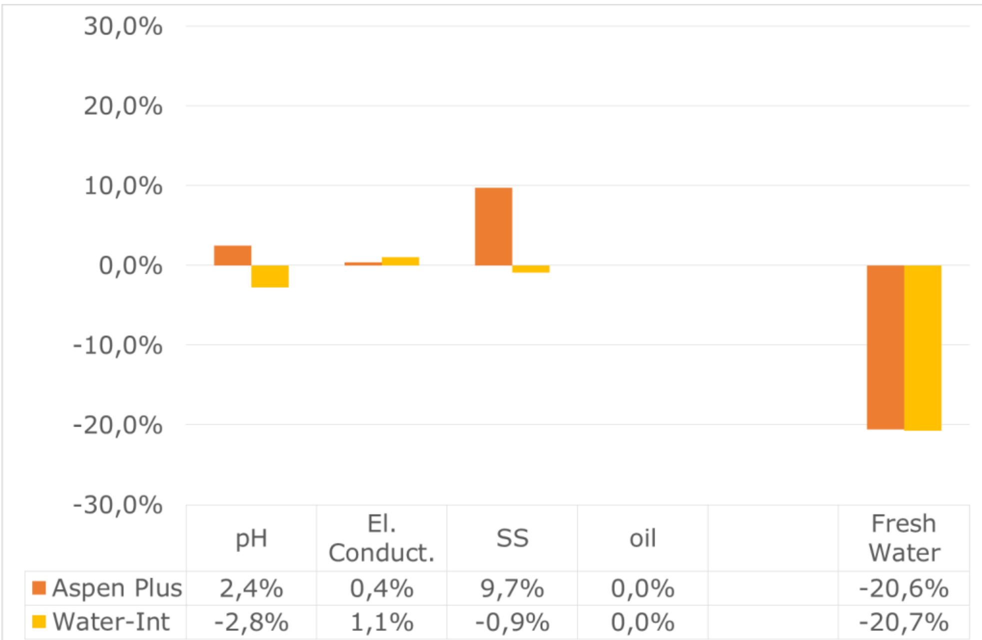


Figure 41: *Water-int™* model to evaluate RIV 1 blowdown reuse in the ILVA TUL1 water network.



	pH	El. Conduct.	SS	oil		Fresh Water
Aspen Plus	2,4%	0,4%	9,7%	0,0%		-20,6%
Water-Int	-2,8%	1,1%	-0,9%	0,0%		-20,7%

Figure 42: Comparison of Aspen Plus® and Water-int™ simulation results related to the discharge parameters after RIV 1 blowdown reuse in TUL1 water network.

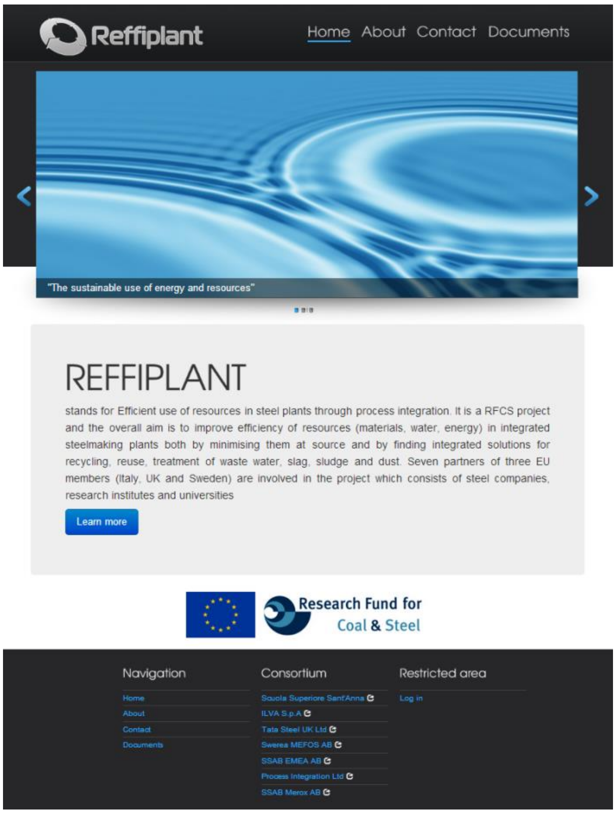
The software reMIND, based the MIND method (Method for analysis of INDustrial energy systems), exploits Mixed Integer Linear Programming (MILP). The MIND method was firstly developed to model industrial energy systems, but an upgrade including the development of ad-hoc superstructures allows its Java-based version to be used as a powerful decision support tool also in the steelmaking field. The analyses carried out by MEFOS and SSSA respectively for SSAB and

ILVA under different conditions and related to different scenarios represented an assessment of the applicability of reMIND also for analyses aimed at improved by-products and waste re-use and recycling.
Indeed the possibility provided by reMIND to develop easily customizable mass and energy superstructure allowed the development of two models related, respectively, to the steelmaking production chain and the main by-products and wastes routes and their exploitation in optimization of resource management. In the particular case of by-products and wastes reuse, the good results obtained by ILVA in the pelletization trials (Task 5.1), following the indication given by optimization study carried out by SSSA through reMIND, attest that the pursued approach, which exploits a reMIND superstructure, can represent a powerful and reliable tool in resources management optimization, suitable also for total site analysis.

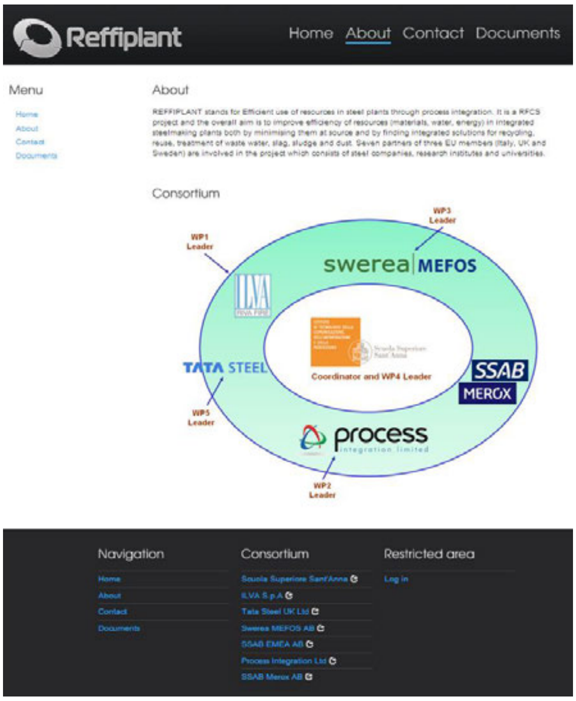
Task 4.5: Technology transfer of the methodological approach and of the total site analysis tools

In the first semester of the project, SSSA developed a website reachable at http://www.reffiplant.com with the aims of collecting documentation and data as well as divulging its goals. The website has been developed in PHP (PHP: Hypertext Preprocessor) by means of the Yii framework (http://www.yiiframework.com).
The website is composed by 4 sections:

- a 'Home page' that contains a summary of the aims of the projects and the links to the partners' websites (see Figure 43.a);
- an 'About' section with a description of the project and the consortium (see Figure 43.b);
- a 'Contact' section containing a contact form
- a restricted "Documents" section that allows partners uploading and exchanging files (documentation, data, presentations, etc.).



a)



b)

Figure 43 The REFFIPLANT website: a) Home page; b) About section

PIL and Tata Steel shared details of its case studies, undertaken within Tata Steel, by means of the Reffiplant reports and papers published. Further one of the publications presented at the REFFIPLANT Workshop (No [14] in the list depicted in Section 5) is specifically aimed at sharing the methodological approach of the BF GW HC overflow recycling related case studies. PIL also produced a document containing generic guidelines for problem types encountered in our case studies. Such guidelines would be useful to engineers from other steel plants who wish to reproduce similar case studies in their respective plants. This guideline document can be found as a separate deliverable and is also available on the REFFIPLANT website.

In addition, PIL also developed a user guide document for WATER-int^{TM} software. This user guide starts with discussion of underlying principles behind water pinch analysis and superstructure based optimisation techniques which forms the basis of the WATER-int^{TM} software development. Then it introduces the WATER-int^{TM} interface & functionalities and how to setup/utilise them correctly for different class of problems. This discussion is further reinforced by demonstration of sample case studies. This user guide document can also be found on the REFFIPLANT website.

SSSA and ILVA shared details of the analysed case studies by means of several publications. In particular, SSSA and ILVA presented a paper at the REFFIPLANT Workshop depicting the approach pursued for the simulation and communicating how simulation techniques can be powerful instruments in the assessment of an efficient use of different kind of resources.

Furthermore SSSA produced a user guide related to a methodological approach that combining simulation and on-site trials supported by collaboration between researchers and plant managers and process engineers. In particular the document describes how the combination of standard analyses techniques (e.g. pinch analyses, analyses of bottlenecks, etc...) and simulation scenario investigations through different simulation software such as Aspen Plus®, Water-Int or reMIND can guide the steelwork staff to identify potential solutions for a better resource management. The document can also be found on the REFFIPLANT website.

2.2.5 WP 5: Implementation and assessment of Process Integration solutions for resource efficiency

Task 5.1: On-site application of the selected novel solutions for resource efficiency

Water efficiency

At ILVA the reduced production and the revamping of some plants allowed on-site tests of only one of the previously simulated water case studies: the reuse of the coke-making area wastewater.
According to the simulation results reported in Appendix I, a pilot plant consisting of UF and RO as main unit operations together with additional chemical and physical treatments was used by ILVA to carry out field tests. In this way the possibility to treat and then reuse wastewater of the coke making area was evaluated.The field tests were carried out with or without the RO stage. The following results was obtained:

- UF is not sufficient to obtain high quality water;
- the overall treatment process (UF followed by RO) allows obtaining high quality water with low contaminants amounts that is suitable for internal reuse;
- the RO produces a high concentrated stream (retentate) that has a low flow rate and that can be purged, as the absolute amount of contaminant does not change.

The assessment of these tests is reported in Appendix N as it is part of Deliverable 5.1.
Tata Steel carried out MF trials at the BF GW area. The aim of these trials was to investigate the recycling of the BF GW HC overflow water with suitable treatment to the following aims:

- Improve the Lagoon 1 water quality (e.g. Suspended solids, Ammonia and Chlorides),
- Lower the cost of running the existing dewatering plant,
- Lower the pumping energy costs,
- Improve cooling tower water quality and associated costs – cooling tower performance, Legionella, maintenance.
- Provide substantial water conservation.

However, HC water recycling increases water concentrations (e.g. Suspended solids, Ammonia and Chlorides) within the BF GW water system.

- Hence, suitable water treatment is needed to reduce the recycled contaminants,

Filtration of suspended solids in the recycled HC overflow is a first step. Additional treatment of the water for reducing Ammonia and Chlorides is also necessary - a 10% side-stream of the cooling tower water may be sufficient.
A commercially available (Automag Skid) magnetic separation unit was assessed for the filtration of suspended solids in the HC overflow (see Figures 44 and 45). The assessment of these on site tests is reported in Appendix N as it is part of Deliverable 5.1.

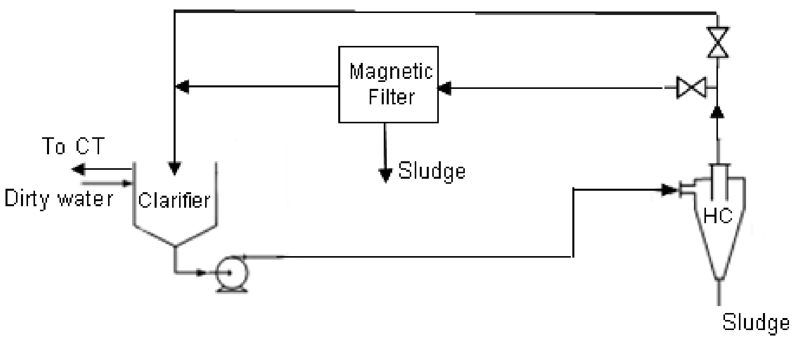


Figure 44: Flow scheme adopted for magnetic filter trials

Figure 45: Pictures captured during magnetic filter trial period

SSAB pursued a trial campaign on the BF gas cleaning system. When historical data were studied in WP 2, correlations were found between an increased recirculation (reduced sludge flow from clarifier) and conductivity, ammonia nitrogen and chlorides. No correlation was found for the concentration of calcium, Zn, iron and suspended solids. In order to investigate the correlations further and to find out the behavior of other substances that might give effects on the process, e.g. the risk of fouling, a trial campaign was designed. During a few days the sludge flow (water leaving the gas treatment system) was reduced, thereby increasing the degree of recirculation. A series of extra samples were taken and analyzed and the results were compared with historical data.
The original plan was to conduct the trials during a period of 5 days (between the 20th of April and the 25th of April 2015). In the morning of the 20th of April, one of the two pipelines that transport sludge to the sludge basin was redirected to transport fresh IV1 water instead of sludge. Consequently, the sludge flow was halved and the degree of recirculation of sludge water to the cooling tower was doubled. Unfortunately, there was an unforeseen maintenance stop at the BF causing the trials to be stopped in advance on the 23rd of April. The trials therefore lasted for 3 days instead of the planned 5 days. Due to a tight time plan for a restauration of the BF there was no possibility to perform additional tests.
The assessment of the on-site tests pursued at SSAB is reported in Appendix N as it is part of Deliverable 5.1.

Resource efficiency related to by-products and wastes
BOF slag is an important by-product of the steelmaking process that is suitable to different uses within the steelmaking process itself. In Italy, BOF slag is usually considered a non dangerous waste. However, in order to reach the "zero waste" European objective, new applications and uses for such material should be found according to the recent new classification as by-product.
ILVA has carried out a deep analysis of BOF slag feature according to the aims of another ongoing RFCS project entitled "Removal of Phosphorus from BOF-slag" (Ref. PSP-BOF). BOF slag appears suitable for internal reuse in the sinter plant or for external use (e.g. as fertilizer for agriculture), if it is separated in two main fractions: an Fe-rich fraction and a second fraction rich in P and Ca but with poor Fe content. A possible recovery treatment process was tested at laboratory scale during the PSP-BOF project and heuristic models of main process units were developed by SSSA (see Appendix H) in order to obtain useful indications to have a good separation of the main BOF slag fractions. The simulations carried out by SSSA and showed in WP4 demonstrated that Fe-rich BOF slag fraction obtained through an ad-hoc developed recovery treatment can be a part of a by-products mixture to produce pellets for sinter plant. To this aim, ILVA carried out an intensive experimentation in order to produce Fe-rich pellets maximizing the BOF slag fraction. A pilot plant has been used during the experimental studies that consists of an Eirich mixer and a pelletizer disc as main process units. In the last two years, based on previous experience, ILVA laboratory tried to create the best recipe for pellets production with an extensive test campaign. ILVA laboratory, after some preliminary tests, followed the indications obtained by SSSA through reMIND simulations. Good pellets, in terms of amount (yield of about 90%) and quality, were obtained with a mixture of BOF sludge and of BOF slag fraction with grain size <2mm and a moisture of about 14% wt. Such pellets were obtained after a preatreatment consisting of grinding and sieving steps followed by a humidification and a homogenation steps. The fate of contaminants such as Zn and Pb, Cr and V that could derive from the used by-products is neglected due to their low content respectively in the BOF sludge and in the BOF slag. More details related to the tests carried out by ILVA are reported in Appendix N as it is part of Deliverable 5.1.

SSAB carried out trials on the integrated material recycling at SSAB Luleå. Recycling of three materials, BF dust, BOF dust and LS were considered in the preliminary case studies. BF dust has for several years been recycled via briquettes but in the case study, injection of BF dust was investigated. Almost half amount of the produced BF dust is now injected into the BF and the rest is recycled through briquettes.
A first set of on-site trials were devoted to recycling of BOF sludge in the BF via briquettes. The ordinary briquettes contain 45% of deS scrap 0-5 mm but current storage of this material will soon be consumed and only newly produced deS scrap will then be available for the briquetting mix. This will cause a decreased briquette production if no replacement can be found.
The on-site application regarding fine grained BOF sludge involves preparation such as drying, piling and mixing before mixed together with other recycling material in the briquettes. The BOF sludge contains around 36 % moisture. During the summertime mainly fresh BOF sludge was dried in prepared areas, such as the one depicted in Figure 46.

Figure 46: Drying of BOF sludge at SSAB Luleå

Moreover SSAB also carried out on-site tests on the addition of Ladle Slag (LS) as slag former in the BF. The on-site tests were carried out along three periods. The environmental relevance of these material is huge considering that the yearly production of LS is 20 000 t and this material is currently landfilled. During the trials, the possibility was investigated to use LS to replace limestone and BOF slag, which are ordinarily used as slag formers in the BF. An amount of 10 to 25 kg/t_{HM} was charged to the BF, totally 6800 tons. The major difference between LS and the two other slag formers is the alumina (Al_2O_3) content. LS contains 20 - >30% Al_2O_3 while BOF slag and limestone contain an amount of alumina which is lower than 2%.
The assessment of all the on-site tests pursued at SSAB is reported in Appendix N as it is part of Deliverable 5.1.

Task 5.2: Assessment of improvements made by implemented solutions

Solutions related to water systems

At ILVA the joint application of UF and RO was assessed in order to maximize the reuse of wastewater in the cokemaking area by producing a stream of high quality water for different internal uses (ILVA holds an internal subnetwork providing high quality water to all the utilities that need it). This stream could partly replace some high quality freshwater. The tests showed that RO is needed, as UF is not sufficient to remove some salts and N species. The joint application of UF and RO allowed an almost complete removal of the contaminants in the original stream,and could be thus effective in order to:

- Reduce the total consumption of fresh water;
- Reduce the total production of waste water;
- Increase the proportion of recoverable waste water for reuse/recycling;

On the other hand, this solution is expensive in terms of CAPEX, which is estimated around 1.2 M€ for a plant treating about 100 m^3/h of wastewater with a permeate yield around 67%, i.e. capable of producing up to 67 m^3/h of high quality water. Also the operating costs, mainly related to energy, maintenance and chemicals, are not negligible. Therefore the economic viability highly depends on the boundary conditions, i.e. the availability and cost of freshwater (which also represents the value of the recovered high quality water) as well as on the cost of chemicals and energy required for running the treatment process. The disposal of the retentate does not represent a cost, as the amount of contaminants allows in any case its discharge. As the operative life of a similar plant whithout substantial revamping is currently around 20 years, the economic

viability has been evaluated in terms of parametric evaluation PBP, as depicted in detail in Appendix O Section 23.1, which also represents part of Deliverable 5.2.
At Tata Steel, a wide range of recycle-reuse opportunities were investigated to the aim to improve the overall efficiency of the water systems. The following benefits can be achieved through the proposed solutions from the analysed case studies:

- Reduce the total consumption of fresh water;
- Reduce the total production of waste water;
- Increase the proportion of recoverable waste water for reuse/recycling by considering the main contaminants;
- Reduce the corresponding energy utilisation leading to lower CO_2 emissions.

All the new solutions developed for the Tata Steel UK site, discussed above, were of direct relevance and great interest to the site management. However, due to the current (2015) extremely difficult economic conditions within Tata Steel UK, and the separation of the site in which the research was undertaken as a semi-independent business, it was not possible to obtain the required capital investment to fully implement the solutions. Hence, the improvements made by full implementations could not be assessed. However, estimated improvements based on simulation results are described in Appendix O Section 23.1, which also represents part of Deliverable 5.2. Table 30 summarises the capital investment and PBP estimated for the implementation of solutions from our case studies.

Sr #	Case Study	CAPEX (£)	**ΔOpex* (£/yr)**	PBP (yr)
5	Lagoon 1 Water Reuse in BF GW	1,005,000	-652,000	1.5
6	Pond A water reuse in BF GW	21,000	63,000	-
7	Hydrocyclone overflow recycling	1,550,000	-1,033,000	1.5
8	HPM-Ancholme water recovery & Control	20,000	-49,864	0.4

Table 30: PBP for Tata Steel case studies

*ΔOpex indicates net increase in operating cost which is equal to increase in operating cost − savings achieved. Thus negative ΔOpex values implies that savings are more than increase in operating costs.

SSAB Pilot trials BF sludge water

The trial campaign on the recirculation of the water coming from the BF gas treatment system was developed in order to obtain more data and an improved model of the BF gas treatment system.
The results show that resource efficiency will not be improved by increased recirculation of the BF sludge water with the current BF gas cleaning process design at SSAB. Increased recirculation by recycling of the decanted water from the sludge basin will cause a build up of compounds causing corrosion (ammonium, chlorides) and fouling in pipes, pumps etc (calcium), even when accompanied by a RO treatment on the recycled water. Increased recirculation of decanted water from the sludge basin combined with RO treatment of water from the clarifier is possible from a chemical build-up perspective. However, it would create a large retentate, which has no application and would require some kind of further treatment.
Increased recirculation might be possible either if another more suitable water treatment method instead of RO is applied or if the process design of the gas treatment system is modified.

Solutions related to material reuse and recycling

The use of almost every Fe-rich by-products is possible in the sinter plant, provided that they are not contaminated by oil, chloride or phosphorus and the minimization of the costs of residues management and the improvement of the environmental impact could be reached.
At ILVA the opportunities to maximize the reuse of by-products, especially BOF slag, were investigated. In accordance with BREF documents and Italian laws, by-products (e.g. BOF sludge, mill scale) are used in the agglomeration process to produce the agglomerate for the BF, but currently in this mixture, BOF slag is not used. As BOF slag is a source of iron, the pellet production using the Fe-rich part of BOF slag was evaluated together with the possibility to obtain a fraction with poor Fe content that is suitable for external reuse.
Currently BOF slag coming from 2 steel shops of ILVA are subjected to iron removal by magnetic separation. The inert amount of BOF slag is used for environmental recovery in internal quarry, after leaching tests to evaluate the compliance of the key parameters with Italian regulation limits. This is a no-cost procedure for ILVA that does not imply an environmental improvement (even if it is in accordance with Italian and European Directive 2008/98). It is important to find an alternative usage of BOF slag to limit the need for environmental recovery in internal quarry. In accordance to both literature and experimental results, the following benefits could be achieved through the proposed solution of pellet production:

- Reduced internal recovery with improvement of environmental sustainability;

- Cost savings related to BOF slag internal handling (e.g. trucks transporting about 100 tons per trip - with special giant trucks named dumpers - of BOF slag between the plant and the magnetic separator have to travel significant distances as 3 km on road with high gradient);
- Environmental improvement avoiding the management of fine grain size by-products at the storage near sinter plant.

At SSAB, some opportunities to reuse some by-products in the BF were investigated to the aim of improving the overall resource efficiency. The following overall benefits can be achieved through the proposed solutions from the analysed case studies:

- Reduced need for landfills, implying both an environmental benefit and relevant cost savings
- Savings of primary raw materials (e.g. iron ore pellets and virgin limestones)

Indeed there are many parameters affecting the outcomes of in-plant recirculation and it is usually difficult to see the definite effects of trials in the BF. The maximum overall savings achievable with the implemented PI-based solutions (in the hypothesis of a yearly production of 2Mton of HM) can be calculated on the basis of both experimental trials and the outcomes of the simulation developed within WP4 Task 3.4 (see Section 5.3.3.) and are summarized in Table 31.
A more detailed discussion on the estimated improvements for both ILVA and SSAB is provided in Appendix O Section 23.2, which also represents part of Deliverable 5.2.

Case Study	Potential savings on landfills (Kton/y)	Saving in Raw material (Kton/y)		
		Iron ore	limestone	Coke
Injecting the BF flue dust into the BF (increased iron content in briquettes)	20	18	6	2.7
Recycling of BOF sludge in the BF via briquettes	25	12	7	1
Use of LS as slag former in the BF	20	5	7	-

Table 31: Estimated savings in the SSAB case studies at an estimated yearly production of HM=2Mton

Task 5.3: Evaluation of technological and economical constraints and barriers for a more resource efficient steelmaking practice

Solutions impacting on water systems

For ILVA, the case study related to the application of UF and RO order to maximize the reuse of wastewater in the cokemaking area was assessed in close cooperation with the site management. The technological and economical constraints were considered and issues in achieving the different objectives were assessed. No environmental issues are foreseen, as UF and RO are widely recognized as environmental friendly technologies for water treatment. The quality of the recovered permeate is high and suitable for most applications, while the quality of the concentrate is suitable to discharge. Due to the high investiment and operating costs, the main barriers are thus of economic nature.
For Tata Steel, the 4 case studies were developed with close cooperation with the site management of infrastructure, water supply, environment, BF and HPM plant management. The steps for the implementations were discussed in detail. The technological and economical constraints of the recommended implementation of each of the case studies were considered and issues in achieving the different objectives were assessed. The most important constraints for the Tata Steel UK site are:

- Capital expenditure;
- Operating costs;
- Environmental issues;
- Water quality impacting process operation;
- Water quality impacting on health and safety.

The on-site trials pursued at SSAB on the recirculation of the water coming from the BF gas cleaning system gave the following main results:

- Ca, Cl and ammonia (NH_4) concentrations increase with increasing sludge flow
- No correlation between increased recirculation and concentration of zinc, TOC, pH, fenols
- No change in chemical composition of BF sludge

A detailed description of the technological and economical constraints and barriers for each case study and solution impacting on water systems is reported in Appendix P Section 24.1, which also represents part of Deliverable 5.3.

Solutions impacting on material recycling

ILVA evaluated the pellets production with BOF slag for different important objectives:

- The reduction of the amount of the BOF slag recovered in the internal quarry;
- The improvement of by-products management to reduce waste production, environmental impact and costs;
- The achievement of "zero waste" European goal.

To promote and improve these objectives, most of the constraints could be related to the Italian regulation on wastes/by-products management and on the interpretation of European Directives. ILVA received an Integrated Environmental Authorization (AIA) on August 2011, in which many limitations and authorizations are included: in order to manage by-products considering new applications and potential uses in the steelwork, a specific and very time consuming authorization procedure must be undergone by the Italian Environmental Ministry. This is however a specific non technical barrier which applies to ILVA but can be less impacting in other European regions (e.g. shorter authorization time). More details on further economical barriers are reported in Appendix P Section 24.1, which also represents part of Deliverable 5.3.

As far as the solutions implemented at SSAB to improve recycling of materials, it must be underlyined that recycling material in the steel industry is common practice and depending on the plant layout, legal restrictions and physical conditions the level of efficient material use can vary between integrated sites.

The integrated steel plants of SSAB in Sweden and Finland all have briquetting plants as a mean to recycle fine material. The common practice in Europe is to use a sinter plant, which in many aspects changes the conditions of material use in the BF and related units. However, the transferability of the results from this investigation covers the common issue of harmful elements in BOF sludge and LS and the savings that can be reached due to increased material efficiency and total energy consumption. For each plant a specific investigation needs to be made with boundaries and restrictions that apply for that plant in that specific region.

The results will be conflicting when trying to minimize deposits with respect to energy consumption and quality parameters in the product. The energy change is mainly related to coke usage in the BF. However, the results show that the energy change is small even when recycling is improved. The test trials show no particular effects on energy consumption and product quality.

A detailed description of the technological and economical constraints and barriers for each investigated solution for improving material re-use and recycling is reported in Appendix P Section 24.2, which also represents part of Deliverable 5.3.

Task 5.4: Dissemination

All the partners were committed to communicate the results achieved by project to the industrial and scientific community through divulgation material (also available on the project Web site), and scientific papers in international journals and conferences. The list of published paper is presented in Section 5.5.1.

In order to give a wider echo and visibility to the REFFIPLANT Workshop, it was organized during the Word Congress on Sustainable Technologies (WCST-2015), a highly qualified conference sponsored, among others, by the IEEE Society which was held in London on 14-16 December 2015. The proceedings, which also represent Deliverable 5.4, are available on IEEEXplore (http://ieeexplore.ieee.org/Xplore/home.jsp).

2.3 Conclusions

Resource efficiency is an objective of very relevant importance in the steel sector. Process Integration (PI) provides ways and means to achieve this target.

Within the present project, a methodological approach was developed through a joint effort of all the partners in order to elaborate and preliminarily assess PI-based solutions and technological improvements to increase resource efficiency based on data analysis and holistic simulation tools. Such approach was applied in the project for a number of case studies, but it is fully transferable to other case studies and to other companies.

The approach in not fundend on a single simulation tool, but proves its efficiency with different general-purpose and specific simulation tools. One of these tools was developed inside the project and is dedicated to holistic simulation and multi-objective optimization of water networks. This proves the general validity and applicability of the proposed approach in a variety of industrial contexts.

In the search for optimal solutions to improve resource efficiency, a trade-off between multiple conflicting objectives must be found. In effect, the application of Multi-objective optimization proves to be valid in the analysed case studies and different solutions can be found dependent on the constraints.

Simulation cannot replace the development of on-site trials, which were also part of the work developed in the project, but are a powerful support to plan useful trials, as the viability of the pre-selected solutions can be assessed in advance at low cost, so that the trials are focused only toward the most promising solutions. In effect the results of the on-site trials developed within the project confirmed in most cases the outcomes of the preliminary simulations, by showing, on one hand, the efficiency of the adopted simulation frameworks and, on the other hand, the validity of the pursued approach.

The overall project results show that it is possible to improve resource efficiency in the steeworks through Process Integration by increasing the reuse of water and the recycle of by-products and waste by also saving energy or maintaining the energy consumption. This is good knowledge for companies handling materials that needs to separated and used either for internal recirculation, external sales or landfill. Major cost savings can be found if internal recirculation can replace raw material such as iron ore, coke and limestone. These benefits are coupled to environmental impact reduction through e.g. virgin material and freshwater savings, smarter material handling and reduction of disposal. On the other hand, investment costs are not always negligible and this can be a barrier.

2.4 Exploitation and impact of the research results

Most of the solutions that were analysed both in the case studies and through the on site trials show a good potential for exploitation in order to improve resource efficiency in integrated steelworks. The full scale implementation was beyond the scope of the project, but the pursued analyses can be exploited in the future.

The developed methodology to approach, investigate and analyse PI-based solutions to improve resource efficiency was duly codified and formalised, therefore it will be applied in the future also to analyse other case studies by the project partners. Moreover, suitable documentation has been developed in order to disseminate the methodology and to transfer it to other steelworks in Europe.

A library of models for treatment units was developed and shared by the partners, which can be exploited in future studies as its use is simple and its results can be exploited within a number of simulators. Moreover a new simulation software for water networks Water-Int^{TM} was developed starting from the original Water software and capable to embed the above-mentioned model library. Such software can be used by all the partners to support internal studies and consultancy services (in the case of partners which are not steel companies).

The results of the project have been disseminated through:

- a web site (see Section 5.3.4)
- several publications (see Section 5.5.1)
- a dedicated REFFIPLANT workshop within a major international conference, the World Congress on Sustainable Technologies WCST-2015 (see Appendix M).
- some public documents which are available on the REFFIPLANT web site (see Appendix M).

2.4.1 Publications / conference presentations resulting from the project

[1] I. Matino, E. Alcamisi, G. F. Porzio, V. Colla. "Evaluation and monitoring of physico-chemical properties of water streams through unconventional techniques". UKSim-AMSS 8th European Modelling Symposium, Pisa, Italy, October20-22 2014, pp. 281-285.

[2] E. Alcamisi, I. Matino, M. Vannocci, V. Colla. "Simplified ionic representation of industrial water streams". UKSim-AMSS 8th European Modelling Symposium, Pisa, Italy, October20-22 2014, pp. 286-290.
[3] I. Matino, E. Alcamisi, G. F. Porzio, V. Colla, L. Romaniello. "Modeling of oily millscale and sludge treatment process for improved by-product recovery and waste minimisation in steel industry". 1st International Process Integration Forum for the Steel Industry 2014, Luleå, Sweden, June 2014.
[4] E. Alcamisi, I. Matino, G. F. Porzio, V. Colla. "Wastewater treatment in iron and steel industry: Process Integration for water re-use". 1st International Process Integration Forum for the Steel Industry 2014, Luleå, Sweden, June 2014.
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[11] E. Alcamisi, I. Matino, V. Colla, A. Maddaloni, L. Romaniello, F. Rosito,"Process Integration Solutions for Water Networks in Integrated Steel Making Plants," Chemical Engineering Transactions Vol. 45 (2015), pp. 37-42.
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[13] J. Riesback, K. Lundkvist, M. Bramming, A. Wedholm, "Applied Investigation on Waste Minimization in an Integrated Steel Site," Proc. of the World Congress on Sustainable Technologies (WCST-2015), December 14-16, 2015, London, UK, pp. 21-26.
[14] M. Saiepour, K. Jain, Y. Lou, "Integrated Optimisation of Blast Furnace Gas Wash Water Treatment, Reuse and Cost Savings Part I: Methodological Approach," Proc. of the World Congress on Sustainable Technologies (WCST-2015), December 14-16, 2015, London, UK, pp. 27-33.
[15] M. Saiepour, K. Jain, Y. Lou, "Integrated Optimisation of Blast Furnace Gas Wash Water Treatment, Reuse and Cost Savings Part II: Analysis of Field Trials," Proc. of the World Congress on Sustainable Technologies (WCST-2015), December 14-16, 2015, London, UK, pp. 41-47.
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[17] J. Riesbeck, A. Wedholm, K. Lundkvist, M. Brämming, "Systematic Study on Recycling of Waste Materials in an Integrated Steel Site", AISTech & ICSTI Proceedings, Cleveland, Ohio, USA, 4-7 May, 2015.

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5 LIST OF ACRONYMS AND ABBREVIATIONS

Abbreviation	Name
BBM	Bloom and Billet Mill
BETP	Biological Effluent Treatment Plant
BF	Blast Furnace
BF GW	Blast Furnace Gas Wash
BF OCC	Blast Furnace Open Circuit Cooling
BOC	A company external to Tata Steel
BOF	Basic Oxygen Furnace
BOS	Basic Oxygen Steelmaking
CC	Continuous Casting
COB	Coke Oven Batteries
CP	Coke Plant
CP1	Coke Plant #1
CP2	Coke Plant #2
CPS	Central Power Station
DW	De-Watering
HPMCP	CPS Recycle Header
CS	Crude Steel
CT	Cooling Tower
DEMIN	Demineralisation Plant
DES	De-Sulphurisation
HDG	Hot Dip Galvanizing
HC	HydroCyclone
HEX	Heat Exchanger
HM	Hot Metal
HPM	Heavy Plate Mill
HRM	Hot Rolling Mill
LS	Ladle Slag
MF	Magnetic Filter
MOO	Multi-Objective Optimization
MSM	Medium Section Mill
PBP	PayBack Period
PI	Process Integration
PP	Power Plant
RM	Roller Mill
RO	Reverse Osmosis
RSC	Rail Service Centre
SM	Secondary Metallurgy
SOO	Single-Objective Optimization
SS	Steel Shop
SW	Structural Workshop
TBH	Turbo Blower House
TOC	Total Organic Carbon
TSS	Total Suspended Solids
UF	UltraFiltration
VS	Volatile Solids

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7 APPENDIX A - Benchmarking documents - D1.4

7.1 Benchmarking on water, by-products and waste

Benchmarking on water and Best Available Techniques

This document summarises the results of a study with the aim of determining the best available techniques and potential benchmark values of water usage in EU steel plants. It is important to note that water issues and how they are managed at specific plants vary greatly, due to local aspects, such as water availability, water quality, plant configuration and legislation. A technique that works well for one plant might not be the best option for another plant. Conditions vary considerably. Therefore, the best water usage data and best techniques cannot be generalised. This study was undertaken with the focus on relevant applications within the project. Three areas have been researched: potential benchmark values for water usage, overall site water management and techniques for water treatments, and cooling water systems.

Determination of potential Benchmark values for water usage [1]

A part of this study is based on the water management survey carried out by the World Steel Association, which was completed in 2010. It is generally accepted that the benchmark value for water usage by steelmaking sites is $5m^3$ per tonne of steel produced. However, the study carried out by the World Steel Association [1] has shown that it is more useful to state the water usage values for individual process plants, i.e. in terms of m_3 per tonne of specific product produced.
The lowest and highest values for the water intake, inflow and discharge for the different process plants in the EU plants that participated in the World Steel Association survey were identified and are shown in Table A1. These EU steel plants are identified by numbers, and their names have not been mentioned in the survey report. The plant numbers are included in Table A1 as they are useful for obtaining further details if needed. The total inflow value is regarded as the most useful parameter for comparison and benchmarking, as it represents the total water consumption by a particular plant. Total inflow is the sum of intake and reuse from other processes - not including the recycled water within the plant. For selecting the lowest inflow, the zero and very low values have been ignored as these values did not appear to be realistic. Also, exceptionally high values were regarded as statistical outliers and are shown in brackets.

Process		Steel Plant Number	Production ton product / year	Water Flow m3/ton Intake	Inflow	Discharge
Cokemaking	Min	21	2,251,225	0.70	0.70	0.27
	Max	2	4,231,325	2.35	2.54 (37)	0.35
Sintering	Min	28	5,411,405	0.02	0.02	0.00
	Max	10	2,704,675	0.70	0.7 (1.8)	0.70
Pelletising	Min	3	4,580,581	0.45	0.46	0.33
	Max	2	138,191	1.11	1.11	0.95
Blast Furnace	Min	9	1,980,000	0.17	0.17	0.13
	Max	26	4,843,509	4.19	7.08 (28)	4.17
Basic Oxygen	Min	28	3,904,529	0.14	0.14	0.00
	Max	20	2,921,000	1.26	1.26 (4.8)	0.04
Casting	Min	27	3,148,736	0.14	0.14	0.00
	Max	12	1,193,734	1.42	1.42 (32)	0.81
Hot Rolling	Min	29	3,144,987	0.21	0.31	0.11
	Max	1	3,470,000	5.35	5.35 (39)	5.05
Cold Rolling	Min	1	130,000	0.12	0.12	0.12
	Max	19	3,027,802	4.71	6.68 (35)	0.01
Finishing	Min	3	949,154	0.23	0.33	0.24
	Max	11	674,968	2.18	2.18 (19.7)	1.09
Briquetting	Min	23	1,004,719	0.12	0.12	0.00
	Max	29	3,782,117	1.06	1.21	0.35
Rest (overall)	Min	28	4,300,000	0.86	0.86	0.00
	Max	20	2,800,000	142.35	142.35	141.78

Table A1: Steel plants with lowest and highest water intake, inflow and discharge per tonne of product for different processes

The average water usage values for each process plant may represent more realistic potential benchmark values. Therefore, average values of water intake, inflow and discharge for the different process plants have also been calculated (Table A2). The exceptionally high values were regarded as statistical outliers, and were removed to provide more representative average values. Each average value is calculated independently, so the average values for intake, inflow and discharge are not necessarily for the same EU plant.

Process	Intake (m3/t)	Inflow (m3/t)	Discharge (m3/t)
Cokemaking	1.42	1.59	0.47
Sintering	0.24	0.27	0.15
Pelletising	0.78	0.79	0.64
Blast Furnace	5.27	5.70	4.81
Basic Oxygen	0.52	0.62	0.18
Casting	0.43	0.50	0.15
Hot Rolling	4.58	5.01	3.96
Cold Rolling	2.28	2.46	1.29
Finishing	0.56	0.60	0.24
Briquetting	0.59	0.66	0.17
Rest (overall)	23.85	24.31	22.75

Table A2: Average water intake, inflow and discharge per tonne of product for different processes

Overall site water management

BAT for Iron & Steel Production [3]

The water management in an integrated steelworks primarily depends on local conditions, above all on the availability and quality of fresh water and on legal requirements.
A driving factor for steadily improving the intake and outlet of water are the costs. The costs for waste water treatment and releasing costs based on legal tax on discharging water into the municipal system can be considerable. Another cost-related factor is that the water taken from the aforementioned bodies depending on the water quality for many applications should undergo a conditioning step before it can be used. Furthermore, the pumping of such heavy water flows requires much electric energy. For these reasons, water consumption has been constantly reduced since 1980.
In particular, at sites with very low fresh water availability, where the water demand should be covered by groundwater or spring water, there may be a need to reduce water consumption intensely. In such cases, the specific water consumption can be lower than 5 m3/t of steel and the interdependencies can be much more intensive.

BAT Conclusions [3]
Water and waste water management
BAT for waste water management is to prevent, collect and separate waste water types, maximising internal recycling and using an adequate treatment for each final flow. This includes techniques utilising, e.g. oil interceptors, filtration or sedimentation. In this context, the following techniques can be used where the prerequisites mentioned are present:

- avoiding the use of potable water for production lines;
- increasing the number and/or capacity of water circulating systems when building new plants or modernising/revamping existing plant;
- centralising the distribution of incoming fresh water;
- using the water in cascades until single parameters reach their legal or technical Limits;
- using the water in other plants if only single parameters of the water are affected and further usage is possible;
- keeping treated and untreated waste water separated; by this measure it is possible to dispose of waste water in different ways at a reasonable cost;
- using rainwater whenever possible.

Applicability

The water management in an integrated steelworks will primarily be constrained by the availability and quality of fresh water and local legal requirements. In existing plants the existing configuration of the water circuits may limit applicability.

Waste Water Treatments

In order to carry out the benchmarking on waste water treatments, the starting point of this study is based on the results achieved by the worldsteel water management survey [1].

Large amounts of water are used in all steelmaking processes, in particular in the integrated route. In order to improve the environmental performances and to meet legal compliance, the water and effluent system management have evolved. This leads to efficient final effluent treatments. In some cases these are represented by basic chemical sedimentation/clarification combined with flocculant treatment, that, on the other hand, lead to the increase of sludge by-product formation, which needs to be further handled and treated.

Furthermore, over the past few years, the use of membrane processes for effluent treatment has increased, such as ultrafiltration (UF), reverse osmosis (RO), electrodialysis (ED) and electrodialysis reversal (EDR), although they cannot be used to treat all kinds of effluent water; for example they have to be free of colloidal particulates, such as silt, iron and manganese oxides.

Techniques applied for treatment processes [1], [2]

Different techniques can be applied, both for pre-treatment and post-treatment processes. The first is used in order to achieve water quality suitable for use in some processes. The second is used to achieve water quality for discharge or reuse.

Techniques used for pre-treatment

A description of the following pre-treatment techniques is presented in [1] and [2].

i) Biological control or disinfection of non-potable water
ii) Demineralisation
iii) Desalination
iv) Distillation
v) Filtration
vi) Reverse osmosis
vii) Softening

Techniques used for post-treatment

A description of the following post-treatment techniques is presented in [1] and [2].

i) Activated carbon adsorption
ii) Aeration
iii) Biological treatment
iv) Biological Nitrogen Elimination
v) Chemical reduction
vi) Chemical hydrolysis
vii) Clarifier and classifier
viii) Demineralization
ix) Desalination
x) Dissolved air flotation
xi) Distillation
xii) Equalisation
xiii) Evaporation
xiv) Filtration
xv) Flocculation and coagulation
xvi) Incineration
xvii) Ion exchange
xviii) Lagoon
xix) Membrane filtration
xx) Neutralization and pH adjustment
xxi) Oil/water separation
xxii) Reverse osmosis
xxiii) Sedimentation or clarification
xxiv) Sludge dewatering
xxv) Softening
xxvi) Stripping

General techniques to consider in the determination of BAT [3]

SINTER PLANT [3]

Waste water

During the sintering process the types of waste water produced are rinsing water, cooling water and waste water from waste gas treatment. These are described in BREF (Best Available Techniques Reference) document for iron and steel production.

General BAT Conclusions [3]

Water and waste water

BAT is to minimise water consumption in sinter plants by recycling cooling water as much as possible unless once-through cooling systems are used.
BAT is to treat the effluent water from sinter plants where rinsing water is used or where a wet waste gas treatment system is applied, with the exception of cooling water prior to discharge by using a combination of the following techniques:
I. heavy metal precipitation
II. neutralisation
III. sand filtration.

The BAT-associated emission levels, based on a qualified random sample or a 24-hour composite sample, are:

- suspended solids <30 mg/l
- chemical oxygen demand (COD(1)) <100 mg/l
- heavy metals <0.1 mg/l
  (sum of arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn)).

(1) In some cases, TOC is measured instead of COD (in order to avoid HgCl2 used in the analysis for COD). The correlation between COD and TOC should be elaborated for each sinter plant case by case. The COD/TOC ratio may vary approximately between two and four.

COKE OVEN PLANT [3]

A description of the use of water, waste water produced and treatment is presented in BREF document for iron and steel production.

General BAT Conclusions [3]

Water and waste water

- BAT is to minimise and reuse quenching water as much as possible.
- BAT is to avoid the reuse of process water with a significant organic load (like raw coke oven waste water, waste water with a high content of hydrocarbons, etc.) as quenching water.

BAT is to pretreat waste water from the coking process and coke oven gas (COG) cleaning prior to discharge to a waste water treatment plant by using one or a combination of the following techniques:

- using efficient tar and polycyclic aromatic hydrocarbons (PAH) removal by using flocculation and subsequent flotation, sedimentation and filtration individually or in combination
- using efficient ammonia stripping by using alkaline and steam.

BAT for pretreated waste water from the coking process and coke oven gas (COG) cleaning is to use biological waste water treatment with integrated denitrification/nitrification stages.
The BAT-associated emission levels, based on a qualified random sample or a 24-hour composite sample and referring only to single coke oven water treatment plants, are:

- chemical oxygen demand (COD(1)) <220 mg/l
- biological oxygen demand for 5 days (BOD5) <20 mg/l
- sulphides, easily released (2) <0.1 mg/l
- thiocyanate (SCN-) <4 mg/l
- cyanide (CN-), easily released (3) <0.1 mg/l
- polycyclic aromatic hydrocarbons (PAH) <0.05 mg/l
  (sum of Fluoranthene, Benzo[b]fluoranthene,
  Benzo[k]fluoranthene, Benzo[a]pyrene,

indeno[1,2,3-cd]pyrene and Benzo[g,h,i]perylene)

- phenols <0.5 mg/l
- sum of ammonia-nitrogen (NH4+ -N), nitrate-nitrogen (NO3- -N) and nitrite-nitrogen (NO2- -N) <15 – 50 mg/l.

Regarding the sum of ammonia-nitrogen (NH4+ -N), nitrate-nitrogen (NO3- -N) and nitrite nitrogen(NO2- -N), values of <35 mg/l are usually associated with the application of advanced biological waste water treatment plants with predenitrification/nitrification and post-denitrification.

(1) In some cases, TOC is measured instead of COD (in order to avoid HgCl2 used in the analysis for COD). The correlation between COD and TOC should be elaborated for each coke oven plant case by case. The COD/TOC ratio may vary approximately between two and four.
(2) This level is based on the use of the DIN 38405 D 27 or any other national or international standard that ensures the provision of data of an equivalent scientific quality.
(3) This level is based on the use of the DIN 38405 D 13-2 or any other national or international standard that ensures the provision of data of an equivalent scientific quality.

BLAST FURNACE [3]

Waste water from BF gas treatment

Water resulting from BF gas scrubbing is normally treated, cooled and recycled to the scrubber and treatment occurs in circular settling tanks. A description including the treatment and reuse of the scrubbing water is present in BREF document for iron and steel production.

General BAT Conclusions [3]

Water and waste water

BAT for water consumption and discharge from blast furnace gas treatment is to minimise and to reuse scrubbing water as much as possible, e.g. for slag granulation, if necessary after treatment with a gravel-bed filter.
BAT for treating waste water from blast furnace gas treatment is to use flocculation (coagulation) and sedimentation and the reduction of easily released cyanide, if necessary.
The BAT-associated emission levels, based on a qualified random sample or a 24-hour composite sample, are:

- suspended solids <30 mg/l
- iron <5 mg/l
- lead <0.5 mg/l
- Zn <2 mg/l
- cyanide (CN-), easily released (1) <0.4 mg/l.

(1) This level is based on the use of the DIN 38405 D 13-2 or any other national or international standard that ensures the provision of data of an equivalent scientific quality.

BOF AND CONTINUOUS CASTING [3]

Waste water

In BOF and Continuous casting water is used for the following purposes:

- scrubbing water from BOF gas treatment;
- scrubbing water from the wet dedusting of desulphurisation;
- water from vacuum generation;
- water from direct cooling from continuous or ingot casting.

A description of the above including treatments are present in BREF document for iron and steel production.

General BAT Conclusions [3]

Water and waste water

BAT is to prevent or reduce water use and waste water emissions from primary dedusting of basic oxygen furnace (BOF) gas by using one of the following techniques:

- dry dedusting of basic oxygen furnace (BOF) gas;
- minimising scrubbing water and reusing it as much as possible (e.g. for slag granulation) in case wet dedusting is applied.

BAT is to minimise the waste water discharge from continuous casting by using the following techniques in combination:
I. the removal of solids by flocculation, sedimentation and/or filtration;
II. the removal of oil in skimming tanks or any other effective device;

III. the recirculation of cooling water and water from vacuum generation as much as possible.
The BAT-associated emission levels, based on a qualified random sample or a 24-hour composite sample, for waste water from continuous casting machines are:

- suspended solids <20 mg/l
- iron <5 mg/l
- Zn <2 mg/l
- nickel <0.5 mg/l
- total chromium <0.5 mg/l
- total hydrocarbons <5 mg/l.

HOT ROLLING MILLS [4]
Water Circuits / Water Management in Hot Rolling Mills

In the whole hot rolling process and linked process steps water is used for cooling and for technological reasons. Electric motors, re-heating furnaces, control rooms and power systems, instruments and process control are usually cooled indirectly. On the other hand steel, rolls, saws, cropped ends, coilers and hot run out tables are cooled directly. Water is also used for scale breaking, flushing scale and for scale transport. The contact with the rolled material (process water) and rolling equipment leads to the water contamination with scale and oil.
The quality of water input depends mainly on the design of the water treatment plant and water treatment measures applied as well as on the specific water consumption. Waste water from scale removal and flume flushing contains, apart form coarse scale, suspended solids and emulsified oil. Large amounts of water are used for roll and material cooling, which also contain oil and suspended solids.
A description of techniques to consider in the determination of BAT for hot forming is provided in BREF document for iron and steel production.
The following release levels from the waste water treatment are associated with BAT:

- SS: < 20 mg/l
- Oil: < 5 mg/l (oil based on random measurements)
- Fe: < 10 mg/l
- Crtot: < 0.2 mg/l (for stainless steel < 0.5 mg/l)
- Ni: < 0.2 mg/l (for stainless steel < 0.5 mg/l)
- Zn: < 2 mg/l

COLD ROLLING MILLS [4]
Water and Process Baths Management in Cold Rolling Mills

In cold rolling mills water is used to clean the surface of rolling stock, in order to prepare it for pickling and degreasing baths, for rinsing and for cooling. Pickling and related processes (rinsing, gas cleaning operations, acid regeneration) cause acidic waste water streams. Alkaline waste water might be produced, if degreasing is part of the processing.
Water/oil emulsions are used for cooling and lubrication in the rolling sections. This produces the oil and suspended solid increase in the waste water streams. Usually emulsion and degreasing solutions are recycled to the process in closed loops. Water used for indirect cooling is also operated in closed loop circuits.
Waste Water Treatment and best available techniques for cold forming are presented in BREF document in the Ferrous Metals Processing Industry. Associated release levels of the waste water treatment are:

- SS: < 20 mg/l
- Oil: < 5 mg/l (oil based on random measurements)
- Fe: < 10 mg/l
- Crtot:< 0.2 mg/l (for stainless steel < 0.5 mg/l)
- Ni: < 0.2 mg/l (for stainless steel < 0.5 mg/l)
- Zn: < 2 mg/l

Cooling water systems
In order to determine the best techniques for improvements on selected processes within the REFFIPLANT industrial partners’ sites, the Best Available Techniques (BAT) Reference Document for Industrial Cooling Systems [5] has been used. The following is a summary of the main points relevant to the project. For further details on a specific improvement or BAT, reference to the document is recommended.

BAT for Industrial Cooling Systems [5]

Due to the large variation, comparisons between techniques leading to general conclusions on BAT are difficult. The identification of a general preventive approach is considered to be possible, based on practical experience with reduction of emissions from cooling systems. In the preventive approach or, primary BAT-approach, the following steps are considered:

1. Process to be cooled,
2. Design and construction of the cooling system,
3. Changes of equipment and the way in which the cooling system should be operated.

Integrated heat management

Industrial cooling

A description is provided in BREF document for Industrial Cooling Systems.

Reduction of the level of heat discharge by optimization of heat reuse

Cooling system and process requirements

Cooling system and site requirements

Reduction of energy consumption

Also see Annex II (Principle of energy saving through optimised cooling)

BREF document for Industrial Cooling Systems provides a description of BAT in the design phase of a cooling system and BAT for increasing overall energy efficiency

Reduction of water requirements

General

For relevance to REFFIPLANT the following statements can be made:

- In the light of the overall energy balance, cooling with water is most efficient;
- The cooling demand should be reduced by optimising heat reuse;
- Where water availability is limited, a technology should be chosen that enables different modes of operation requiring less water for achieving the required cooling capacity at all times;
- In all cases recirculating cooling is an option, but this needs careful balancing with other factors, such as the required water conditioning and a lower overall Energy efficiency.

BREF document for Industrial Cooling Systems presents a Table of BAT for reduction of water requirements and provides examples of techniques for cooling water savings through water reuse

Reduction of emissions to water

General BAT approach to reduce chemical emissions to water

Measures should be taken in the design phase of wet cooling system using the following order of approach:

- identify process conditions (pressure, T, corrosiveness of substance);
- identify chemical characteristics of cooling water source;
- select the appropriate material for heat exchanger combining both process conditions and cooling water characteristics;
- select the appropriate material for other parts of the cooling system;
- identify operational requirements of the cooling system, select feasible cooling water treatment (chemical composition) using less hazardous chemicals or chemicals that have lower potential for impact on the environment (Section 3.4.5, Annex VI and VIII);
- apply the biocide selection scheme (Chapter 3, Figure 3.2);
- optimise dosage regime by monitoring of cooling water and systems conditions.

BREF document for Industrial Cooling Systems provides Tables of BAT for reduction of emissions to water by design and maintenance techniques, and BAT for reduction of emissions to water by optimised cooling water treatment

Reduction of risk of leakage

General approach

To reduce the risk of leakage, attention must be paid to the design of the heat exchanger, the hazardousness of the process substances and the cooling configuration. The following general measures to reduce the occurrence of leakages can be applied:

- select material for equipment of wet cooling systems according to the applied water quality;
- operate the system according to its design;
- if cooling water treatment is needed, select the right cooling water treatment programme;
- monitor leakage in cooling water discharge in recirculating wet cooling systems by analysing the blowdown.

BREF document for Industrial Cooling Systems provides a Table of BAT to reduce the risk of leakage.

References

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[2] IPPC, 2003. Reference Document on Best Available Techniques in Common Waste Water and Waste Gas Treatment / Management Systems in the Chemical Sector: http://eippcb.jrc.ec.europa.eu

[3] IPPC, 2012. Best Available Techniques Reference Document for Iron and Steel Production: http://eippcb.jrc.ec.europa.eu

[4] IPPC, 2001. Reference Document on Best Available Techniques in the Ferrous Metals Processing Industry: http://eippcb.jrc.ec.europa.eu

[5] European Commission (2001). Best Available Techniques (BAT) Reference Document for Industrial Cooling Systems: http://eippcb.jrc.ec.europa.eu

7.2 By-products and waste benchmarking

This document summarises the results of a benchmarking investigation of by-products and waste management in steel plants within the world steel membership. The aim with this benchmark study is to determine the situation of best performers around the world within the scope of by-products and waste management. Some additional information about waste management processes has also been briefly studied. This benchmark document is intended to support the work regarding by-products and waste within the REFFIPLANT-project.
Road construction, the foundry- and cement industry are important markets for the steel industry to recover slag and sludge externally. To increase the internal recycling possibilities and production of valuable by-products for the external market some plants uses recycling processes, e.g. OxyCup shaft furnace and the DK-process. Table A3 shows the minimum and average generation of slag, dust & sludge and scales from various processes. The information about slag, sludge and dust management and good example plants is based on the by-products survey carried out by the World Steel Association, which was completed in 2010 (Book: Steel Industry By-Products [1]).

Process	Avg production, Mton product/year	By-prod and waste flow, kg/ton			Unit
		Slag	Dust & Sludge	Scales	
Sintering	7.1	-	4.0/36.3	-	kg/t sinter
Blast Furnace	5.0	240/275	10.6/34.0	-	kg/t HM
Desulphurisation	5.2	0.8/11.1	-	-	kg/t CS
Basic Oxygen	5.7	46/111	2.0/26.0	-	kg/t CS
Secondary Metallurgy	5.7	2.9/14.8	0.1/4.2	-	kg/t CS
Casting	4.9	-	0.3/1.4	0.03/5.1	kg/t CS
Hot rolling	3.0	-	0.1/4.5	2.2/18.5	kg/t RS

Note1: SSAB Luleå has a BF slag generation of 160 kg/ton HM

Table A3: By-product & waste generation per ton of product from different processes (min/avg) [1]

Sintering

Sinter dust and sludge are mainly recovered within the integrated steel plant, and the main part is recycled back to the sinter plant. External recovered material goes to other sinter plants or the cement industry and 14 % of the sinter sludge is sent to landfill. The recovery rate of sinter dust and sludge are limited mainly due to the high lead and Zn content in fine fractions.

Blast Furnace

The main part of BF slag is utilised for internal or external applications, e.g. cement making or as aggregates for road construction. BF slag is granulated as *granulated BF slag* (GBFS), *pelletized* or *air-cooled*. Around 80 % of all BF slag is granulated. The lowest levels of stockpiled slag can be found for pelletized slag, where only one plant reported stockpile of less than 50 kton and the rest zero. For GBFS one plant has a stockpile of 500 to 1000 kton and the rest below 200 kton, while the air-cooled slag responds for one plant with 500 to 1000 kton and two plants with 1000 to 2500 kton in stockpile and the rest below 200 kton. The overall trend of stockpiled BF slag is stable and even decreasing.
The coarse fraction of BF dust and sludge are almost recovered internally to 100 %, the main recovery route is BF and sinter plant. The fine fraction contains a higher amount of lead and Zn compared to the coarse fraction which is one of the limiting factors for recycling of the material. 16 % of the fine BF dust & sludge is sent to landfill, internally or externally.
Baosteel in Shanghai, China, produces 15 Mt steel per annum where 98,5 % of the BF slag is granulated by water producing slag powder or sold directly to cement industry. BF sludge is collected by a cyclone, which separates a high and low Zn-fraction. The low Zn-fraction is recycled to the BF via the sinter plant and the higher Zn-fraction is separated again by a HC separator: low Zn-fraction is mixed into sinter plant ore blend and high Zn-fraction is reused external.

Desulphurisation

Desulphurisation slag is commonly internally recycled in sinter plants or BF at a level of 54 %, 25 % is external recovered and 21 % is landfilled. The lowest slag generation rate, in average 2.2 kg/ton CS, is found in the region of Asia developed countries while EU countries have an average of 11.6 kg/ton CS. Examples of external recovery of deS slag may be road construction and recovery by external EAF plants. Obstacles to recover deS slag internally or externally are lime, sulphur and fluoride contents (due to the use of slag former). Half of the plants responded 100 % recovery of deS slag.

Steel plant (BOF-converter)

The total recovery of BOF slag amounts to 81 %, where 58 % were used in external applications and 23 % internally. BOF slag that goes for external applications will mainly be used as road construction material, and some minor applications are within cement industry, de-pollution of waste water and agricultural soil improvement. Recycled slag back to the BOF accounts for 58 % of slag recovered internally. In the study 13 of the plants reported 100 % recovery of BOF slag. A common limitation for the internal recovery rate is the phosphorus content, which has a negative impact at the economy and quality of steel. High phosphorus content in the converter will demand more lime and a higher slag rate. The free lime content in the slag may be a problem for some external applications due to its expansion properties and high pH in water. The benefits with internal recycling of BOF slag will be the iron and free lime content.
BOF dust and sludge are recovered to an extent of around 90 % and the rest is landfilled due to high Zn levels and fine particles that are problematic to charge. There is a potential to reduce landfill of these materials by reuse it internally via briquetting, recovery and water separation techniques and externally via the cement industry.
U.S. Steel in Pittsburgh, USA produces 2.5 Mt slab per annum. Here, cold bounded briquettes are charged into the BF at a rate of 40 kg per tHM. Wastes with high Zn-load makes it problematic to charge into the BF, therefore a BOF-briquette is produced of this material and is recycled in the BOF.

Secondary Metallurgy

About 39 % of the SM slag is sent to landfill, and the rest is recovered internal, external or stockpiled. Almost exclusively all external recovered slag is used as construction material, while the internal recovered slag mainly is used in the BOF, BF or sinter plant. The external recovery could be economical valuable as raw material for cement kilns, calcium aluminates and the cement and rockwool industries, if the transport distance is short enough. SM slag has been tested successfully to charge in the BOF as fluidiser due to its high alumina content (Al2O3) and reduce the need of lime due to its high CaO content. There are examples of plants that manage to recycle 100 % SM slag internally and externally.
SM dust is mainly reused in the sinter plant, 19 % is landfilled. CC sludge is recovered to an extent of 57 %, where most of the material goes for external recovery in the cement industry.

Casting and Rolling

Hot rolling sludge is recovered to an extent of 86 %, which is mainly recovered in sinter plant, BF and cement industry. Scales from CC or hot rolling are recovered to 100 %, mostly internally via sinter plant and BF. Main issues with scales and sludge from CC and hot rolling are the oil content. Oily scales may be recovered within the cement industry and internally if the material is treated, e.g. de-watered, de-oiled, pelletized or briquetted.

Summary

Table A4 shows a summary of the destinations for the generated slag and sludge & dust. The material is recycled internally or externally, landfilled internally or externally or stored at the site for future recovery.

Process	Recycling		Stored	Landfill	
	Internally	Externally		Internally	Externally
Sintering	-/93	-/4	-/1	-/3	-/0.4
Blast Furnace	10/74	89/17	0/2	0.3/5	0.1/3
Desulphurisation	54/-	24/-	1/-	19/-	3/-
Basic Oxygen	23/59	58/29	7/6	12/12	0/0.3
Secondary Metallurgy	28/6	29/67	5/8	34/2	5/17
Casting	-/89	-/10	-/1	-/0.2	-/1
Hot rolling	-/75	-/23	-/0.1	-/1	-/0.4

Note2: Some of the rows does not sum up to exactly 100 % due to rounding
Note3: The information in the reference book about SM dust is contradictory. It says SM dust is completely recovered in the process and mainly in the sinter plant.

Table A4: Summary of the destination for generated slag and sludge & dust, numbers are given in % of total generation for each process (slag/dust & sludge).

Recycling and treatment processes

The main goal for the REFFIPLANT-project within the by-products and waste management is to reduce the flaring and landfill. This may be achieved by different recycling processes for processing of the material, but also by structuring the by-products and waste management in a more efficient way. ArcelorMittal in Tubarão, Brazil produces 7.5 Mt steel per annum. A structured waste and by-product management plan is developed by the steel plant and is called PDCA, "Plan, Do, Check, Act". This centralizes the routines for recovery of by-products and waste.

The information about the recycling processes has been collected in the European Commission report BAT Reference Document for Iron and Steel Production [2]. The processes increase the possibility to recycle slag, sludge and dust with high iron- and coal content that cannot be reused mainly due to high Zn, alkali and lead content.

- *HC treatment of BF sludge.* Separation of the sludge to a Zn-rich and a Zn-poor sludge by HC technique. The Zn-poor sludge is recycled back to the process.
- *Dust hot briquetting.* Recovery of BOF fine and coarse dust is possible through hot briquetting. The fine Zn-rich dust is pelletized and sent to external zinc industry when the Zn content is around 20 % or more.
- *Cold bonded pellets/briquettes.* Agglomeration of fine iron-bearing material, e.g. BOF sludge, BF/BOF dust and BOF slag fines enables charging of the materials back to the process. Cold bounded briquettes are produced and recycled to the BF or BOF by SSAB in Luleå and Oxelösund, Sweden, and ILVA in Taranto, Italy.
- *Direct injection of BF dust.* This technique will recover the BF dust from the BF, and is favourable due to the high carbon content in the material. The technique is adopted at SSAB in Oxelösund and has recently started at SSAB in Luleå, Sweden.
- *HRM Sludge treatment process* [6]. Scale sludge consists of very fine particles (<0.1 mm), which absorb oil to a degree of 5-20%. To facilitate the reuse of scale sludge in the process the oil is removed. To do this there are several options;
    - Briquetting and charging into converter
    - A mixture of oily mill scale sludge, lime and coal dust are injected into the blast furnace. The technique is adopted by Voestalpine Stahl, Linz, Austria
    - A 3-stage flotation process where the result is a Fe-product, an oily-product and a mixture. The technique is a THYSSEN method.
- *OxyCup® shaft furnace* [3]. Out of sludge, dust and coke a cold bonded self-reducing briquette is produced and charged at the top of the furnace together with coke. Similar to a conventional blast furnace, hot blast and oxygen are injected in the lower part of the shaft furnace. The products are slag, hot metal and process gas. During the gas cleaning process Zn-enriched dust and sludge are collected and sent to the Zn industry. Thus, it is possible to recycle waste with high Zn content, which is one of the benefits with the OxyCup shaft furnace compared to a conventional BF. An example plant is located in Duisburg-Hamborn, Germany, and is operated by Thyssen Krupp Steel. Figure A1 shows an example of the OxyCup shaft furnace integrated at an integrated steel plant. ThyssenKrupp Steel in Duisburg, Germany produces 11 Mt HM per annum. Through the OxyCup shaft furnace fine grained material is recycled by charging cold bonded bricks into the shaft furnace.

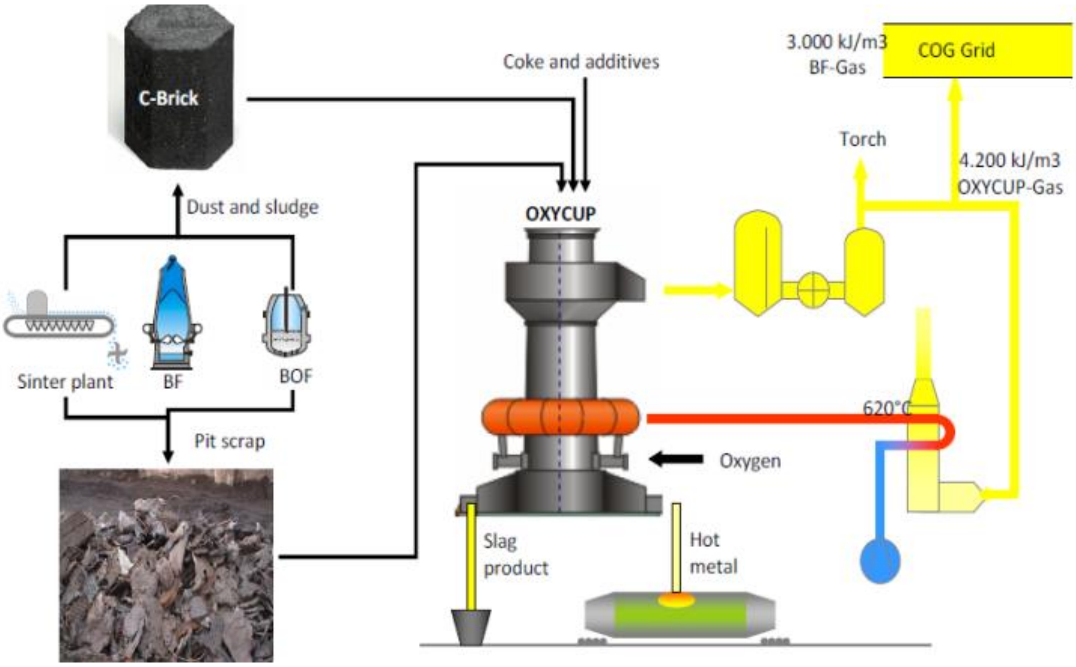


Figure A1: Hot metal production from the OxyCup shaft furnace. [3]

- *DK-process.* [4] This process consists of a BF and a sinter plant and is developed by DK Recycling und Roheisen located in Duisburg, Germany. Here, recycling of dust, sludge, mill scale and other wastes with high iron content is executed. The products are Zn concentrate sent to the zinc industry, pig iron to the foundry industry, slag and process gas.
- *Smelting reduction processes.* Various smelting reduction processes, e.g. RedSmelt, RedIron and Primus are developed by Paul Wurth [5]. The primary goal with these recycling technologies is to recycle dust, sludge and mill scales from the EAF-route and the BF/BOF-route. The RedIron-technology uses an RHF to convert the residues to DRI or HBI and the melting is performed in a BF, BOF or EAF. The RedIron-process may be found at the Lucchini plant in Piombino, Italy.

References

[1] World Steel Association (2010). Steel Industry By-Products: Project group report 2007-2009.
[2] European Commission (2013). Best Available Techniques (BAT) Reference Document for Iron and Steel Production.
[3] Küttner. Webpage <www.kuettner.com/>, accessed: 13/8 -2013.
[4] DK Recycling und Roheisen. Webpage <http://www.dk-duisburg.de/index_en.html/>, accessed: 13/8 -2013.
[5] Paul Wurth. Webpage <www.paulwurth.com/>, accessed: 13/8 -2013.
[6] European Commission (2001). IPPC, Reference Document on Best Available Techniques in the Ferrous Metals Processing Industry.

8 Appendix B - Internal Process Constraints Tables

		Contaminants limiting value																									
		Replenishing Water	Av. Consumption	TSS	El. Cond.ity	Temp	pH	LSI	Alkalinity	Ca hardness	TDS	COD	THC	NH4	NO2	NO3	H_2S	Tox	Cl	Zn	V	Pb	Ni	Cr	Fe	Sn	SiO_2
Area	Use	Water Source	mc/h	mg/l	µS/cm	°C	---	---	mg of CaCO3	mg/l ofCaCO3	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
IMA1	Dust suppression	Tara	10	5	3500	20	6 - 8.5	1	---	---	---	<10	<0.5	<1	<0.1	5	---	---	1000	---	---	---	---	---	---	---	15
PAR	Wetting tracks	Tara	30	20	3500	20	6 - 8.5	1	---	---	---	<100	<1	<15	<0.1	<0.1	---	---	200	---	---	---	---	---	---	---	15
PAR	Filming heaps	Tara	5	20	3500	20	6 - 8.5	1	---	---	---	<10	<0.5	---	<0.1	5	---	---	50	---	---	---	---	---	---	---	15
COK	SOT refrigerants and other uses	Tara	100	10	3500	20	---	1	---	---	---	<10	<0.5	<1	<0.1	5	---	---	---	---	---	---	---	---	---	---	15
COK	Coke Quenching	Mix ABS	300	20	500	40	---	---	---	---	---	<10	<0.5	<1	<0.1	<1.5	---	---	200	---	---	---	---	---	---	---	5
AGL	Dust suppression	Mix ABS	5	5	250	20	---	1	---	---	---	<10	<0.5	<1	<0.1	<1.5	---	---	200	---	---	---	---	---	---	---	5
AFO1	Gas washing	Tara	60	50	6000	55	---	1,5	---	---	---	20	<2	---	<0.3	<10	---	---	---	---	---	---	---	---	---	---	---
AFO2	Gas washing	Tara	60	50	6000	55	---	1,5	---	---	---	20	<2	---	<0.3	<10	---	---	---	---	---	---	---	---	---	---	---
AFO4	Gas washing	Tara	60	50	6000	55	---	1,5	---	---	---	20	<2	---	<0.3	<10	---	---	---	---	---	---	---	---	---	---	---
AFO5	Gas washing + INBA	Tara	250	20	6000	40	---	1,5	---	---	---	20	<0.5	---	<0.3	<10	---	---	---	---	---	---	---	---	---	---	---

AFO5	Tuyeres cooling	Tara	130	10	4500	30	---	2	---	---	---	<10	<0.5	<1	<0.3	<10	---	---	---	---	---	---	---	---	---	---	---
ACC1	Other coolings Converters	Tara	20	10	4500	30	---	2	---	---	---	<10	<0.5	<1	<0.3	<10	---	---	---	---	---	---	---	---	---	---	---
ACC1	Gas washing	Tara	100	20	6000	40	---	---	---	---	---	<100	<2	<1	<0.3	<10	---	---	1000	---	---	---	---	---	---	---	---
ACC1	RHOB direct coolings	Tara	5	200	4500	30	---	2	---	---	---	---	<0.5	<1	<0.3	<10	---	---	1500	---	---	---	---	---	---	---	---
ACC1	RHOB indirect coolings	Tara	3	5	4500	30	---	2	---	---	---	---	<0.5	<1	<0.3	<10	---	---	1500	---	---	---	---	---	---	---	---
ACC1	CCO1 spray circuit	Mix ABS	80	10	1300	30	---	2	---	---	---	<100	<2	<1	<0.2	<5	---	---	300	---	---	---	---	---	---	---	---
ACC1	CCO1 machines cooling	Mix ABS	30	10	800	30	---	2	---	---	---	---	<0.5	<1	<0.2	<5	---	---	300	---	---	---	---	---	---	---	---
ACC1	CCO5 air mist compressors cooling	Mix ABS	5	10	800	30	---	2	---	---	---	<10	<0.5	<1	<0.2	<5	---	---	300	---	---	---	---	---	---	---	---
ACC1	CCO5 spray circuit	Tara	80	10	4500	30	---	1,5	---	---	---	<100	<2	<1	<0.3	<10	---	---	1500	---	---	---	---	---	---	---	---
ACC1	CCO5 machines cooling	Tara	40	10	4500	30	---	1,5	---	---	---	<10	<0.5	<1	<0.3	<10	---	---	1500	---	---	---	---	---	---	---	---
ACC2	COV cooling and other uses	Tara	80	10	4000	30	---	1,5	---	---	---	<10	<0.5	<1	<0.3	<10	---	---	1500	---	---	---	---	---	---	---	---
ACC2	Gas washing	Mix ABS	90	10	1200	40	---	---	---	---	---	<100	<2	<1	<0.2	<1.5	---	---	300	---	---	---	---	---	---	---	---
ACC2	RHOB direct coolings	ACC 2 + mix	45	200	600	30	---	2	---	---	---	---	<2	<1	<0.2	<10	---	---	300	---	---	---	---	---	---	---	---
ACC2	RHOB indirect coolings	ACC 2 + mix	5	10	600	30	---	2	---	---	---	---	<0.5	<1	<0.2	<10	---	---	300	---	---	---	---	---	---	---	---

ACC2	CCO2/3/4 spray circuits	ACC 2 + mix	130	10	1300	30	---	2	---	---	---	<100	<2	<1	<0.2	<5	---	---	300	---	---	---	---	---	---	---	---
ACC2	COB 5	Mix ABS	3	10	600	30	---	2	---	---	---	<10	<0.5	<1	<0.2	<5	---	---	300	---	---	---	---	---	---	---	---
TNA1	Direct coolings	Mix ABS	100	20	2000	30	---	2	---	---	---	<100	<5	<1	<0.2	<5	---	---	500	---	---	---	---	---	---	---	---
TNA1	Engine and thyristors cooling	Mix ABS	20	10	800	30	---	2	---	---	---	---	<0.5	<1	<0.2	<5	---	---	500	---	---	---	---	---	---	---	---
TNA2	FAL1/2/3 cooling	Mix ABS	150	10	400	30	---	2	---	---	---	---	<0.5	<1	<0.2	<5	---	---	500	---	---	---	---	---	---	---	---
TNA2	Direct coolings	Mix ABS	150	20	1200	30	---	2	---	---	---	<100	20	<1	<0.2	<5	---	---	500	---	---	---	---	---	---	---	---
TNA2	Engine and thyristors cooling	Mix ABS	25	10	800	30	---	2	---	---	---	<10	<0.5	<1	<0.2	<5	---	---	500	---	---	---	---	---	---	---	---
FNA	Various indirect coolings	Tara	5	10	4500	30	---	2	---	---	---	<10	<0.5	<1	<0.3	<10	---	---	1500	---	---	---	---	---	---	---	---
TLA2	Plates controlled cooling	RO TLA	75	10	600	30	---	1,5	---	---	---	<100	<0.5	<1	<0.1	<5	---	---	500	---	---	---	---	---	---	---	---
TLA2	Direct coolings	RO TLA		20	2000	30	---	2	---	---	---	<100	20	<1	<0.2	<5	---	---	500	---	---	---	---	---	---	---	---
LAF	ELZ coolings and washings	Mix ABS	70	10	300	30	---	2	---	---	---	<10	<0.5	<1	<0.1	<1.5	---	---	300	---	---	---	---	---	---	---	---
LAF	ZNC1 coolings	Mix ABS	30	10	600	30	---	2	---	---	---	<10	<0.5	<1	<0.1	<5	---	---	300	---	---	---	---	---	---	---	---
LAF	ZNC2 coolings	Mix ABS	30	10	600	30	---	2	---	---	---	<10	<0.5	<1	<0.1	<5	---	---	300	---	---	---	---	---	---	---	---
LAF	Annealing coils	Mix ABS	30	10	600	30	---	2	---	---	---	<10	<0.5	<1	<0.1	<5	---	---	300	---	---	---	---	---	---	---	---

TUL1	Pipes and hydraulic press washing	Aquifer	10	20	4500	30	---	---	---	---	---	---	20	<1	<0.1	<5	---	---	1500	---	---	---	---	---	---	---	---
TUL2	Pipes and coolings washing	Tara	20	20	3500	30	---	---	---	---	---	---	20	<1	<0.1	<5	---	---	1500	---	---	---	---	---	---	---	---
ERW	Pipes and hydraulic press washing	Aquifer	5	20	4500	30	---	2	---	---	---	---	20	<1	<0.1	<5	---	---	1500	---	---	---	---	---	---	---	---
RIV1	PE and compressors cooling	Demi	5	10	100	30	---	2	---	---	---	<100	<2	<1	<0.1	<1.5	---	---	300	---	---	---	---	---	---	---	---
RIV2	PE and compressors cooling	Demi	10	10	100	30	---	2	---	---	---	<100	<2	<1	<0.1	<1.5	---	---	300	---	---	---	---	---	---	---	---
RIV 3	PE and compressors cooling	RO RIV3	8	10	600	30	---	2	---	---	---	<100	<2	<1	<0.1	<1.5	---	---	300	---	---	---	---	---	---	---	---
ENE	Compressors cooling (room 2 Bis)	Mix ABS	20	10	600	30	---	2	---	---	---	<10	<0.5	<1	<0.1	<5	---	---	300	---	---	---	---	---	---	---	---
PGT	Oxygen plant coolings	Mix ABS	200	10	600	30	---	2	---	---	---	<10	<0.5	<1	<0.1	<1.5	---	---	300	---	---	---	---	---	---	---	---
PGT	OXIAL coolings	Tara	90	10	4000	30	---	2	---	---	---	<10	<0.5	<1	<0.1	<10	---	---	1500	---	---	---	---	---	---	---	---
PGT	Hydrogen plants	Mix ABS	25	10	600	30	---	2	---	---	---	<10	<0.5	<1	<0.1	<1.5	---	---	300	---	---	---	---	---	---	---	---
PAD	Demi water production	Mix ABS	500 *	50	200	20	---	---	---	---	---	<10	<0.5	<1	---	---	---	---	50	---	---	---	---	---	---	---	5

* It is not a production process that uses water but it produces water of defined quality by the manufacturing processes - It is held to close the budget

Notes
1) Consumption refers to the maximum productivity of the plant
2) MIX ABS = mixing of water from river Sinni and permeated from RO of Area 12
3) Meaning of the values in the table:
- if the datum is indicated, this refers to the circulating water
- if indicated "---", the parameter is needless or not known
- if the datum has the symbol "<", the concentration refers to the reintegration and derives from the limits of law for the discharges

9 Appendix C - Water treatment Process models

Clarifier model

Clarifiers are primary wastewater treatment processes mainly devoted to the removal of suspended solids. Water is sent to a clarification basin, where settling of the solids suspended in the water phase takes place. Various configuration are possible, however, in general, 4 main areas can be identifies within a clarifier: an inlet zone, a settling zone, a sludge zone and an outlet zone (see Figure C1).

Basically, the design of the settling basin defines the fundamental parameter of the clarifier, the basin overflow rate, defined as:

$$V_0 = Q/A$$

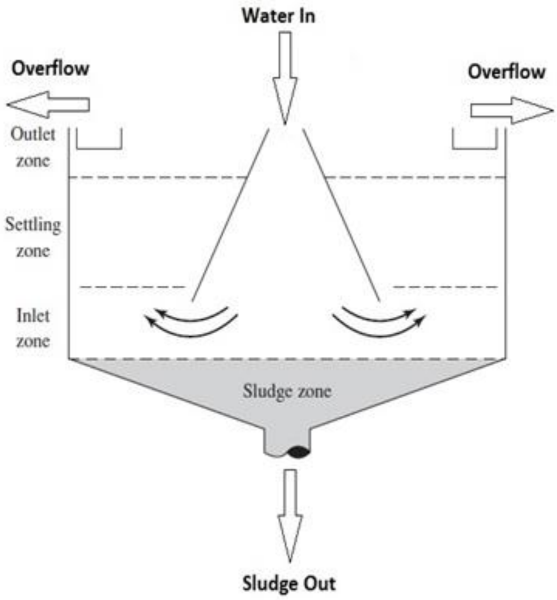


Figure C1. Clarifier model schematic representation

Where V_0 is the overflow rate [m/h], A the surface area of the tank [m^2], and Q the volumetric inlet flow rate [m^3/h]. In order to determine the removal efficiency of the clarifier, the particle settling velocity v_P needs to be calculated as well (see Figure C2).

The calculation of the particle settling velocity can be carried out by carrying out a balance of the forces acting on the solid particles in the liquid (NALCO, 2009). In particular, as far as the forces are concerned the following relationships subsist:

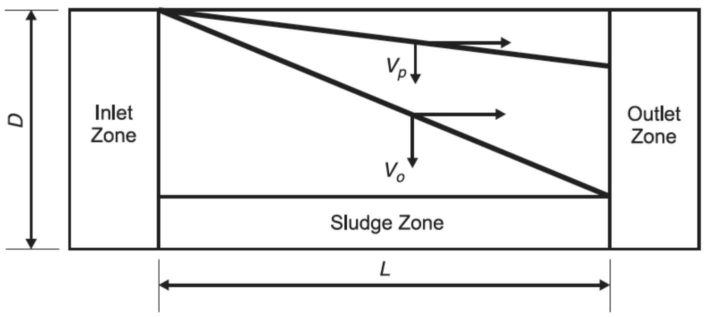


Figure C2 Settling of discrete particles in clarifiers (NALCO, 2009)

$$F_G = \rho_S g V_P$$
$$F_B = \rho g V_P$$
$$F_D = C_D A_P \rho \frac{v^2}{2}$$

where:

F_G = Gravitational force
F_B = Buoyancy force
F_D = Drag force
ρ_S = Density of particle, kg/m^3
ρ_S = Density of fluid, kg/m^3
g = Acceleration due to gravity, m/s^2
V_P = Volume of particle, m^3
C_D = Drag coefficient
A_P = Cross - sectional area of particle, m^2
v = Velocity of particle, m/s

Therefore, the forces balances can be written as:

$F_D = F_G - F_B$

The settling velocity, according to the Stokes' Law for sedimentation, can be calculated as follows:

$$V_P = \frac{g(\rho_S - \rho)d^2}{18\mu}$$

where
18 = Constant
μ = Dynamic viscosity, Pa·s

Activated Sludge treatment - Biological plant

The gas flow coming from coke production area needs to be purified from gas contaminants (e.g. H_2S, NH_3) and coal tar. For this reason it is sent to by-products plant where several unit operations use water to treat the gas flowrate. The participating water streams result have to be treated before re-use in other equipments or discharge. After a main stripping process, where the major amounts of H_2S and NH_3 are removed, the distilled water is sent to a biological plant to reduce its COD content.

Activated sludge treatment plants are secondary wastewater treatments and fundamental components in the removal of organic matter (COD and BOD) from industrial wastewater (Smith, 2005). Such a treatment is particularly suited in the treatment of coke ovens wastewater, where BOD, COD, cyanate, thiocyanate, phenols, ammonia, TKN, nitrates, phosphates and nitrites as well as other suspended solids are present (Papadimitriou et al., 2006; van Hoorn, 2005; Melcer et al., 1984).

The physical, chemical and biological phenomena regulating the functioning of an activated sludge plant are very complex. Strains of microorganism are responsible for the breaking down of the organics into a stabilized waste sludge. In industrial applications, nutrients that are fundamentals for the sustaining of the microorganisms, such as oxygen, carbon, N, F, and inorganic substances such as calcium, magnesium and P might have to be added to the process (Smith, 2005; and NALCO, 2009). Moreover, problems can occur due to the presence of inhibitors and toxic compounds that can compromise the performances or even the survival of the microorganisms.

For the purposes of this work, an activated sludge model was realised based on the publications by (Gujer et al., 1999; Koch et al., 2001a; Koch et al., 2001b; Siegrist and Gujer, 1994), which describe a series of reactors for treatment of waste water (see Figure C3).

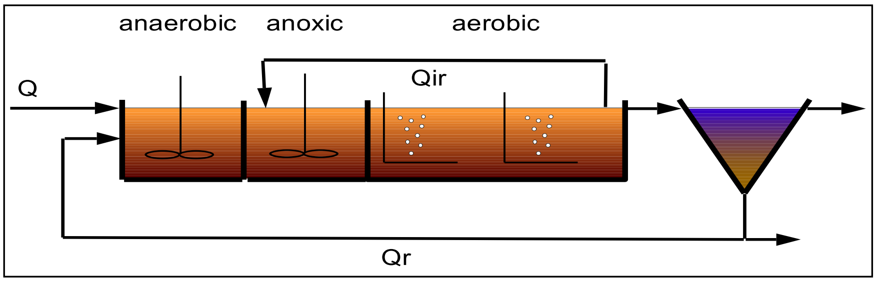


Figure C3 Schematic representation of the activated sludge model (Koch et al., 2001a)

The water flows first through an anaerobic reactor (reactions that occur without the presence of oxygen, deriving the energy from the organic compounds in the waste), then an anoxic zone (reactions similar to the aerobic ones in lack of oxygen and generally responsible for de-nitrification of nitrates into nitrogen) and finally an aerobic zone (reactions in presence of air bringing to stable compounds such as CO_2 and H_2O), before a final clarifier. Nitrification reactions can occur in this part of the plant, converting organic nitrogen and ammonia into nitrate. A part of the sludge from the clarifier is circulated back to the anaerobic zone, in order to recycle the nutrients and control the nitrogen cycle. A list of the main model inputs and outputs in terms of variables and parameters is presented in Table C1.

	Inputs	
Variable name	UOM	Description
Influent (average load)		
Qo	m3/h	average inlet flow
X_TSS,o	mg/l	total suspended solids in influent
C_COD,o	mg/l	total COD in influent
S_S,o	mg/l	dissolved degradable COD in influent
C_TKN,o	mg/l	total KjN in influent
S_NO,o	mg/l	Nitrate and Nitrite-N in influent
C_P,o	mg/l	total P in influent
X_Pinorg,o	mg/l	inorg. partic. P in influent ca. 0.1·C_P,o
S_O,o	mg/l	oxygen in influent
Effluent		
X_TSS,e	mg/l	total suspended solids in effluent
S_TKN,e	mg/l	dissolved KjN in effluent
S_Porg,e	mg/l	dissolved organic P in effluent
Plant design and operation		
Return sludge to anaerobic zone		
S_O,r	mg/l	O_2 in return sludge > O_2 surplus sl. blanket
S_NO,r,estim	mg/l	Nitrate and Nitrite-N in return sludge
Qr/Qo	-	ratio of return flow to inlet >0.3
Internal recirculation from aerobic to anoxic zone		
S_O,ir	mg/l	O_2 in recirculation
Qir/Qo	-	ratio of internal rec. to inlet
Design		
X_COD,tank,max	mgCOD/l	activated sludge conc. for design load
SRTaer	d	aerobic solid retention time
Ldesign / Laver	-	design to average load
Vanaer/Vtank	-	anaerobic volume fraction
Vano/Vtank	-	anoxic volume fraction >0.1
b_blanket	-	>= 0.05, mass fraction of sludge blanket
Temp.	°C	and/or return sludge denitrification
S_O,tank	mgO2/l	O_2 in effluent of aeration tank
Kla,mixing	d-1	Kla from stirring in non aerated zones (VBB/Qo ~ 10 h, S_sat ~ 9 mg O_2/l)
Sludge characteristics		
i_COD,TSS	gCOD/gTSS	COD-content of excess sludge
i_N,COD	gN/gCOD	N-content of excess sludge
	Outputs	
Variable name	UOM	Description
Effluent		
S_I,e	mg/l	inert soluble COD in effluent
Plant design and operation		
Design		
SRTtank	d	observed solid retention time (without blanket)
Vtank	m3	total activated sludge volume
Sludge production (X_PP > 0)		
SP_COD	mgCOD/l	total sludge production (= effluent+excess sludge)
P-removal (X_PP > 0)		
X_Porg	mgP/l	particulate organic P in excess sludge
X_Pinorg	mgP/l	particulate inorganic P in excess sludge
X_PP	mgP/l	particulate poly-P in excess sludge
X_P,e	mgP/l	total particulate P in effluent sludge
S_PO4,e	mgP/l	dissolved PO4-P in effluent
S_Porg,e	mgP/l	dissolved organic P in effluent
hP	%	total P-removal
N-removal (X_PP > 0)		
S_NO,den	mgN/l	denitrified N
X_Norg	mgN/l	particulate organic N in excess sludge
X_N,e	mgN/l	particulate organic N in effluent sludge
S_NO,e	mgN/l	Nitrate and Nitrite-N in effluent
S_TKN,e	mgN/l	dissolved KjN in effluent
hNtot	%	total N-removal

Table C1: Main inputs and outputs for the ASM in (Koch et al., 2001)

Currently, no evidence in the literature of a model representative of the industrial partner's situation subsists; therefore, a model validation was not carried out; instead, a simplified approach to the modelling was adopted for the purposed of WP4.

Ammonia stripping model

The final treatment for the waste water coming from coke production area is the stripping of the ammonia from wastewater, prior to discharge after the biological unit. An amount of soda solution (50% wt.) is also added to the inlet flow according to solubility data of NH_3 in the water to adjust the stream pH and facilitate the stripping process by addition of saturated steam.
For this type of treatment, an Aspen Plus ® model was developed.
The objective was the study of the unit operation to optimize the operative conditions in terms of NaOH and steam reduction.
Two different operating cases were simulated for ILVA ammonia stripping process: standard operative conditions (nominal plant capacity) and current operative conditions, which differ from the nominal case due to fouling of the heat exchangers and in inlet flowrate.
Figure C4 and Table C2 show the simulated process flowsheet and the operative conditions.

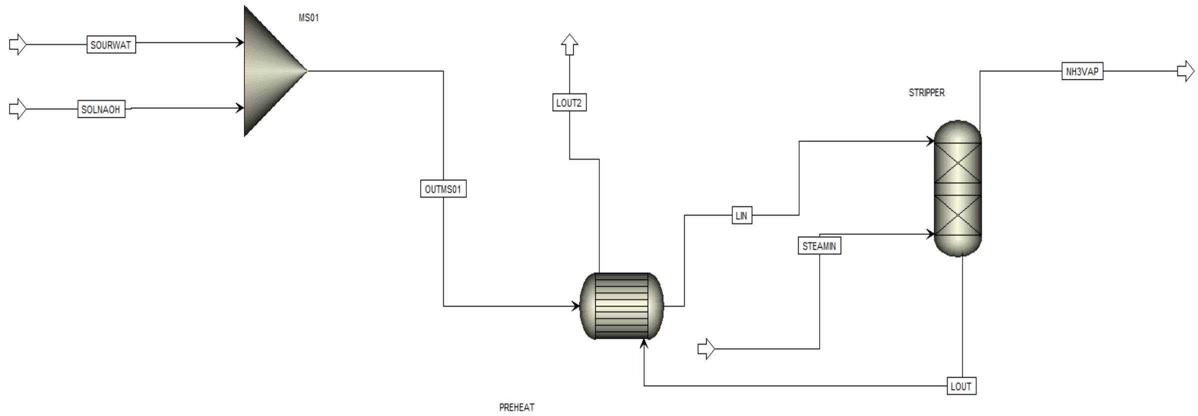


Figure C4.Simulated process flowsheet of the ammonia stripping process

	Standard value	Current value
WASTE WATER TO TREATMENT:		
Mass flow [kg/h]	80000	70000
Volumetric flow [m3/h]	80	70
Average mass density [kg/m3]	1000	1000
pH	8	8,3
Temperature [°C]	30	30
Main contaminants concentration:		
NH_3	500 ppm	500 ppm
NH_4Cl	100 mg/L	-
NaOH SOLUTION TO TREATMENT:		
Mass flow [kg/h]	240	195
Volumetric flow [m3/h]	0,16	0,13
Average mass density [kg/m3]	1500	1500
Temperature [°C]	30	30
Mass fraction:		
NaOH	50%	50%
H_2O	50%	50%
INLET STEAM TO COLUMN:		
Saturated steam		
Mass flow [kg/h]	15000	13000
Pressure [bar]	2,2	2,2
INLET WASTE FLOW TO COLUMN		
Temperature [°C]	70	37
Pressure [bar]	1	1
COLUMN OPERATIVE CONDITIONS:		
Condenser type	Full reflux with vapor outlet	
Stage number	18	
Outlet condenser temperature [°C]	96	96
Top pressure [bar]	1	1
Top temperature [°C]	100,7	100,5
Bottom pressure [bar]	1,2	1,2
Bottom temperature [°C]	103,5	103,5

Table C2: Comparison between standard and current operating cases

Because of the objective of this unit, the main contaminants in the inlet waste water to consider are the ones which involve ammonia nitrogen to remove. The stream contains also residual COD, HCN (not relevant in this study because they pass through the unit without reduction) and other pollutants but an exact chemical composition is not available. This fact causes an initial difference in terms of pH of the inlet stream between the real case and the simulated one.

Standard operative conditions: simulation results

Tables C3 and C4 depict the main results related to mass balances and removal efficiency.

	Units	SOURWAT	SOLNAOH	LIN	LOUT	STEAMIN	NH3VAP
Phase:		Liquid	Liquid	Liquid	Liquid	Vapor	Vapor
Mass Flow	KG/HR	80000	240	80240	95021	15000	219
Temperature	C	30	30	70	103,62	123,3	95,15
Pressure	BAR	6	3	1,5	1,15	2,2	1,05
Vapor Fraction		0	0	0	0	1	1
Liquid Fraction		1	1	1	1	0	0
Solid Fraction		0	0	0	0	0	0
Mass Density	GM/CC	0,996	1,52	0,979	0,957	0,00121	0,0006
Average Molecular Weight		18,02	18,96	18,02	18,02	18,02	17,82
Component Mass Flow							
WATER	KG/HR	79951,4	120	80074,51	94898,21	15000	176,34
NAOH	KG/HR	0	0	0	0	0	0
NH3	KG/HR	39,695	0	42,63	0,00166	0	42,6
HCN	KG/HR	0,00625	0	8,51E-05	0,00016	0	1,09E-05
NH4CL	KG/HR	0	0	0	0	0	0
H3O+	KG/HR	9,08E-08	trace	1,02E-08	5,89E-08	0	Trace
NA+	KG/HR	0	68,97	68,97	68,97	0	Trace
NH4+	KG/HR	3,143	0	0,0352	1,29E-06	0	Trace
HCL	KG/HR	trace	0	trace	trace	0	Trace
CN-	KG/HR	0,0902	0	0,0962	0,0961	0	Trace
OH-	KG/HR	0,36	51,03	48,45	48,42	0	Trace
CL-	KG/HR	5,30	0	5,30	5,30	0	Trace
Component Mass Fraction							
WATER		0,999	0,5	0,998	0,999	1	0,805
NAOH		0	0	0	0	0	0
NH3		496,18 E-06	0	531,27 E-06	1,74E-08	0	0,1948
HCN		7,81E-08	0	1,06E-09	1,71E-09	0	4,98E-08
NH4CL		0	0	0	0	0	0
H3O+		trace	trace	trace	trace	0	Trace
NA+		0	0,287	0,00086	0,00073	0	Trace
NH4+		3,93E-05	0	4,38E-07	1,35E-11	0	Trace
HCL		trace	0	1 trace	trace	0	Trace
CN-		1,13E-06	0	1,20E-06	1,01E-06	0	Trace
OH-		4,52E-06	0,213	0,000604	0,000509	0	Trace
CL-		6,63E-05	0	6,61E-05	5,58E-05	0	Trace
Phase: Liquid							
pH		10,24	17,53	11,26	10,58		
pH at 25 C		10,39	17,75	12,46	12,39		

Table C3: Simulation results in standard operative conditions

	Standard real value	Simulated value	Error %
WASTE WATER TO TREATMENT:			
Mass flow [kg/h]	80000	80000	0
pH	8	10,24	28
Temperature [°C]	30	30	0
NaOH SOLUTION TO TREATMENT:			
Mass flow [kg/h]	240	240	0
Temperature [°C]	30	30	0
Mass fraction:			
NaOH	50%	50%	0%
H_2O	50%	50%	0%
INLET SATURATED STEAM TO COLUMN:			
Mass flow [kg/h]	15000	15000	0
Pressure [bar]	2,2	2,2	0
INLET WASTE FLOW TO COLUMN			
Temperature [°C]	70	70	0
Pressure [bar]	about 1	1,5	
Main contaminants concentration:			
NH_3 [ppm]	500	500	0
NH_4Cl [ppm]	100	100	0
HCN [ppm]	1	1	0
COLUMN OPERATIVE CONDITIONS:			
Outlet condenser temperature [°C]	96	95,2	-0,833
Top pressure [bar]	about 1	1,05	
Bottom pressure [bar]	about 1,2	1,15	
Bottom temperature [°C]	103,5	103,6	0,096
OUTLET TREATED FLOW			
Mass flow [kg/h]	N.A.	95021	
Temperature [°C]	103,5	103,6	
Pressure [bar]	about 1,2	1,15	
Main contaminants concentration:			
NH_3 [ppm]	N.A.	0,02	
NH_4Cl [ppm]	N.A.	100	
HCN [ppm]	N.A.	1	
Discharge pH at 25°C	≤ 9,5	12,39	

Table C4: Simulation error of the main process parameters

The most important values are highlighted: Italian limit law for ammonia nitrogen is 15 ppm and the simulation shows that it is generously respected. Furthermore, there is a substantial difference in pH of the inlet stream, as expected. However, the delta pH between inlet and outlet stream which is in reality about 1,5 is similar to the one obtained by simulation. More accuracy in characterization of the stream could decrease this difference.

Current operative conditions: simulation results

Similar observations can be done for the second case study which represents the current operative conditions. The following Tables C5 and C6 show the main simulation results.

	Units	SOURWAT	SOLNAOH	LIN	LOUT	STEAMIN	NH3VAP
Phase:		Liquid	Liquid	Liquid	Liquid	Vapor	Vapor
Mass Flow	KG/HR	70000	195	70195	82976	13000	219
Temperature	C	30	30	37	103,6	123,3	96,3
Pressure	BAR	6	3	1,5	1,15	2,2	1,05
Vapor Fraction		0,00	0	0,00	0,00	1	1,00
Liquid Fraction		1	1	1	1,00	0	0,00
Solid Fraction		0,00	0,00	0,00	0,00	0	0,00
Mass Density	GM/CC	0,996	1,524	0,995	0,957	0,00122	6,14E-04
Average Molec. Weight		18,02	18,96	18,02	18,02	18,01	17,85
Comp. Mass Flow							
WATER	KG/HR	69963,9	97,5	70062,33	82878,47	13000	183,9
NAOH	KG/HR	0,00	0,00	0,00	0,00	0	0,00
NH3	KG/HR	34,189	0	35,07	0,00126	0	35,10
HCN	KG/HR	0,00242	0	5,57E-05	1,66E-04	0	1,36E-05
NH4+	KG/HR	0,97	0	0,03	9,83E-07	0	trace
H3O+	KG/HR	2,86E-08	trace	1,34E-09	5,19E-08	0	trace
NA+	KG/HR	0	56,04	56,04	56,04	0	trace
CN-	KG/HR	0,0939	0	0,0962	0,0961	0	trace
OH-	KG/HR	0,8505	41,46	41,43	41,4	0	trace
Comp. Mass Frac.							
WATER		0,999	0,5	0,998	0,9988	1	0,84
NAOH		0	0	0	0,00	0	0
NH3		4,88E-04	0	5,00E-04	1,51E-08	0	0,16
HCN		3,46E-08	0	7,94E-10	2,01E-09	0	6,22E-08
NH4+		1,38E-05	0,00	4,26E-07	1,18E-11	0	trace
H3O+		trace	trace	trace	trace	0	trace
NA+		0,00	0,287	7,98E-04	6,75E-04	0	trace
CN-		1,34E-06	0	1,37E-06	1,16E-06	0	trace
OH-		1,22E-05	0,213	5,90E-04	4,99E-04	0	trace
Phase: Liquid							
pH		10,68	17,53	12,08	10,57		
pH at 25 C		10,84	17,75	12,46	12,38		

Table C5 Simulation results in current operative conditions

	Current real value	Simulated value	Error %
WASTE WATER TO TREATMENT:			
Mass flow [kg/h]	70000	70000	0
pH	8,3	10,68	28,67
Temperature [°C]	30	30	0
NaOH SOLUTION TO TREATMENT:			
Mass flow [kg/h]	195	195	0
Temperature [°C]	30	30	0
Mass fraction:			
NaOH	50%	50%	0%
H_2O	50%	50%	0%
INLET SATURATED STEAM TO COLUMN:			
Mass flow [kg/h]	13000	13000	0
Pressure [bar]	2,2	2,2	0
INLET WASTE FLOW TO COLUMN			
Temperature [°C]	37	37	0
Pressure [bar]	about 1	1,5	
Main contaminants concentration:			
NH_3 [ppm]	500	500	0
NH_4Cl [ppm]	N.A.	0	
HCN [ppm]	1	1	0
COLUMN OPERATIVE CONDITIONS:			
Outlet condenser temperature [°C]	96	96,3	0,3125
Top pressure [bar]	about 1	1,05	
Bottom pressure [bar]	about 1,2	1,15	
Bottom temperature [°C]	103,5	103,6	0,097
OUTLET TREATED FLOW			
Mass flow [kg/h]	N.A.	95021	
Temperature [°C]	103,5	103,6	
Pressure [bar]	about 1,2	1,15	
Main contaminants concentration:			
NH_3 [ppm]	N.A.	0,02	
HCN [ppm]	N.A.	1	
Discharge pH at 25°C	≤ 9,5	12,38	

Table C6: Simulation error of the main process parameters

Cooling Tower Models

Cooling tower models are discussed below in order to illustrate the features and advantages of modelling at multiple levels. A schematic description of a cooling tower is provided in Figure C5.

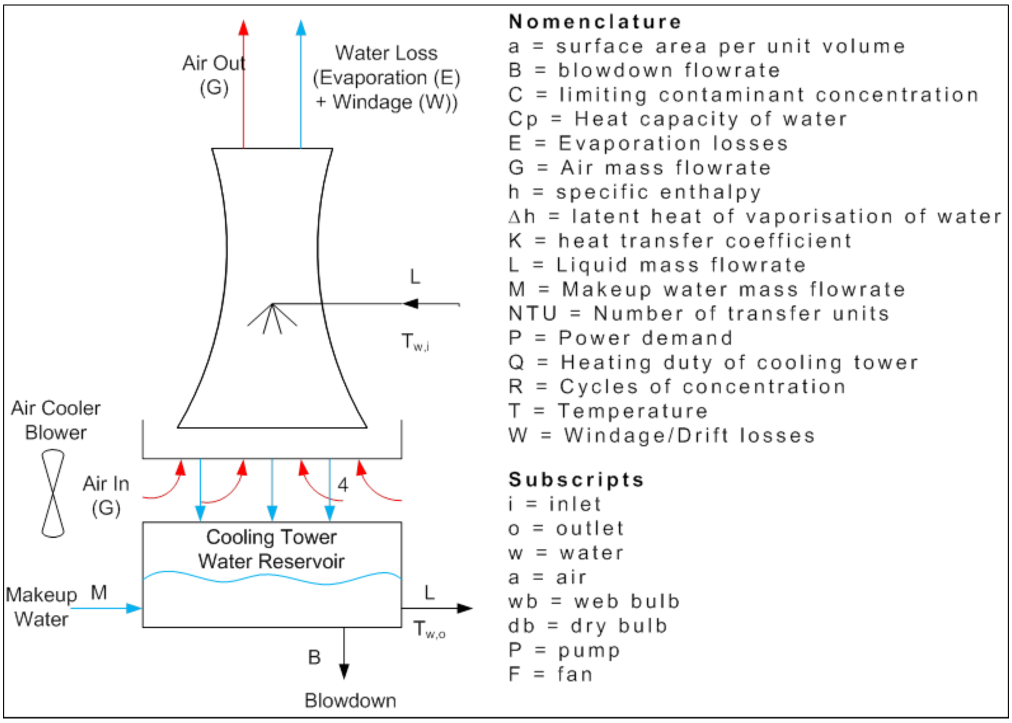


Figure C5. Cooling Tower Model Flow Diagram

Level 1 Model

This model is based on simple mass balance, energy balance and contaminant balance. Here properties of water such as density, specific heat, latent heat of vaporisation are assumed constant. Also simple correlations are developed for air side calculations and operating cost of fan and pump. Note that the resulting model is linear in nature and can be used for optimisation purposes.

Equations of this model are as follows:

1. Mass Balance $M = E + W + B$
2. Energy Balance $Q = L * Cp * (T_{w,i} - T_{w,o}) = E * \Delta h_w$
3. Contaminant Balance $M * C_M = B*C_B + W * C_W$

Assumptions / Thumb Rules:

4. Properties of water remain constant

i.e. density = 1000kg/m^3, specific heat = 4.186 kJ/(kg-K) and latent heat = 2276 kJ/kg

5. Outlet air from cooling tower is at saturated conditions. Thus $\Delta h_a = (h_{a,i} - h_{a,o})$ = constant
6. Drift losses = 0.2% of total water inlet

i.e. $W = 0.002 * L_i$ (Genskow et al., 2008)

Correlations used in this model are as follows:

7. Air Side Energy balance $G = Q / (\Delta h_a) = Q/59$
8. Fan power $P_F = 2.9716E\text{-}05 * L$ (Leeper, 1981)
9. Pump power $P_P = 4.616E\text{-}05 * G$ (Leeper, 1981)

Level 2 Model

This model also includes mass, energy and contaminant balance equations as stated in level 1 model. However properties of water like density, specific heat and latent heat are correlated with ambient conditions in this case. Also instead of assuming that air outlet stream is at saturated conditions for all operating points, equipment specific correlations are developed from publications by Lu & Cai (2002) and Goyal (2012).

Equations of this model are as follows:

1. Mass Balance $M = E + W + B$
2. Energy Balance $Q = L * Cp * (T_{w,i} - T_{w,o}) = E * \Delta h_w$
3. Contaminant Balance $M * C_M = B*C_B + W * C_W$

Water properties correlations as function of ambient temperature T (°C):

4. Density, $\rho = =-0.0048*T^2 - 0.0053*T + 1000.3$
5. Wet Bulb Temperature, $T_{wb} = 0.9422 * T - 1.2342$
6. Specific heat of water, $Cp = 3E\text{-}05 * T^2 - 0.0019 * T + 4.2103$
7. Latent heat of vaporisation, $\Delta h_w = -4.3187 * T + 2709.1$

Note that these correlations are developed internally by PIL for operating range around average ambient conditions at Tata Steel site (i.e. ambient temperature of 20°C and 85% relative humidity).

<u>Rating mode correlations – equipment specific</u>

From this section of the model, water outlet temperature ($T_{w,o}$) can be predicted from effectiveness (ϵ) factor using following equation:

8. $\epsilon = \frac{T_{w,i} - T_{w,o}}{T_{w,i} - T_{wb}}$ (Goyal, 2012)

Here water inlet temperature ($T_{w,i}$) is input variable while wet bulb temperature can be calculated from ambient temperature based correlation discussed above.

Now effectiveness factor (ϵ) is estimated by following correlation:

9. $\epsilon = \frac{1- e^{-NTU(1-m^*)}}{1-m^* e^{-NTU(1-m^*)}}$ (Lu & Cai, 2002)

where m* is ratio of air to water capacitance rate and is calculated by following correlation:

10. $m^* = c * (L/G)$, where $c = Cs/Cp$ (Lu & Cai, 2002)

while NTU stands for number of transfer units (NTU) and is calculated by following correlation:

11. $NTU = j * (L/G)^m$ (Goyal, 2008 and Lu & Cai, 2002)

where both *j* & m are both equipment specific constants and can be obtained by regression analysis over multiple operating data points.

Operating cost specific correlations remain same as in level 1:

12. Fan power $P_F = 2.9716E\text{-}05 * L$ (Leeper, 1981)
13. Pump power $P_P = 4.616E\text{-}05 * G$ (Leeper, 1981)

As can be seen here, level 2 model has fewer assumptions and take into equipment specific details. In this particular case, level 2 model is able to better predict air side flow rate and also both air and water side properties can be predicted as a function of ambient conditions. In particular cooling duty constraints and process changes in terms of L/G ratio can be studied using this model.

However equations involved in level 2 modelling are non-linear in nature. Adopting such equipment models in the later network retrofit optimisation work will result in an overall MINLP model. This could cause significant difficulties in solving the optimisation problem. On the other hand, to produce equipment specific models as level 2, equipment structural data and historical operating data are required; this could also be problematic in many cases.

Reverse Osmosis (RO)

Past investigations and experiments allowed to assess the recovery rate and quality of the permeated water and to define the basic operating parameters for running a (possibly new) industrial plant. These results are exploited here in order to assess the conditions in which RO can be evaluated as a solution for water re-use as well as to develop a simplified model of an RO unit to be used in WP4. In particular the following pre-conditions to use RO are considered:

- as the production of RO water is constant, it must be used to treat continuous wastewater flows: discontinuous operations can favour the biological fouling of membranes, unless they are stored with non-oxidizing biocides, which is however quite costly; moreover the production flow can be reduced by up to 70% of the project, therefore in absence of demand, the flow of osmotic water can be discharged or recirculated upstream with a useless increase of costs.
- RO is sensitive to biological and colloidal fouling and to scaling. With respect to these phenomena, the feed water parameters to check are:
  - For biological fouling the Total Bacterial or microbes concentration;
  - for colloidal fouling turbidity, TSS, SDI, TOC, Fe, Mn, Si and all metals that can precipitate as hydroxides;
  - For scaling Ca, alkalinity, sulphates, fluorides, Ba and Sr.

  The sensitivity to fouling and scaling also depends on the adopted membrane: within REFFIPLANT in most of the cases membranes for brackish water will be considered, which have a quite high recovery rate and an acceptable rejection rate on most of salts. Table D7 summarizes some threshold values for the above listed parameters which are typical for that kind of membranes and will be exploited within REFFIPLANT.
- In order to avoid fouling, pre-treatments must be applied, such as flocculation, chemical precipitation, multimedia filtration, ultra-filtration (UF). If UF is applied, the discharge of suspended solids and oils must be minimized so that the limits reported in Table 1 for fouling problems are respected. For instance in the application for the treatment of wastewater from HRM, a preliminary UF stage is needed to remove colloids.
- Membranes can be also subjected to degradation due to a chemical attack (e.g., oxidation by residual chlorine or frequent membrane cleaning) or physical stress (e.g., water hammer or excessive pressure drop), which decreases the performance leading to low salt rejection and higher TDS in the permeate. Table C7 also includes parameters to monitor and their typical limit value in order to avoid membrane degradation for the kind of membranes that will be considered within REFFIPLANT.

Problem	Parameter	Threshold value	Unit
Biological fouling	Microbes	1000	Colony forming units/ml
Colloidal fouling	Turbidity	1	NTU
	SDI	3	
	TOC	3	mg/l
	Fe	0.05	mg/l
	Mn	0.05	mg/l
	SiO_2	150	mg/l
	H_2S	0.1	mg/l
	Other metals	0.05	mg/l
Scaling	Ca hardness	L_{Ca}[2]	mg/l as $CaCO_3$
	SO_4^{--}	L_{SO4}[3]	mg/l
	Fluorides	L_F[4]	mg/l
	Ba	0.05	mg/l
	Sr	0.05	mg/l
Membrane degradation	Free Clorine	0.02	mg/l
	pH – normal operations	6-8	
	pH – cleaning operations	2-11	
	Temperature	40	°C
	Fe	0.05	mg/l
	Mn	0.05	mg/l
	Co	0.05	mg/l

Table C7: Limit values for properties and composition of the feed water to avoid fouling, scaling and membrane degradation.

The most relevant operating parameters for an RO industrial unit are:

- type and area A_m of the membranes;

[2] This threshold depends on the saturation index of $CaCO_3$ that is reached in the concentrate as a function of the recovery rate. Such index is computed through LSI

[3] This threshold depends on the saturation index of $CaSO_4$ that is reached in the concentrate as a function of the recovery rate.

[4] This threshold depends on the saturation index of CaF_2 that is reached in the concentrate as a function of the recovery rate.

- number of stages, as RO plants are usually composed by a series of cascaded single units. As this parameter affect both the recovery rate and the removal efficiency, the single stages will not be simulated within the project;
- N_m of the membranes per each stage: a common choice consists in adopting the same kind of membranes in all the stages, therefore the total membrane area A_{tot} can be computed by summing the areas of the membranes in each stage;
- temperature T (the colder the water, the higher the salt rejection as the TMP decreases)
- recovery rate r (i.e. the percentage of the feed water which is purified and becomes permeate): typical values for the industrial application of interest lie in the range 60%-75%;
- operating pressure (related to required water recovery rate);
- removal efficiency of the different contaminants (depending on the type of membrane);

Table C8 summarises the range of operating parameters that will be taken into account.
The adopted simplified RO model is a block taking as input a single water stream F with flow rate Q_F and outputting two streams, the permeate P with flow rate Q_P, which has a low salts content and is therefore re-used, and the concentrate C with flow rate Q_C, that has a high salinity and is usually discharged (provided it complies with current environmental regulations: this factor will be taken into account in the simulations). Obviously $Q_F=Q_P+Q_C$ and $Q_P=r \cdot Q_F$ and $Q_C=(1-r) \cdot Q_F$.

Parameter	Value range	Unit
No of membranes (in each stage)	5	
Membrane area	40-45	m^2
Operating temperature	10-35	° C
Operating input pressure	8-16	Bar
Water recovery rate	50-80	%

Table C8: Typical ranges of operating parameters

Each membrane is characterised by the so-called Trans-Membrane Pressure *TMP* that affects in a direct way the salt removal efficiency and must be referred to a specific reference temperature e.g. 20 or 25 °C: in fact the colder the water, the lower the TMP (thus the colder the water the lower the removal efficiency of the salts, but also the lower the energy consumption). A relevant parameter related to the TMP is the specific permeability $S_P=Q_p/(A_{tot} \cdot TMP)$, which therefore also depends on the water temperature.
In the model the content of each contaminant in the permeate is calculated from its associated removal efficiency which is given by $RE = 100\frac{[X]^F - [X]^P}{[X]^F}$, where $[X]^F$, $[X]^P$ and $[X]^C$ are the contents of the element or compound X in the feedwater, in the permeate and in the concentrate, respectively. The salts content in the concentrate is calculated through a mass balance. Typical performance ranges of a RO unit with membranes for brackish water are reported in Table C9.

Quality parameter	Value range in Feed water (mg/l)	Value in Permeate (mg/l)	Rejection rate %
Conductivity	2000	80	96
TDS	2300	46	98
Chloride	480	17	96.5
Sulphate	120	0.5	99.6
Fluoride	5	0.1	98
Nitrate	5	0.7	86
Bicarbonates (as $CaCO_3$)	165	9.1	94.5
Calcium	85	0.17	99.8

Table C9:Typical ranges of RO performances

10 Appendix D – List of potential solutions for water and energy efficiency (D2.1)

SSAB's solutions and their effect on Key parameters and performance indicators					
Potential solution	Contaminants	Operating costs for water network	Amount of fresh water	Amount of discharge	Comment
Optimised recirculation quenching water CC	X	X	X	X	Cost and energy savings mainly due to decreased need for pumping (energy saving). Concentration of contaminants in discharge may increase.
Optimised recirculation BF gas cleaning	x	X	X	X	Possible need for extra treatment before recirculation
Optimised recirculation cooling water CP		X	X	X	Cost and energy savings mainly due to decreased need for pumping
Reuse of water for slag quenching			X	X	Savings mainly due to decreased water consumption
Alternative primary cooling water CC		X	X		Savings of high quality water. Possible need for additional pretreatment on site.
Reuse of water for coke quenching	X		X	X	Use of rain water may lead to altered air emissions, but more stable water emissions.
Reuse of cooling water from BF cooling system			X	X	Might be used at the LD-process in the steel plant.
Quality of raw water to power plant	X	X	X		Additional on-site treatment/control may reduce the amount of municipal water.
Constant temperature of BF cooling water inlet temperature		X	X	X	A more even temperature in the inlet of cooling system will give a more stable flow and probably affect the need for maintenance and simplify the operation of the cooling system.
Alternative use of RH VD water	X		X		Possible need for extra treatment before reuse

Table D1: Potential solutions for a more efficient SSAB water system – influence on key parameters and performance indicators.

TATA STEEL's solutions and their effect on Key parameters and performance indicators					
Potential solution	Contaminants	Operating costs for water network	Amount of fresh water	Amount of discharge	Comments
CPS & TBH cooling - Quality of recirculating water	X	X	X	X	Additional on-site treatment/control may improve heat exchanger efficiency, cooling tower operation, reduce makeup water usage and reduce BD.
Concast Machine and Spray cooling – improve water quality	X	X	X	X	Reducing chlorides, SS and oil can lower maintenace costs, improve the product and improve discharge quality.
BOS Gas Clean – using rain water for makeup water			X		Additional makeup water from rain water storage can reduce fresh water usage.
BOS Gas Clean – lower SS and pH	X	X	X	X	May Lower maintenace costs. Improves discharge quality. May require better treatment or increased makeup water.
BF cooling water – Reuse of BD in e.g. BF GW, Pond A etc.	X	X	X	X	May improve quality of BF GW water. Can dilute NH3 in Pond A and Lagoon 1.
BF Gas Wash – Reduce SS & NH_3 concentrations	X	X	X	X	Additional on-site treatment/control may reduce SS (reduces maintenance costs / problems) and reduce NH_3 (discharge limits).
Lagoons - Water conservation by recovery and reuse of 1) lagoon 1 water, 2) streams flowing into lagoon 1	X	X	X	X	Treatment of the low quality individual process effluents before entering the main lagoon to recover the lagoon water for reuse instead of discharging into river. Treatment of lower flowrates may be much more cost-effective than treating the high flowrate from the lagoon.

Table D2: Potential solutions for a more efficient Tata Steel water system – influence on key parameters and performance indicators.

ILVA's solutions and their effect on Key parameters and performance indicators					
Potential solution	Contaminants	Operating costs for water network	Amount of fresh water	Amount of discharge	Comment
Partial reuse of blow down water from cooling system of PTG for direct cooling on the HSM2	X	X	X	X	Decrease of required high quality water amount. Decrease of discharge amount. Increase of water contaminant amount after direct cooling. Possible need for treatment before discharge.
Reuse of blow down water from CC No 1 for the off-gas cleaning of the BOF No 1	X	X	X	X	Decrease of consumption of water coming from Tara river. Decrease of discharge amount.
Reuse of blow down water from the cooling system of the OXIAL plant for the off-gas cleaning of the BF No 2	X	X	X	X	Decrease of consumption of water coming from Tara river. Decrease of discharge amount.
Reuse of blow down of the HSM1	X	X	X	X	Need for RO treatment before reuse.
Reuse of blow down of the coil washing at the CRM	X	X	X	X	UF is required before RO in order to remove oils and other colloids.
Reuse of blow down water from 17 AI for the off-gas cleaning of the BOF No 1	X	X	X	X	Decrease of consumption of water coming from Tara river. Decrease of discharge amount.
Reuse of blow down water from 41/2/3 AI for the off-gas cleaning of the BOF No 2	X	X	X	X	Decrease of consumption of high quality water Decrease of discharge amount. Possible need for treatment before reuse.
Reuse of water from A2 sheet mill equipment cooling for cooling operation in HRM2 plant	X	X	X	X	Decrease of consumption of high quality water Decrease of discharge amount.
Reuse of blow down water from 33 AI for the TUL1 pipe mill cooling	X	X	X	X	Decrease of consumption of high quality water Decrease of discharge amount.
Reuse of RIV2 blow down water from 52 AI for the TUL2 pipe mill cooling	X	X	X	X	Decrease of consumption of high quality water Decrease of discharge amount.
Reuse of RIV3 blow down water for the TUL2 pipe mill cooling	X	X	X	X	Decrease of consumption of high quality water Decrease of discharge amount.
Reuse of T12 blow down water from oxygen plant for cooling operation in HRM2 plant	X	X	X	X	Decrease of consumption of high quality water Decrease of discharge amount.
Recover through a second RO stage of concentrate stream of the biggest RO plant	X	X	X	X	Increase of high quality water for internal use.
Optimise ammonia stripping process	X	X	X	X	Savings of NaOH and steam flowrates.
Optimise gas washing process	X	X	X	X	Decrease of CN and consequently environmental impact.
Alternative use of process water streams for off gas cleaning	X	X	X	X	To be investigated in WP4.

Table D3: Potential solutions for a more efficient ILVA water system – influence on key parameters and performance indicators

11 Appendix E - Case studies on BF gas wash system

Tata Steel Blast Furnace Gas Wash Circuit

Provisional schematics of blast furnace gas wash circuit is shown in Figure E1. Note the stream numbers assigned in this schematic, as these numbers will be frequently referred to as subscripts in subsequent discussion.

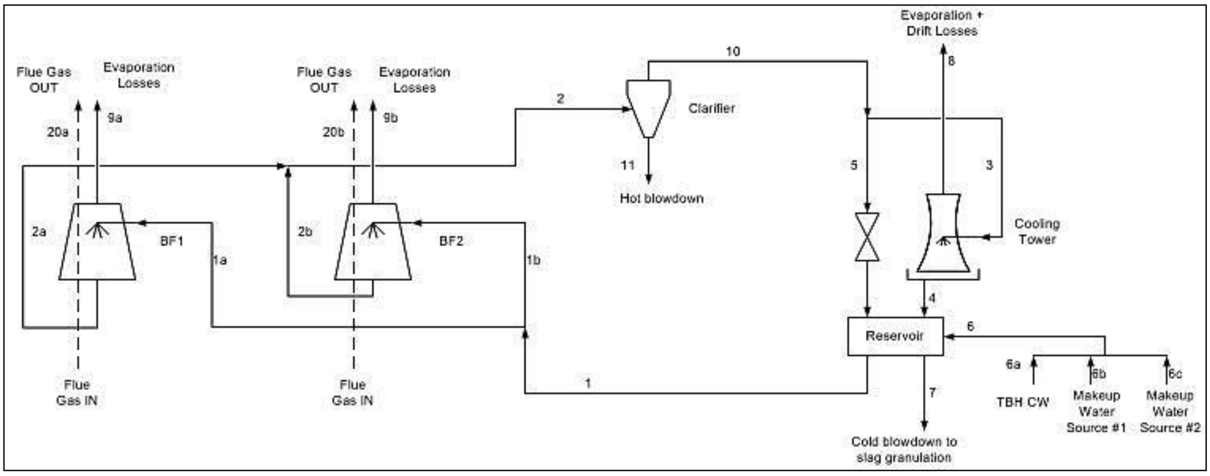


Figure E1. Provisional schematics of BF gas wash circuit

Given data from Tata Steel

Information provided by Tata Steel is listed below in points 1-3. As will be highlighted in subsequent discussions, this data is not enough to simulate the entire circuit and leaves the engineer with number of degrees of freedom. Here unknown parameters are estimated based on mass, energy and contaminant balance constraints and from typical values available in literature. Further these degrees of freedom are exploited to minimise the residual errors from such balances.

1. Provisional plant data provided by Tata Steel are reported in Table E1.

#	Stream	Temp. °C	Flow m³/hr	TDS ppm	TSS ppm	Cl ppm
1a	BF1 - Gas Scrubber Inlet	25	900	2594	33.5	630
2a	BF2 - Gas Scrubber Outlet	36				
11	Hot Blowdown from clarifier		35.4			
6b	Makeup water from source #1			715	8	101
6c	Makeup water from source #2			800	0	90

Table E1 Provisional plant data provided by Tata Steel

2. Operational observations
   a. Cooling tower bypass flowrate is greater than flow going into cooling tower (i.e. $F_5 > F_3$)
   b. 25% of TBH circuit blowdown is fed to BF GW circuit.
3. Simulation data from other water circuits
   a. Total makeup water from source #1 to BF = 83.7 m^3/h
   b. TBH circuit blowdown to lagoon 1 = 5.5 m^3/h

Calculations

Simulation work was carried out in two stages. In the first stage, flowrates of the streams are fixed based on mass and energy balance achieved from flowrate and temperature data available. Thereafter contaminant balance is worked out on the basis of these flowrates in the second stage. Steps involved in both these stages are explained below.

Stage 1 – Mass and Energy balance

Stream 1: Gas scrubber water inlet (F_1 = 1800 m^3/h; T_1 = 29°C)
Since both the blast furnaces (BF1 and BF2) have roughly same steel processing capacity, it is assumed that inlet water is equally divided into both of them. Thus $F_{1a} = F_{1b} = F_1 * 0.5$.
Stream 2: Gas Scrubber water outlet (T_2 = 36°C; F_2 unknown)
Estimation #1 - Water losses in each gas scrubber, $F_{9a} = F_{9b}$ = 22.5 m^3/h
Here it is assumed that water required to saturate the gas will be more than that required for quenching the gas. Secondly based on typical literature value, it is assumed that liquid/gas ratio used in scrubber is 10 US gallons/1000 ft³ (=0.002674 m^3 liq/m^3 gas). Thus gas flowrate can be estimated by dividing inlet water flow rate with this ratio. Thereafter based on standard

psychrometric correlations for air, water required to saturate the gas can be predicted. After water loss estimation, remaining water in the outlet can be calculated by simple subtraction.
Stream 11: Hot blowdown from clarifier bottoms (F_{11} = 35.4 m^3/h)
Here it is assumed that there is no temperature change across clarifiers. Thus $T_2 = T_{11} = T_{10}$
Stream 10: Overflow from clarifier ($T_{10} = T_2$ = 36ºC; F_{10} unknown)
Flow rate is calculated from mass balance across clarifier. $F_{10} = F_2 - F_{11}$ = 1755 - 35.4 = 1720 m^3/h
Stream 5: Cooling tower bypass (F_5 unknown; $T_5 = T_{10}$ = 36ºC)
Cooling tower bypass flowrate affects drift losses since these losses are a function of water inlet to cooling tower. However it is a very weak function and has little effect on overall mass balance and thus bypass flowrate can be safely considered as a degree of freedom in current version of the model. However following constraints helps in deciding this number:

a. $F_5 > F_3$
b. Cooling tower outlet temperature, $T_4 \geq$ 22ºC

Second constraint is based ambient conditions assumed for this case study i.e. 20ºC and 85% relative humidity. Also based on typical industrial practice, cooling tower approach temperature is fixed as 3.9ºC (or 7ºF). Thus theoretical minimum temperature to which water can be cooled down in cooling tower is calculated as 22ºC.
Assumption #1: T_4 = 22ºC
F_5 can be back-calculated from energy balance around the cooling tower reservoir box (shown in the PFD) if we assume temperature of stream 4 i.e. T_4. Here stream 4, 5 and 6 are incoming streams while 1 and 7 are exiting streams. As seen later, only two variables F_5 and T_4 remains unknown in this energy balance and hence F_5 is calculated as 907 m^3/h by assuming T_4 = 22ºC in this case. This assumption seems reasonable since it satisfies the first constraint i.e. $F_5 > F_3$.
Stream 3: Cooling tower inlet ($F_3 = F_8 - F_5$ = 1755 - 907 = 812 m^3/h; $T_3 = T_{10}$ = 36ºC)
Stream 8: Evaporation + Windage losses (F_8 unknown; T_8 =100ºC)
Estimation #2: Evaporation losses = 19.4 m^3/h
Evaporation losses are equal to cooling tower duty divided by latent heat of vaporisation. Here cooling tower duty is calculated by energy balance across the whole circuit. In this case,
Cooling tower duty = enthalpy added by gas scrubber - enthalpy removed by hot blowdown
Enthalpy added by gas scrubber = $F_2 * C_{pw} * (T_2 - T_1)$ = 1755 m^3/h *1000 kg/m^3 * 1 h/3600 s * 4.186 kJ/kg-ºC * (36ºC - 29ºC) = 14242 kW
Enthalpy removed by hot blowdown = $F_{11} * C_{pw} * (T_{11} - T_7)$ = 35.4 m^3/h *1000 kg/m^3 * 1 h/3600 s * 4.186 kJ/kg-ºC * (36ºC - 22ºC) = 287 kW
Therefore evaporation losses = cooling tower duty/ latent heat = (14242-287) kW / 2588 kJ/kg * 3600 s / 1 h / 1000 kg/m^3 = 19.4 m^3/h
Note that evaporation loss calculations are sensitive to temperature measurements which are not so accurate. Thus temperature can be changed up to 3ºC in order to match flow measurements. This provides another degree of freedom for engineer which can be used to satisfy mass balance.
Estimation #3: Windage losses = 0.2% of total water inlet = 1.6 m^3/h
0.2% is typical value obtained from Perry's handbook [1]. Therefore Windage losses = 0.002* F_3 = 1.6 m^3/h. Thus, F_8 = 19.4+1.6 = 21 m^3/h
Stream 4: Cooling tower inlet ($F_4 = F_3 - F_8$ = 812 – 21 = 791 m^3/h; T_4 = 22ºC)
Stream 7: Blowdown to slag granulation (F_7 unknown, $T_7 = T_1$ = 29ºC)
Since both water to gas scrubber and blowdown to slag granulation is sent from the same cooling tower reservoir, $T_7 = T_1$ = 29ºC.
Assumption #2: F_7 = 0
F_7 is not measured on site and thus is another degree of freedom available in current mass and energy balance. Here it is assumed as zero, however any other value assumed for F_7 shall not affect the mass balance, since it is only related to makeup water (F_6 = 102 + F_7).
Stream 6: Makeup water ($F_6 = F_{6a} + F_{6b} + F_{6c}$ = unknown; $T_{6a} = T_{6c}$ = 20ºC, T_{6a}= 33ºC)
Makeup water demand can be calculated from overall mass balance as shown below:
Makeup water = losses in gas scrubber + clarifier blowdown + losses in cooling tower
$F_6 = F_9 + F_{11} + F_8 + F_7$ = 45.6 + 35.4 + 21 + 0 = 102 m^3/h
Three sources contribute towards the makeup water for this circuit. These are TBH circuit blowdown (6b), water source #1 (6a) and water source #2 (6c). Their individual flow rates needs to be estimated in order to calculate resulting makeup water quality in terms of contaminants concentrations.
Estimation #3: TBH circuit blowdown to BF GW circuit, F_{6b} = 1.8 m^3/h
Blowdown from TBH circuit is sent into two destinations i.e. BF GW makeup and lagoon 1. As per operating manual guideline mentioned earlier, 25% of total blowdown shall be sent to BF GW circuit while remaining 75% to lagoon 1. From recent flow measurement campaigns around lagoons, it is measured that TBH blowdown into lagoon is 5.5 m^3/h. Thus TBH blowdown into BF GW circuit is calculated as, F_{6b} = 25/75 * 5.5 = 1.8 m^3/h.
Assumption #3 – Water Source #1 makeup to BF GW circuit, F_{6a} = 68 m^3/h
Water source #1 is supplied to two circuits of blast furnace namely BF OCC and BF GW. Total water supplied from source #1 to blast furnace is estimated by Tata Steel as 83.7 m^3/h, but their individual distribution in each of these circuits is unknown. Similarly water distribution from source

#2 in both these circuits is unknown. Thus makeup water flowrate is a degree of freedom and needs to be estimated in this case.
Here as an initial guess, it was assumed that same amount of makeup water is being used from both sources in BF OCC circuit. Since total makeup water demand is 31 m^3/h, water source #1 makeup to BF OCC = 15.5 m^3/h and as a result, F_{6a} = 83.7 − 15.5 = 68.2 m^3/h.
Rest of the makeup water demand is fulfilled by water source #2. Therefore F_{6c} = 102 − 1.8 − 68.2 = 32 m^3/h. However this is just an initial guess and these flowrates will be varied further in order to minimise errors in contaminant balance during next stage.

Stage 2 – Contaminant Balance

Contaminant balance is started from process inlet stream and is usually carried out in backward direction. Change in contaminant concentration can be predicted across cooling tower and various other mixing and splitting junctions based on contaminant load mass balance equations. However the contaminant level changes across process operations (e.g. gas wash or spray cooling) and treatment units (e.g. clarifiers or sand filters) cannot be estimated in this simulation. Typical literature values or additional plant measurements are required to characterise these processes.
Workings of contaminant balance calculations are presented below. Note that all contaminant concentration values mentioned here are in ppm.
Stream 1: Gas scrubber water inlet (TSS_1 = 33.5; TDS_1 = 2594, Cl_1 = 630)
Stream 7: Blowdown to slag granulation ($TSS_7 = TSS_1$ = 33.5; $TDS_7 = TDS_1$ = 2594, $Cl_7 = Cl_1$ = 630)
Both stream 1 & 7 come from cooling tower reservoir and hence will have same contaminant concentrations.
Stream 6: Makeup water (TSS_6 = 6, TDS_6 = 764, Cl_6 = 102)
Contaminant concentration of water source #1 & #2 are available from plant data, while TBH blowdown is available from TBH circuit simulations. Also from stage 1 flowrates of all these three water sources are known. Thus resulting contaminant concentration (say X) can be calculated by mass balance of contaminant load as shown below.
$F_6*X_6 = F_{6a}*X_{6a} + F_{6b}*X_{6b} + F_{6c}*X_{6c}$ where X can be either TSS, TDS or Cl
Stream 3, 5, 8, and 4: Streams around cooling tower (TSS, TDS, Cl unknown)
Contaminant calculations around cooling tower involve iterative procedure. Here contaminant concentration at the cooling tower inlet is assumed first and then the same is back-calculated from the contaminant balance. Thereafter initial guess is revised once again and this iteration continues until both guess value and calculated value match each other. These iterations can also be automated by using 'Goal Seek' function of MS-Excel. Here difference between guess value and calculated value can be set as zero and manipulated variable as initial guess value.
Calculations involved in this iterative procedure are described below.

a) Initial guess value for cooling tower inlet are assumed same as process inlet i.e. TSS_3 = 33.5, TDS_3 = 2594 and Cl_3 = 630
b) Both cooling tower inlet and bypass streams are from the same source i.e. clarifier overflow. Thus $X_{10} = X_5 = X_3$ where X is any of the three contaminant considered in this case.
c) Stream 4 contaminant values can be calculated from mass balance around cooling tower reservoir box as shown below.

$TSS_4 = (F_1*TSS_1 + F_7*TSS_7 - F_5*TSS_5 - F_6*TSS_6) / F_4$ = (1800*33.5-907*33.5-102*6)/791 = 37
Similarly TDS_4 = 2830 and Cl_4 = 698

d) Contaminant loss in cooling tower (stream 8) is estimated from stream 4 using following assumptions:
    a. None of the contaminants are transferred in evaporated water i.e. X_{evap} = 0
    b. Contaminants concentration in drift losses is same as inlet water i.e. $X_{drift} = X_3$

Thus $TSS_8 = (F_{evap}*TSS_{evap} + F_{drift}*TSS_{drift})/F_8 = TSS_{drift}*F_{drift}/F_8$ = 33.5*1.6/21 = 2.55
Similarly $TDS_8 = TDS_{drift}*F_{drift}/F_8$ = 2594*1.6/21 = 197.64 and $Cl_8 = Cl_{drift}*F_{drift}/F_8$ = 48

e) Finally stream 3 is back-calculated from mass balance around cooling tower as shown below.

$TSS_3 = (F_4*TSS_4 + F_8*TSS_8)/F_3$ = (791*37 + 21*2.55)/812 = 36.11, TDS_3 = 2762 and Cl_3 = 682

f) Now we can observe differences between initial guess and calculated contaminant values for stream 3 ($Error_{TSS}$ = 36.1 - 33.5 = 2.6, $Error_{TDS}$ = 2762 - 2594 = 168, and $Error_{Cl}$ = 682 - 630 = 52). These differences are termed as errors and will be minimised to zero by using iterative procedure as described above.

Stream 10: Clarifier overflow (TSS_{10} = 2672, TDS_{10} = 34.8 and Cl_{10} = 654)
As discussed earlier clarifier overflow is split into cooling tower inlet and bypass streams. Thus all these three streams have same contaminant concentrations.
Stream 2 & 11: Clarifier related streams
Estimation #4: TSS_2 = 101.6 ppm
As per UK Emissions report 'AEAT-6270 Issue 2' published by UK Department of Environment, Food and rural Affairs, average air side particulate emissions before gas scrubber is 300 g/t LS (grams per ton of steel produced) and it gets reduced to 30 g/t LS after passing it through gas scrubber [2]. Now steel production at Tata Steel site = 4.5 MT/yr = 513.7 kg/h. Thus total contaminant mass load transferred from gas side to water side = 513.7 kg/h * (300-30) g/t = 138699 g/h.

TSS mass load at the inlet = F_1*TSS_1 = 1800*33.5 = 60300 g/h. As discussed earlier, it is assumed that none of the contaminants are lost in water losses due to saturation in gas scrubber. Thus TSS mass load at gas scrubber outlet = 138699 + 60300 = 198999 g/h and TSS_2 = 198999/1755 = 113.4 ppm

Thereafter from contaminant balance around clarifier, TSS_{11} = (F_2*TSS_2 − F_{10}*TSS_{10})/F_{11} = 3933 ppm

Assumption #5: Only TSS concentration changes across clarifier

i.e. TDS_2 = TDS_{11} = TDS_{10} = 2672 ppm and Cl_2 = Cl_{11} = Cl_{10} = 654 ppm

Contaminant balance around gas scrubber

Due to mass transfer of contaminants from air side to water side, increase in contaminant concentration can be observed across the gas scrubber. As discussed above, total suspended solids are estimated to increase from 33.5 to 113.4 across the scrubber. While change in concentration for TDS and Cl can be inferred from the difference in contaminant levels between stream 1 & 2. Final simulation results are shown in Table E2.

#	Stream	Temp. °C	Flowrate m^3/hr	TDS ppm	TSS ppm	Chloride Ppm
1a	BF1 - Gas Scrubber Inlet	29	900	2594	33.5	630
1b	BF2 - Gas Scrubber Inlet	29	900	2594	33.5	630
9a	Air Saturation Losses	100	23	2594	0	630
9b	Air Saturation Losses	100	23	2594	0.0	630
2a	BF1 - Gas Scrubber Outlet	36	877	2672	113.4	654
2b	BF2 - Gas Scrubber Outlet	36	877	2672	113.4	654
7	Water into clarifiers	36	1755	2672	113.4	654
11	Hot Blowdown to BOS lagoon	36	35.4	2672	3933	654
8	Water after clarifiers	36	1720	2672	35	654
5	Cooling tower bypass	36	907	2672	34.8	654
3	Water into cooling tower	36	812	2672	34.8	654
	Evaporation Losses		19	0	0	0
	Drift Losses		2	2672	34.8	654
8	Evaporation + Drift Losses	100	21	206	2.7	50
4	Water exit cooling tower	22	791	2738	35.6	670
7	Cold Blowdown to Slag Granulation	25	0	2594	33.5	630
6	Makeup water	20	102	764	6	102
6b	Makeup water from TBH CW	33	2	1933	25	348
6a	Makeup water from source #1	20	68	715	8	101
6c	Makeup water from source #2	20	32	800	0	90

Table E2: Final Simulation for BF GW circuit

Systematic identification of measurement list

As seen in above exercise, a number of estimations and assumptions were made in order to fix the degrees of freedom. These estimations need to be validated with actual measurements. For instance, plant specific contaminant mass load changes observed across gas scrubber and clarifier needs to be validated with typical values used in this example. With this objective in mind, a measurement list was generated and is indicated in blue cells in Table E2.

Advantages of this approach are that number of measurement points necessary can be minimised and prioritised depending on the criticality and confidence on some of these estimation methods. Also convenient measurement points can be selected as all these points are connected together by mathematical correlations.

Future measurement campaigns can be planned based on this measurement list. However since these spot measurements will not be compatible with average plant data, these spot measurements will not be used as it is, rather they will be used as guiding principles to validate or fine-tune existing estimations.

ILVA BF gas wash cycle simulation

The ILVA BF gas wash system and wastewater treatment is represented in Figure E2.

In particular, the section of gas washing treats a volumetric gas flowrate inlet equal to 380,215 m^3/h. The section scrubber + demister works to minimize the evaporation losses, so the makeup water is reduced. To evaluate the evaporation losses, an energy balance has been carried out:

- Heat exchanged gas-water: $Q=m_{gas}cp_{gas}\Delta T_{gas}=m_{H2O}cp_{H2O}\Delta T_{H2O}+m_{H2O}(h^{*}-h_{SL})$
- Steam quality: $x_s=(h^{*}-h_{SL})/(h_{SV}-h_{SL})$
- Mass evaporated: $m_{eva}=x_s m_{H2O}$

Where the h* is the evaporating liquid enthalpy and it’s calculated from heat exchanged, x_s is the steam quality. From energy balance, the evaporation losses are 5.34 m^3/h. Stream results regarding the simulated circuit are reported in Table E3.

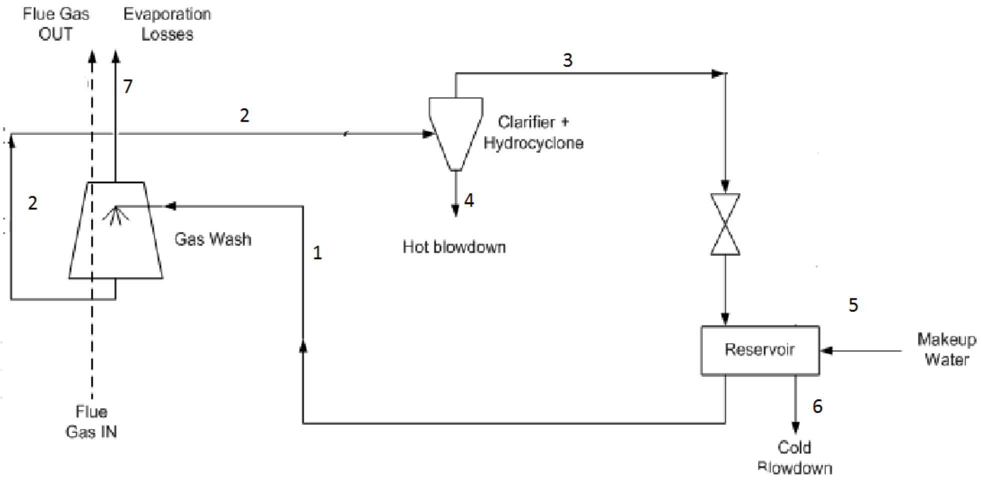


Figure E2 PFD of BF gas wash circuit

Flow Mass	Number	Unit	Value
Gas washer inlet	F1	m^3/h	1100
Evaporation losses	F7	m^3/h	5.34
Clarifier inlet	F2	m^3/h	1095
Clarifier blowdown (data plant)	F4	m^3/h	150
Clarifier overflow outlet	F3	m^3/h	945
Makeup water (data plant)	F5	m^3/h	150
Cold Blowdown (data plant)	F6	m^3/h	150
Concentration	Number	Unit	Value
Water inlet cont. conc.	F2	ppm	799
Slugde cont. conc.	F4	ppm	4367
Water overflow cont. conc.	F3	ppm	133

Table E3 - Water and contaminants mass balances in the BF gas washing circuit.

In the clarifier section, the water flow inlet is 1095 m^3/h (regarding the evaporation losses) and the clarifier blowdown is 150 m^3/h, so the clarifier overflow outlet is 945 m^3/h. The assumptions for the clarifier model are: sedimentation type I, spherical particles, adiabatic system, no change in pH, and laminar flow. The sizes of clarifier tank (cross sectional area of clarifier is 616 m^2) are necessary to calculate the limiting velocity of sedimentation, in this case equal 1.77 m/h.
The recovery ratio of total suspended solids is calculated on the basis of the particle size distribution, which is the basis for the calculation of total contaminant mass load for the overflow and sludge. The clarifier model values the contaminant concentration for the overflow water and sludge blowdown, in particular the water overflow concentration is 133 ppm and the sludge concentration is 462 ppm. The PSD also determines the removal efficiency (recovery ratio), as shown in Table E4.

Particle Size Distribution – Inlet Clarifier		
Particle Size (μm)	V_s (m/h)	Recovery Ratio
0.5	0.000637	0.000358
1	0.00258	0.00143
2.5	0.0159	0.00895
5	0.0637	0.0358
10	0.254	0.143
15	0.573	0.322
30	2.29	1

Table E4 - Particle size distribution data in the clarified.

12 Appendix F – List of potential solutions for waste minimization (D3.1)

Solutions and their effect on Key parameters and performance indicators										
Potential solutions	Company	Oil content	Water content	Zn content	Fe content	C content	Operating costs	Possibilities for re-use	Amount of disposal	Comment
Reuse of BOF fine sludge	SSAB		X	X	X	X	X	X	X	Cost saving due to reduced need for pellet and limestone. Landfill reduction.
BF dust injection	SSAB			X	X	X				Will make some space to other materials in the briquettes.
Reuse of ladle slag	SSAB						X		X	Cost saving due to reduced need for limestone. Landfill reduction.
Reuse of BF sludge	SSAB ILVA		X	X	X	X	X	X	X	Cost saving due to reduced need for pellet and carbon. Landfill reduction.
Recover secondary BOF dust	SSAB			X	X	X	X	X	X	Cost saving due to reduced need for pellet and carbon. Landfill reduction.
Increased reuse of BOF slag	SSAB ILVA				X		X	X	X	Separation of usable substances for utilisation in different external applications (es. P and Ca as fertilizer) and in internal recycling (es. Fe-rich pellets in sinter plant). Separation of different substances required. Cost saving due to reduced need for pellet and limestone. Landfill reduction (SSAB). Reduction of amount for recovery in internal quarry (ILVA).
R1 Process (distillation and pyrolysis of oily materials) for oil, water and not oily sludge/scale recovery.	ILVA	X	X		X		X	X	X	Reduction of amount of disposal (sludge). Separation of products (oil, water, not oily scale) and possible reuse. Energy-intensive, could increase operating costs.
Mill Scale washing process for not oily scale recovery.	ILVA	X	X		X		X	X		Improved not oily scale recovery possibilities. Degreaser use and water treatment/disposal could increase operating costs
Use of BOFS as fertilizing material.	ILVA						X	X	X	Reduce amount of material. Cost saving due to external use as fertilizer. Could affect soil fertility, crop yields and plant health. Heavy metals leaching must be evaluated.

Table F1: Potential solutions for a more efficient utilization of by-products and waste – influence on key parameters and performance indicators.

13 Appendix G - By - products and waste treatment models

R1 process model

The experimentation campaign is been the basis for the development of an Aspen Plus® model. The objective was the study of some parameters that can affect the oil removal from sludge/scale. Figure G1 shows the simulated flowsheet; the various plant parts are marked.

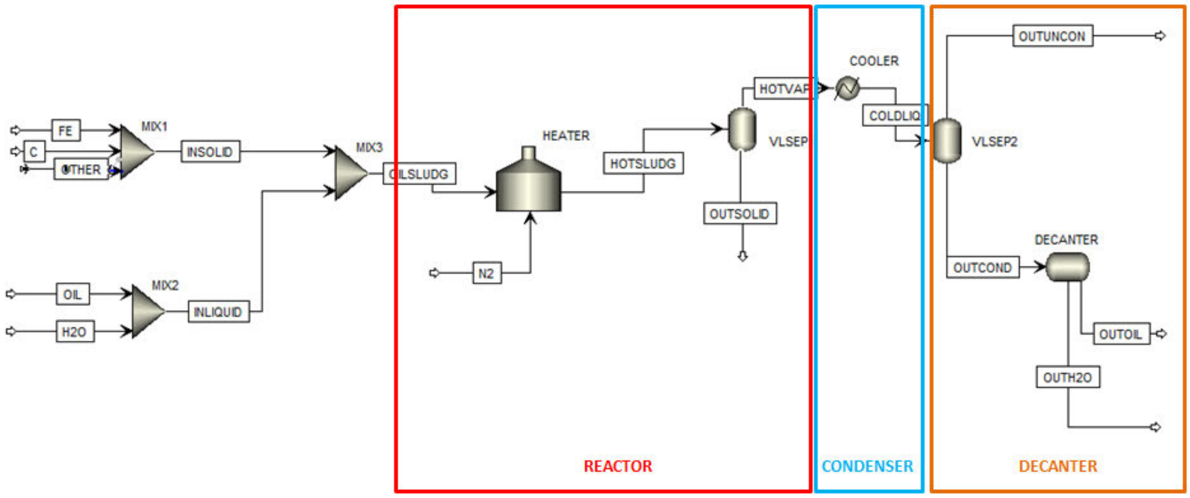


Figure G1: R1 Process simulated flowsheet

Some assumptions were required to develop the model:

- The oily sludge was simulated as a mixture of water, oil, inorganic components and elemental carbon.
- Oil is, in turn, an hydrocarbon mixture and so it was simulated as a mixture of pseudocomponents created by Aspen Plus from a typical distillation curve of a lubricant oil [8] shown in Figure G2. A light ends fraction and a given API gravity of 27.1 [8] were also included in oil model.

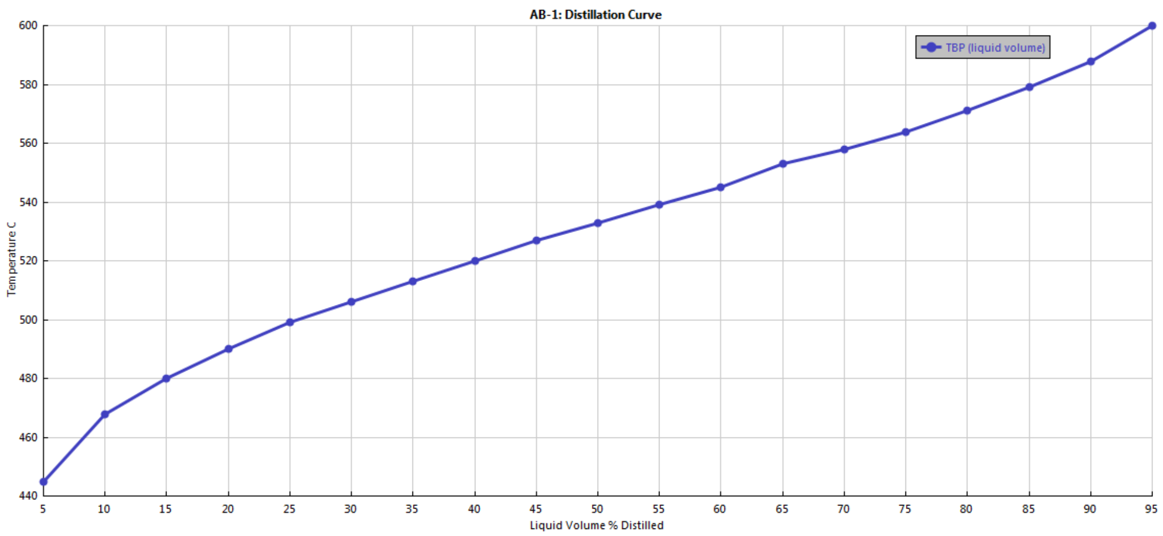


Figure G2: Lubricant Oil Distillation Curve

- The solid phase was simulated as a mixture of Fe compounds (FeO, Fe_2O_3 and Fe(0)), elemental carbon and other compounds; the composition of every stream is based on ILVA data on mill scale and it is shown in Table G1. The mass content of Total Fe is based on ILVA data on R1 experimentation sample.
- A typical mill scale particle size distribution is used in the simulation of Fe and other compounds streams [42].
- A typical carbon black particle size of 0-0.5 micron is used in the simulation of elemental carbon [43].
- N_2 mass flowrate was supposed.

The simulation was carried out only on sludge of hot rolling mill (A3) and mill scale (A5) due to the major amount of experimental data. Table G2 lists the operating conditions in the simulated cases. The simulation results for A3 samples are listed in Table G3 and are shown in Figures G3 and G4.

	Mass Fraction
Fe Compounds STREAM	
FeO	0.631
Fe_2O_3	0.351
Fe	0.018
Elemental Carbon STREAM	
C	1
Other Coumponds STREAM	
CI SOLID SUBSTREAM [% wt of total O.C. Stream]	51.9
S	0.0056
SiO_2	0.3082
Al_2O_3	0.0872
CaO	0.303
MgO	0.1877
TiO_2	0.0046
Mn	0.0712
P	0.0046
Na_2O	0.023
K_2O	0.0013
Cr	0.0002
Ni	0.0001
Pb	0.0023
Cu	0.0002
Zn	0.0008
MIXED SUBSTREAM [% wt of total O.C. Stream]	48.1
Cl_2	0.0078
CO_2	0.9922

Table G1: Mass fraction of solid phase.

Sample	A3	A5
OILY SLUDGE TO TREATMENT		
Mass Flow [kg/h]	1.95	2.50
Temperature [°C]	25	25
Oil [%wt]	9.44	1.36
Water [%wt]	5.44	7.36
TIC + Inorganic component [% wt]	85.12	91.28
ELEMENTAL CARBON STREAM		
Mass Flow [kg/h]	0.041	0.024
INORGANIC STREAM		
Mass Flow [kg/h]	1.66	2.28
Fe COMPOUNDS STREAM		
Mass Flow [kg/h]	1.25	1.87
OTHER COMPOUNDS STREAM		
Mass Flow [kg/h]	0.37	0.38
WATER STREAM		
Mass Flow [kg/h]	0.11	0.18
OIL STREAM		
Mass Flow [kg/h]	0.18	0.034
REACTOR (HEATER) OPEVATING CONDITIONS		
Temperature [°C]	600	610
Entrainment [%wt of solids]	0.0006	0.0006
N2 mass flow [kg/h]	0.005	0.005
COOLER OPERATIVE CONDITIONS		
Temperature [°C]	50	60

Table G2: Operating condition of R1 process model

Sample	A3
SOLID RESIDUE	
Mass Flow [kg/h]	1.484
Oil [% wt]	-
Water [% wt]	-
CONDENSATES	
OIL STREAM	
Oil recovered [kg/h]	0.18
Water in Oil stream [%wt]	0.05
Solids in Oil stream [%wt]	-
Oil removal efficiency [%]	>99.9
WATER STREAM	
Water recovered [kg/h]	0,10
Oil in Water stream [%wt]	0.01
Solids in Oil stream [%wt]	0,09
UNCONDENSABLES	
Mass Flow [kg/hr]	0,19
N_2 [%wt]	1.75
H_2O [%wt]	2.94
Other [%wt]	95.31

Table G3: Results of R1 process simulation with A3 sample

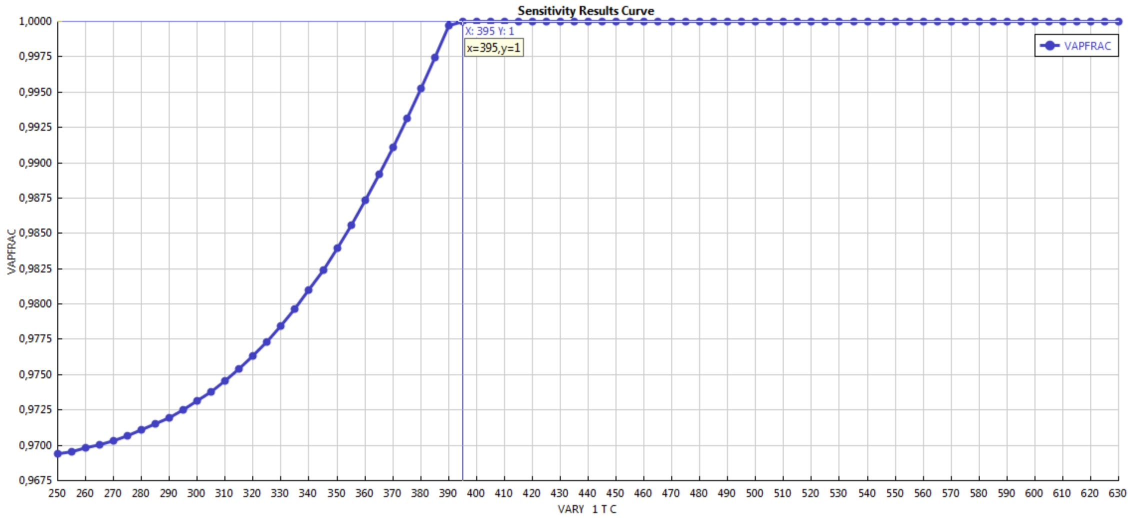


Figure G3. Trend of Vapour Fraction of Outlet Reactor Stream with changes in Reactor Temperature (A3 sample)

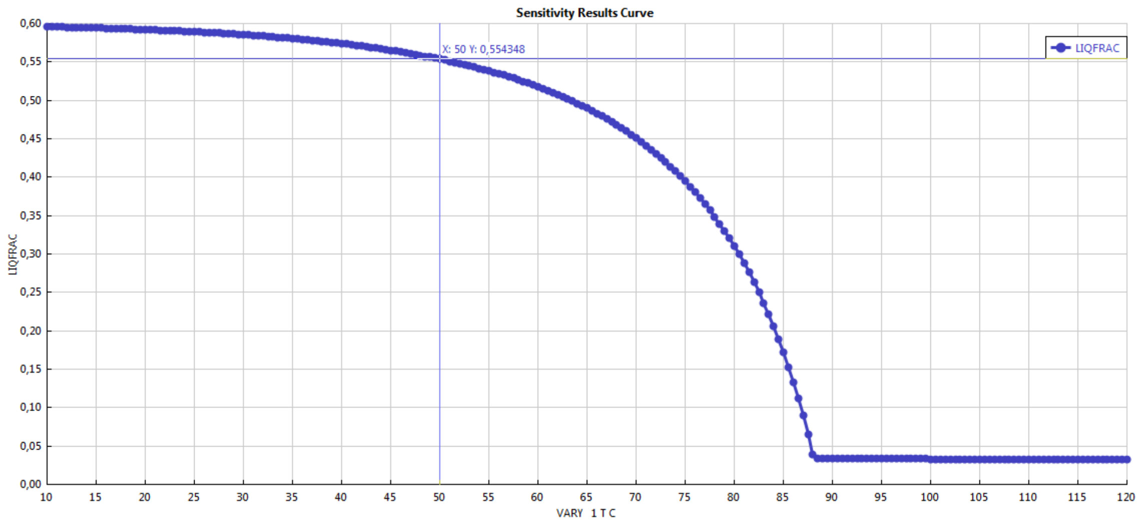


Figure G4 Trend of Liquid Fraction of Outlet Cooler Stream with changes in Cooler Temperature (A3 sample)

The oil removal efficiency in real and in simulation case is about 100% at the imposed operative conditions. The oil and water recovered are almost pure.

The analysis of the dependence of the reactor temperature on the vapour fraction (relative to the reactor outlet stream)shows that in a steady state process a temperature of about 395°C is sufficient to obtain total separation between solid and liquid (vapour fraction=1).
Furthermore, the trend of liquid fraction of outlet cooler stream VS cooler temperature shows that a temperature of about 50°C allows to obtain the condensation of the almost total condensable components; uncondensable gases prevent a liquid fraction of 1.
The simulation results for A5 sample are listed in the following Table G4 and are shown in Figures G5 and G6.

Sample	A5
SOLID RESIDUE	
Mass Flow [kg/h]	2.1
Oil [% wt]	-
Water [% wt]	-
CONDENSATES	
OIL STREAM	
Oil recovered [kg/h]	0.034
Water in Oil stream [%wt]	0.05
Solids in Oil stream [%wt]	-
Oil removal efficiency [%]	>99.9
WATER STREAM	
Water recovered [kg/h]	0,18
Oil in Water stream [%wt]	0.01
Solids in Oil stream [%wt]	0,07
UNCONDENSABLES	
Mass Flow [kg/hr]	0,21
N_2 [%wt]	2.43
H_2O [%wt]	7.71
Other [%wt]	89.86

Table G4 Results of R1 process simulation with A5 sample

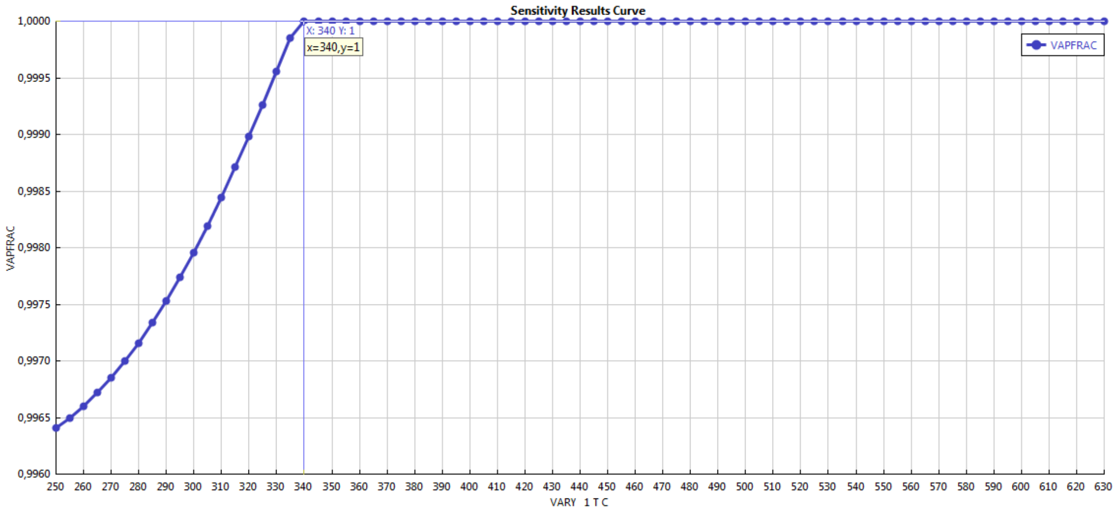


Figure G5 Trend of Vapour Fraction of Outlet Reactor Stream with changes in Reactor Temperature (A5 sample)

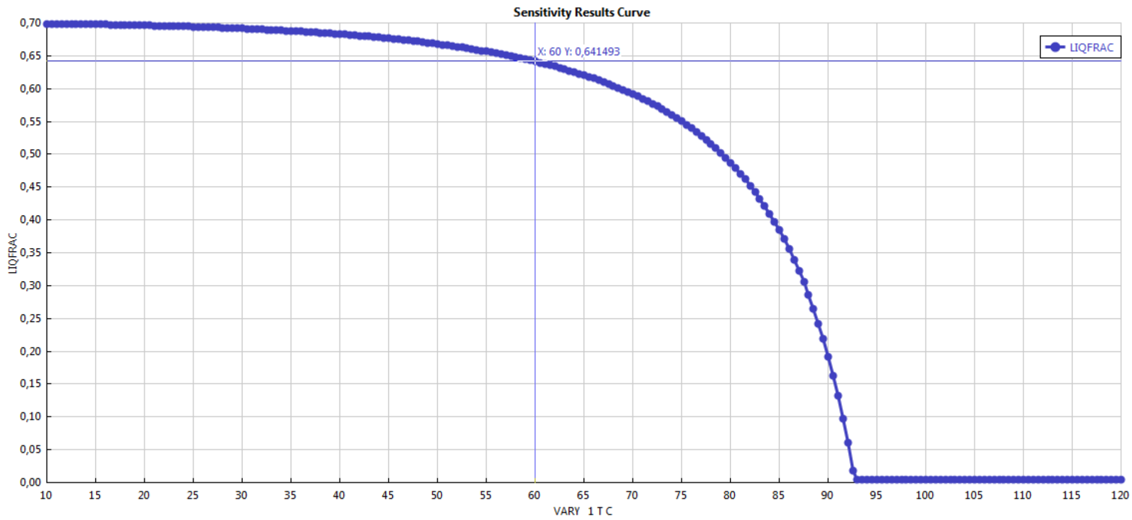


Figure G6 Trend of Liquid Fraction of Outlet Cooler Stream with changes in Cooler Temperature (A5 sample)

Similar consideration to the previous simulation may be carried out with regard to the simulation with A5 sample. The lower amount of oil allows to obtain the almost total vaporization of liquid phase at a lower temperature (about 340°C).
To highlight the dependence of total vaporization temperature with changing in oil content in the initial sludge (corresponding to change oil/water and oil/solids ratios) a sensitivity analysis was carried out. The results are presented in Figure G7, which shows that an increase in the oil content results in an increase in the temperature of total vaporization.

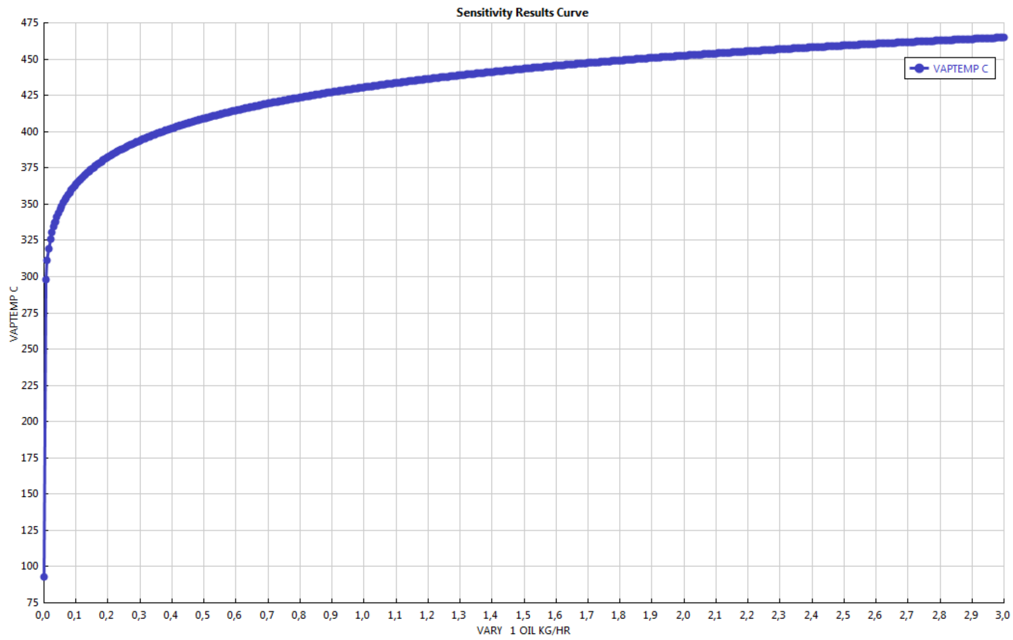


Figure G7. Trend of Temperature of total vaporization with changes in Oil Content in initial oily sludge. (A5 sample)

ILVA&SSSA Washing process model

SSSA developed an Aspen Plus® model based on ILVA experimental data about the oily scale washing process. The objective was the study of some parameters that can affect the oil removal from oily scale. Figure G8 shows the simulated flowsheet.

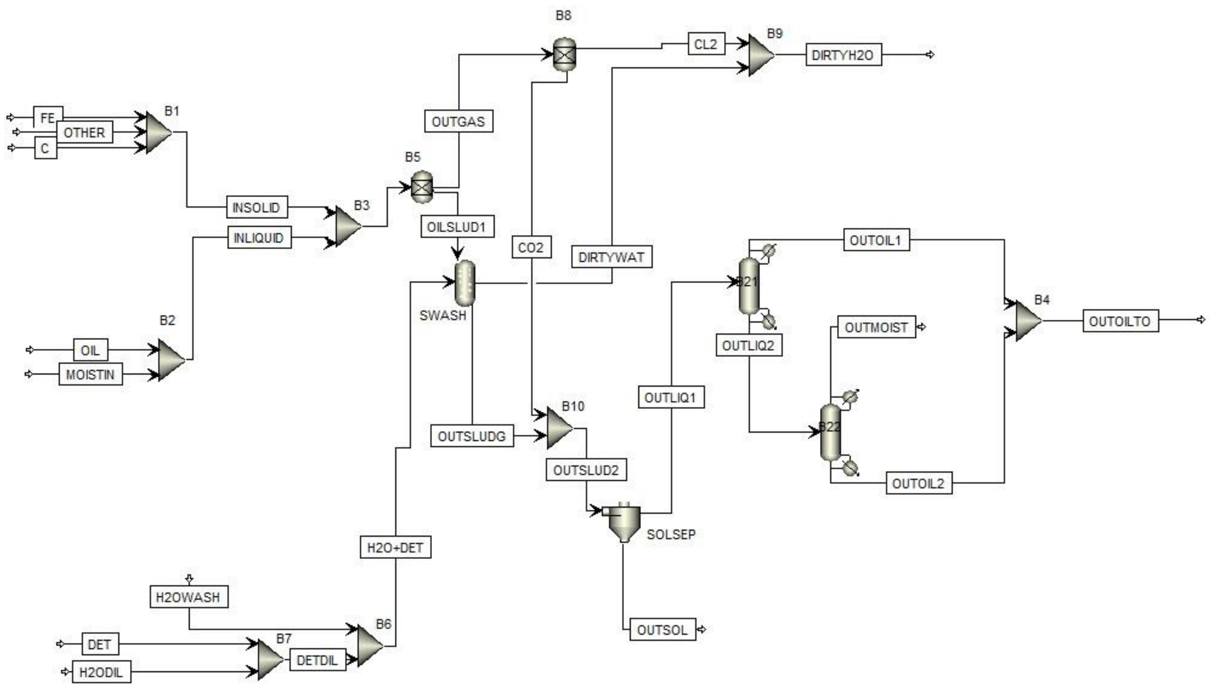


Figure G8: Washing Process simulated flowsheet

Some assumptions were required to develop the model:

- The oily scale was simulated as a mixture of moisture, oil, inorganic components and elemental carbon.
- Oil is, in turn, an hydrocarbon mixture and so it was simulated as a mixture of pseudo-components created by Aspen Plus from a typical distillation curve of a lubricant oil [41] shown in Figure G9. A light ends fraction and a given API gravity of 27.1 [41] are also included in oil model.
- The solid phase was simulated as a mixture of Fe compounds (FeO, Fe_2O_3 and Fe(0)), elemental carbon and other compounds; the composition of every stream is based on ILVA data on mill scale and it is shown in Table G1.
- A typical mill scale particle size distribution is used in the simulation of Fe and other compounds streams. [42]
- A typical carbon black particle size of 0-0.5 micron is used in the simulation of elemental carbon. [43]

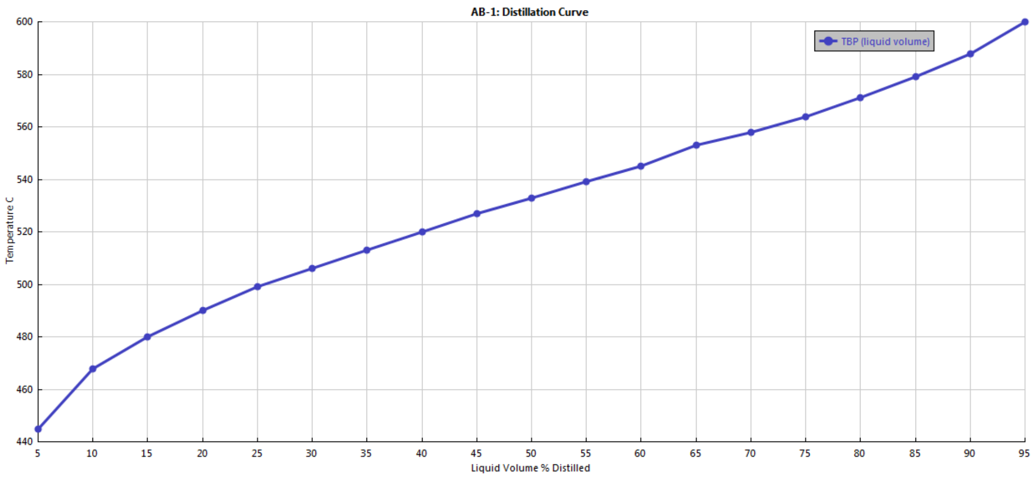


Figure G9: Lubricant Oil Distillation Curve

- Due to the lack of some physical properties in the Aspen Plus database, the degreaser was simplified assimilating it to an aqueous solution of only KOH with about a pH of 12 (the real degreaser has a pH of 12-14, and contains tetra potassium pyrophosphate, sodium silicate, KOH and etidronic acid, HEDP).
- For the purpose of the model and for its steady state nature, the process was considered composed of only a stage.
- Lost solids was neglected.
- Cl_2 loss in dirty water was considered.

The simulation was carried out on plate millscale at room temperature but some sensitivity analysis was carried out too to evaluate how the oil removal is influenced from some parameters (oil initial content, mixing efficiency, degreaser mass flow, water mass flow, treatment temperature). Table G5 lists the operating conditions in the simulated case.

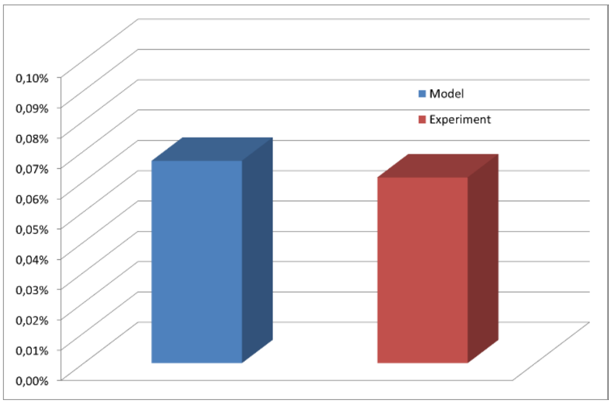
Sample	OILY PLATE MILL SCALE
OILY PLATE MILL SCALE TO TREATMENT	
Mass Flow [kg/h]	22.26
Temperature [°C]	25
Oil [%wt]	0.39
Water [%wt]	2.59
TIC + Inorganic component [% wt]	97.02
INORGANIC STREAM	
Mass Flow [kg/h]	21.59
ELEMENTAL CARBON STREAM	
Mass Flow [kg/h]	0.10
Fe COMPOUNDS STREAM	
Mass Flow [kg/h]	19.71
OTHER COMPOUNDS STREAM	
Mass Flow [kg/h]	1.78
MOISTURE STREAM	
Mass Flow [kg/h]	0.58
OIL STREAM	
Mass Flow [kg/h]	0.086
SOLID WASHER OPEVATING CONDITIONS	
Liquid-to-Solid Mass ratio	0.022
Mixing efficiency	0.78
DEGREASER STREAM	
Mass Flow [kg/h]	10
WASHING WATER STREAM	
Mass Flow [kg/h]	40

Table G5: Operating condition of Washing process model

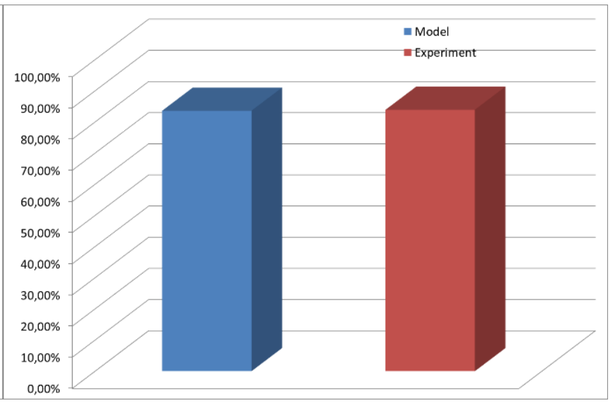
The simulation results are listed in the following Table G6 and are shown in Figure G10.

OUTLET TREATED SCALE	
Mass Flow [kg/h]	21.21
Oil [% wt]	0.07
Water [% wt]	2.18

Table G6: Results of Washing process simulation



(a)



(b)

Figure G10: (a) Oil content in outlet treated scale; (b) Oil removal efficiency

The experiment and model have similar oil removal and the oil content in outlet scale satisfies AIA prescription to reuse millscale in sinter production. The trend of oil removal with change in some parameter was studied. The results are showed in Figures G11-G14.
The analysis of the dependence of the oil removal on the washing water mass flow shows that 40 kg/h of only water is sufficient to obtain about 85% of oil removal. With the increasing of washing water the oil removal efficiency asymptotically stabilizes (see Figure G11). The degreaser mass flow poorly affects the oil removal maybe (see Figure G12.a), as the degreaser type is not appropriate. On the other hand, the mixing efficiency of the solid washer hardly affect the oil removal and so a good mixing must be ensured (see Figure G12.b).

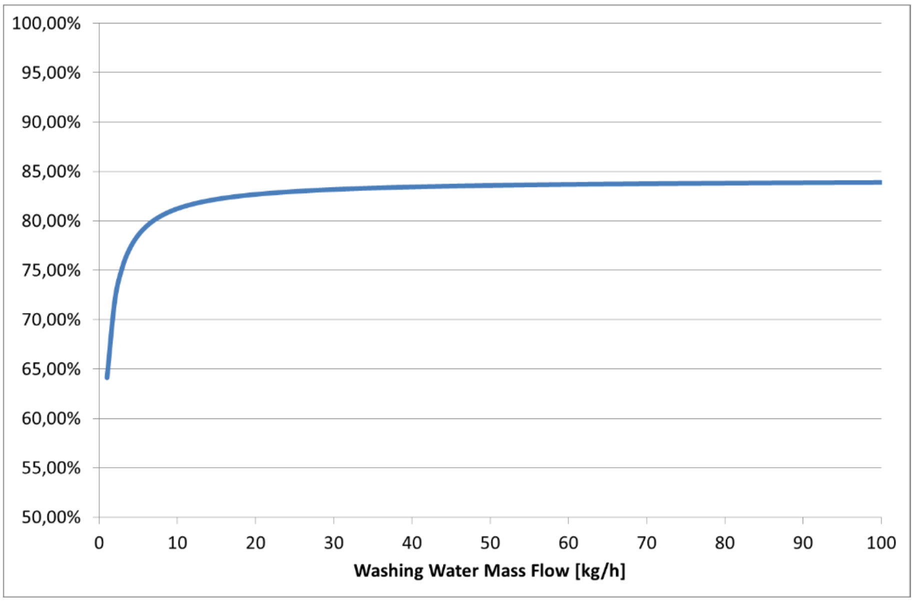
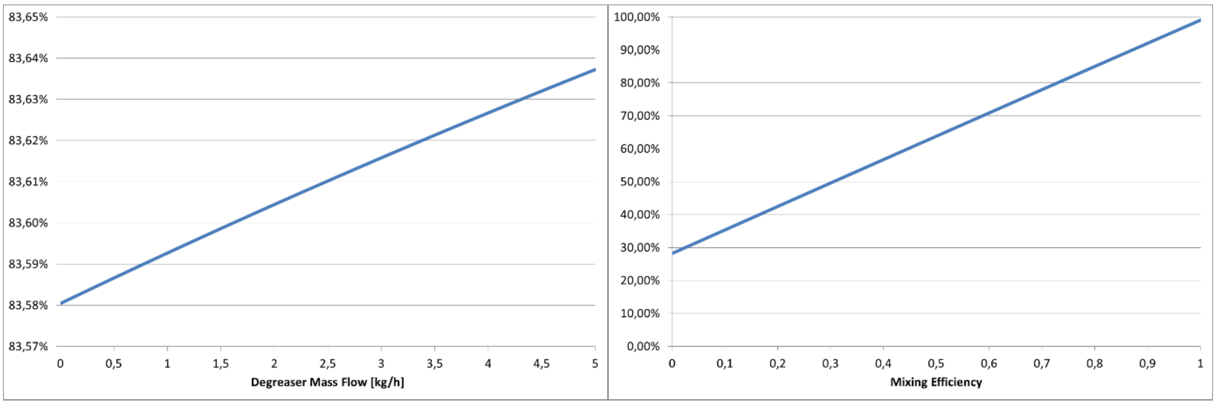


Figure G11. Oil Removal vs. Washing Water Mass Flow without degreaser.



(a) (b)

Figure G12. (a) Oil Removal vs. Degreaser Mass Flow and fixed Washing Water Mass Flow; (b) Oil Removal vs. Mixing Efficiency of Solid Washer

Figures G13 and G14 show that the more initial oil content, the more oil removal efficiency even if the oil content in the treated scale is higher.

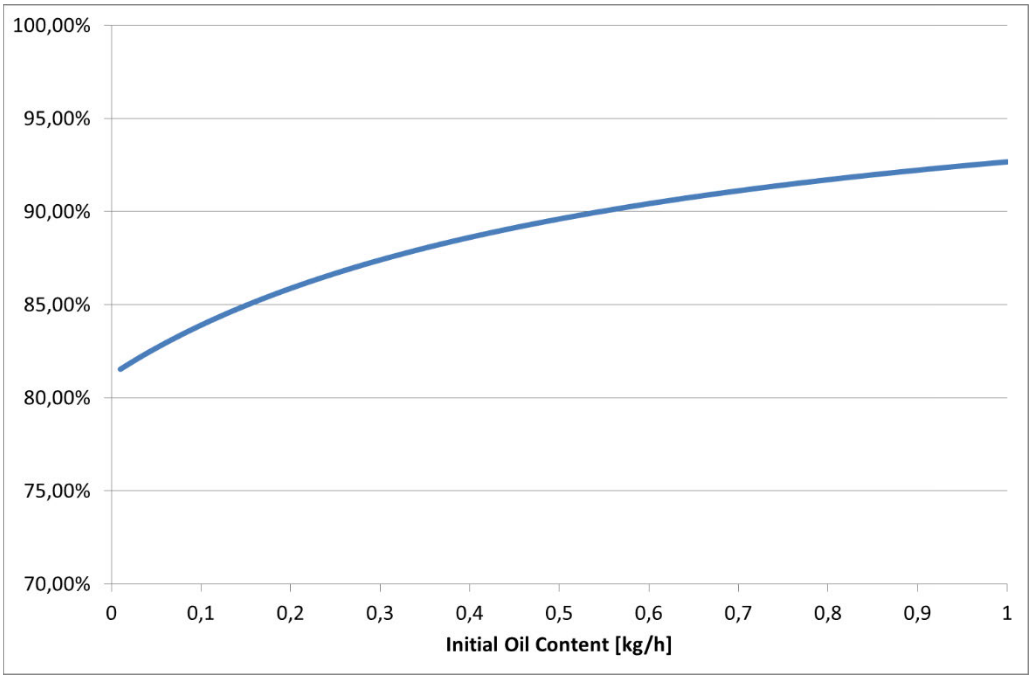


Figure G13. Oil Removal vs. Initial Oil Content.

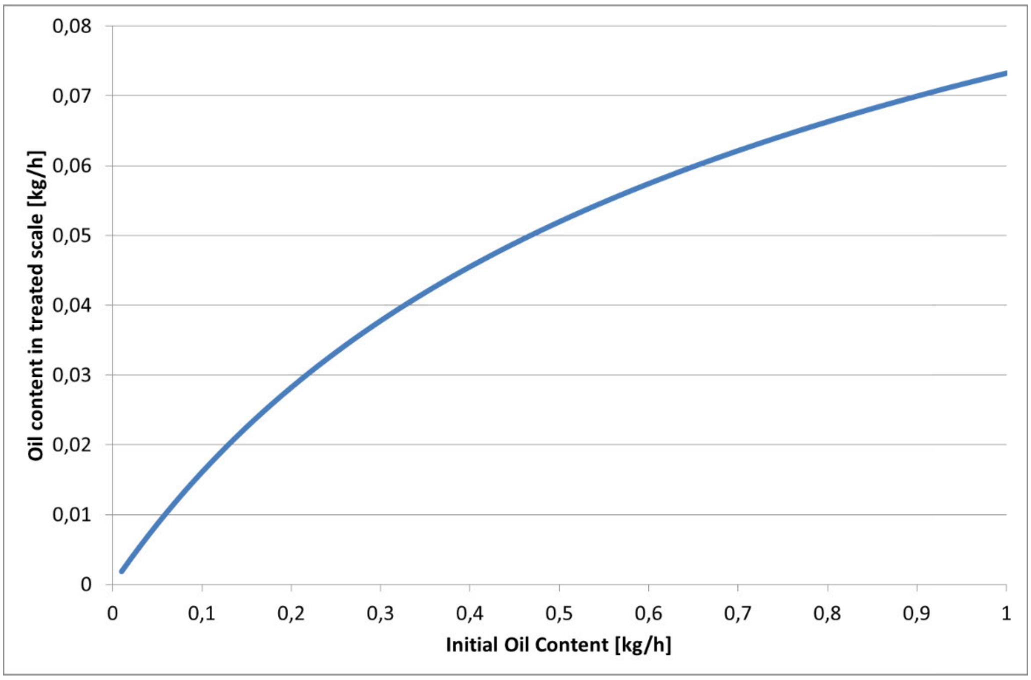


Figure G14. Oil content in treated scale vs. Initial Oil Content.

A same analysis was carried out with change in the treatment temperature until 70°C and it shows that the temperature does not affect appreciably oil removal.
With regard to these analysis it is possible to conclude that a high oil removal from millscale can be achieved with a good compromise between washing water content, mixing and a good choice in degreaser type.
To remove more efficiently the oil from millscale can be suggested to use more stages and so to remove dirty water every stage. The stages should have a different length and different amount of water and degreaser in each stage: for instance, a greater amount of water and degreaser must be used in the initial stages in which oil is more concentrated.

14 APPENDIX H - Holistic simulation models for MOO (D4.1)

14.1 Holistic simulation models - water

Hereinafter the holistic models library is presented, including the main treatments and processes representations involved in the industrial case studies to analyze, which was added up in common with all the research partners.

Cooling tower

PIL developed an Excel-based holistic model for a cooling tower derived from the model depicted in detail in Appendix C and shown in Figure C5.

Input data for the cooling tower are:

- The allowable temperature rise across the water side during process cooling ΔT;
- the water circulation flowrate across the process cooler *C*;
- the contaminant concentration in the cooling water sump CC_c;
- the contaminant concentration in the makeup water CC_m;
- the density of water in cooling tower sump;
- Chemical Engineering Plant Cost Index for the present year *CEPCI*;
- the ambient temperature $T_{ambient}$;

The model is able to calculate as outputs:

- the cycles of concentration for contaminants *R*;
- the cooling tower duty *Q*;
- the evaporation rate *E*;
- the water loss in cooling tower due to windage *W*;
- the blowdown flowrate *B*;
- the makeup water demand *M*;
- the cooling water supply and return temperature across the process;
- the cooling tower approach temperature with respected to wet bulb temperature;
- the power consumption in circulating pumps;
- the power consumption of fan in case of forced draft cooling tower;
- the purchased capital cost of cooling tower;

Nomenclature[5]

C = Water circulation
G = Air flow rate
M = Makeup water flowrate
W = Windage losses
E = Evaporation losses
B = Blowdown
CCm = concentration of limiting contaminant in the makeup water, ppm
CCc = concentration of limiting contaminant in circulating water, ppm
R = Cycles of concentration = Pc/Pm
ΔT = Temperature change in water during process cooling
Q = Cooling Duty

Main assumptions

1	Ambient Temperature =	ºC	20
2	Limiting contaminant		Chloride
3	Relative humidity of site		85%
4	Water loss through Windage		0,2%
5	Cooling Tower water outlet temperature is same as ambient temperature		
6	Pump Efficiency (η)	%	95%
7	USD to GBP conversion rate	-	1,6

Main equations for the unit model

Mass balance:	$M = E + W + B$
Contaminant mass balance (Cl in this case):	$M * Pm = (B + W) * Pc$
or	$M = (B + W) * R$
combining eqn (1) and (2) we get	$E + W + B = B*R + W*R$
After rearragement	$B = E / (R - 1) - W$
Energy Balance:	Cooling duty (Q) = heat of evaporation
	$C * Cp * \Delta T = E * \Delta H$
	$E = C * Cp * \Delta T / \Delta H$
Thumb Rule:	$W = 0.002 * C$
	$R = 5$
Air Side - Energy Balance	$G = Q / (\Delta H_{air}) = Q / 59$

i.e. cooling duty = (specific enthalpy difference between air inlet and outlet)*air flow rate

Correlations:	$T_{wb} = 0.9422 * T_{ambient} - 1.2342$

[5] all flowrates are in mass basis (kg/h) in this model

P_P = 2.9716E-05*C
P_F = 4.616E-05*G

Gas scrubber

PIL developed an Excel-based model for a gas scrubber, which is summarized in Figure H1.

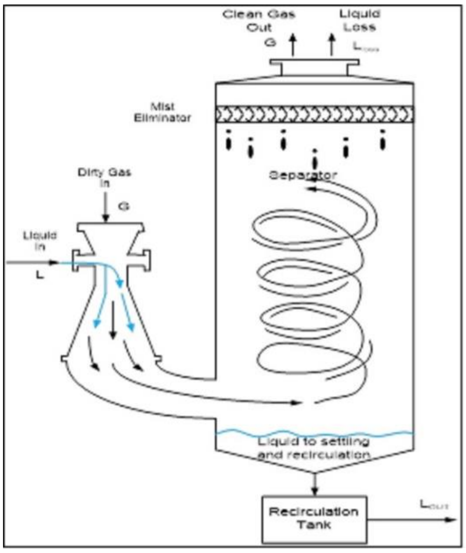


Figure H1: Gas Scrubber holistic model

Input data for the gas scrubber are:

- the inlet water flowrate to gas scrubber;
- the total suspended solids concentration in the inlet water stream;
- the desired liquid to gas ratio in the gas scrubber;
- the desired suspended solids concentration in the gas outlet;
- slope and intercept values for the empirical correlation (to be curve fitted from available operational data);

Model is able to calculate as outputs:

- the volumetric flowrate of outlet gas
- the water loss in saturated outlet gas;
- the particle capture efficiency;
- the evaporation rate;
- the suspended solids concentration in inlet gas stream;
- the suspended solids concentration in outlet water stream;

Nomenclature

L = Liquid In flowrate
G = Gas In Flowrate
L/G ratio = Liquid/Gas flowrate ratio
L_{loss} = water lost along with gas
L_{out} = net water exit from the scrubber system
$T_{G,in}$ = Gas Inlet temperature
$T_{G,out}$ = Gas Outlet temperature (35ºC assumed)
$X_{G,in}$ = contaminant concn. In gas inlet
$X_{G,out}$ = contaminant concn. In gas outlet
$X_{L,in}$ = contaminant concn. in total liquid inlet
$X_{L,out}$ = contaminant concn. in liquid outlet
Z = particle size, µm

Main equations for the unit model

Mass Balance $L = L_{loss} + L_{OUT}$
Contaminant Balance $L_{out}*X_{L,out} - L*X_{L,in} = G*X_{G,in} - G*X_{G,out}$

Assumption / design parameters:

Exit gas is satuared @35ºC
Evaporation losses will be less than water requirement for gas saturation
L/G ratio = 10 gallon liquid / 1000 ft^3 gas = 0.0013368 m^3 liq / m^3 gas

Resulting equations

L_{loss} = 1.9373E-05 * G
L = 0.0013368 * G

Particle capture efficiency (η)

$\eta = 1 - (X_{G,out} / X_{G,in})$
η = 10^ (M*log(z) + C) or log(η) = M*log(z) + C

Pumps

PIL developed an Excel-based model for a water pump, which is depicted in Figure H2.

Input data for the pumps & piping systems are:

- the inlet water flowrate;
- the elevation difference between suction and discharge points;
- the total length of the pipe;
- the fluid density;
- the pump efficiency (based on performance curves)
- the cost of the electricity
- the number of operating hours per year;

Model is able to calculate as outputs:

- the diameter of the pipe;
- the pressure drop across the pipe length;
- the pressure increase across the pump;
- the power consumption of the pump;
- the annual operating cost of the pump.

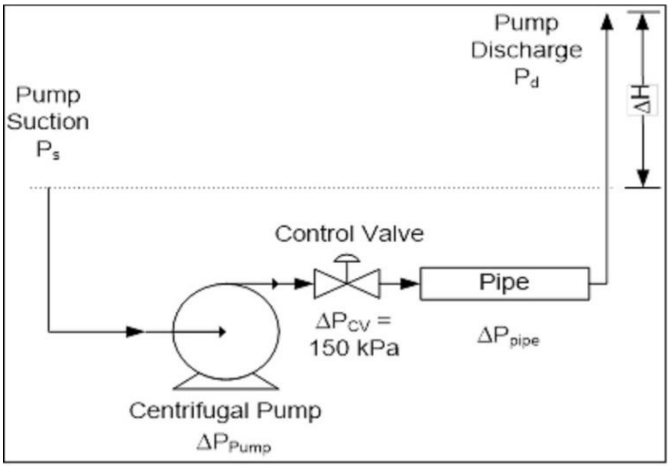


Figure H2: Pump holistic model

Nomenclature

L = pipe length between source and destination

ΔP_{pipe} = pressure drop across pipe length

ΔP_{CV} = pressure drop across control valve

ΔP_{pump} = pressure increase generated by pump

P_s = suction pressure

P_d = discharge pressure

ΔH = Elevation difference between suction and discharge pt

r = density of fluid (water in this case)

η = pump efficiency

F = Fluid flowrate, m^3/h

J = Power consumed by pump

C = Cost of power supplied

D = pipe diameter

A = cross-sectional area of pipe

Main equations for the unit model

Pressure balance $\Delta P_{pump} = \Delta P_{CV} + \Delta P_{pipe} + (\Delta H*9.8*r)$

Assumption / design parameters

Pipe velocity, V = 2 m/s

Fluid density, r = 1000 kg/m^3

Control valve pressure drop, ΔP_{CV} = 150 kPa

Pump efficiency, η = 65%

$P_s = P_d$

Piping pressure drop = 0.23 psi/100 ft = 5.2E-04 bar/m

Miscellaneous Calculations

Area of pipe	A = F/V
Pipe diameter	D = (A*4/π)^0.5
Power consumption	$J = F * \Delta P_{pump} / \eta$
Annual Operating Cost	C = J*0.07*8400/3600

Hydrocyclone

PIL developed an Excel-based model for a HC, which is depicted in Figure H3.
Input data for the clarifier model are:

- The cut-point of the HC i.e. size of the particle that has a 50% chance of leaving in either the underflow or overflow;
- the separation index of the HC (it is used as an empirical parameter which is obtained by curve fitting of empirical correlation on available operational data);
- the inlet volumetric flowrate;
- the flow ratio between outlet and inlet flowrates;
- the density of inlet water stream;
- the total suspended solids concentration in the HC inlet;
- the suspended solids particle size distribution;
- the total suspended solids concentration in the bottom sludge stream;

Model is able to calculate as outputs:

- the suspended solids concentration in HC outlet
- the suspended solids particle size distribution in the outlet and sludge streams;
- the removal ratio or the separation efficiency of the HC;

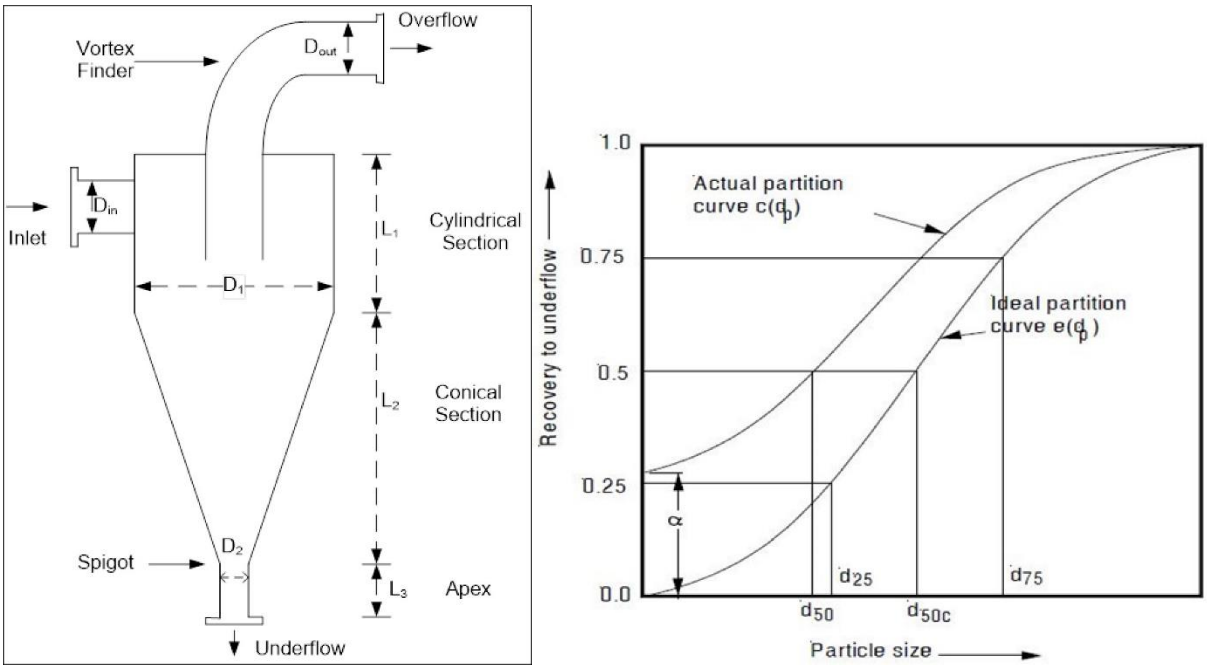


Figure H3: Hydrocyclone holistic model

Main Assumptions

1. Centrifugal force field >> gravitational field
2. d_{50c} & SI are function of HC geometry and remains constant irrespective of the variation in flowrate and/or suspended solids concentration
3. Short circuit fraction (α) will be varying as a function of suspended solids mass load
4. Density of water = 1000 kg/m^3. This assumption enables to use units (m^3/h and t/h) interchangeably

Main equations for the unit model

Global mass balance:

$$M_{IN} = M_{OF} + M_{UF}$$

Global mass balance on solids:

$$M_{IN} * TSS_{IN} = M_{OF} * TSS_{OF} + M_{UF} * TSS_{UF}$$

Empirical performance Model

$$SI = d_{25}/d_{75}$$

$$x = d_p/d_{50c}$$

1. Rosin-Rammler Model

$$e(d_p) = 1 - \exp(-0.693x^{\lambda})$$

2. Exponential Sum Model

$$e(d_p) = \frac{\exp(\lambda x) - 1}{\exp(\lambda x) + \exp(\lambda) - 2}$$

$$SI = \frac{\ln[(\exp\lambda + 2)/3]}{\ln[3\exp\lambda - 2]}$$

$$\lambda = 1.099\frac{(1+SI)}{(1-SI)}$$

3. Logistic Model

$$e(d_p) = 1/(1 + x^{-\lambda})$$

$$(SI)^{-\lambda} = 9$$

$$SI = \exp(-2.1972/\lambda)$$

$$\lambda = \frac{-2.1972}{\ln(SI)}$$

$$SI = \exp(-1.572/\lambda)$$

$$\lambda = \frac{-1.572}{\ln(SI)}$$

$$c(dp) = e(dp) + a$$

Note: Logistic model was selected for Tata Steel case studies due to closer match with measured PSD data

Clarifier

SSSA developed an Excel-based model for clarifier unit, which is presented in detail in Appendix C and is depicted in Figure C1.

Input data for the clarifier model are:

- the surface area of the tank;
- the temperature of the system, which is considered isothermal;
- the pH value of the water inlet stream (the clarifier unit has the objective to remove solids in the stream and changes in pH are therefore negligible);
- the water dynamic viscosity;
- the density of inlet water stream;
- the mean particle diameter of solids contaminants;
- the particle density;
- the inlet mass flowrate;
- the contaminant concentration in inlet stream;
- the sludge outlet moisture.

Model is able to calculate as outputs:

- the inlet volume flowrate;
- outlets temperature;
- the pH value of coarse stream;
- the mean particle diameter;
- the limiting velocity for sedimentation;
- the settling velocity;
- the removal ratio;
- the inlet contaminant mass flow;
- the outlet mass flow of sludge stream;
- the outlet contaminant mass flow in sludge;
- the outlet water mass flow in sludge;
- the mass contaminant concentration in sludge stream;
- the outlet mass flow of overflow stream;
- the outlet contaminant mass flow in overflow;
- the outlet water mass flow in overflow;
- the mass contaminant concentration in overflow stream.

Activated sludge

An Excel-based Activated Sludge Model was developed by SSSA which is a simplified version of the extended Matlab-based model presented in detail in Appendix C. Figure H4 shows a block diagram of the model.

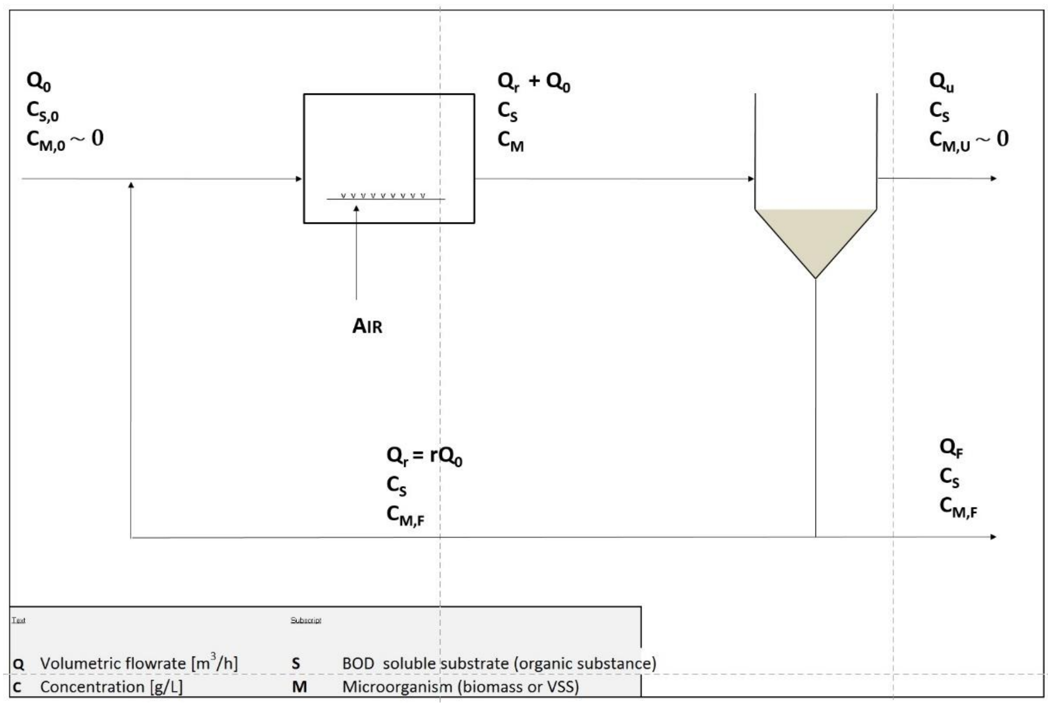


Figure H4: Activated sludge treatment holistic model

Input data for the model are:

- the aeration tank volume;
- the initial volumetric flowrate;
- the kinetic constant of microorganism growth;
- the kinetic constant of microorganism decay;
- the growth limiting substrate concentration;
- the growth yield factor;
- the mean initial soluble substrate concentration;
- the reflux ratio;
- the removal efficiency of the whole system.

Outputs of the model are:

- the residence time in aeration tank;
- the reflux volumetric flowrate;
- the sludge age;
- the rate of the growth reaction;
- the rate of the decay reaction;
- the outlet streams soluble substrate concentration;
- the inlet clarifier microorganisms concentration;
- the sludge microorganisms concentration;
- the outlet sludge volumetric flowrate;
- the outlet water volumetric flowrate;
- the Sludge Volume Index.

Assumptions

1. Concentration of microorganism in wastewater inlet flowrate not significant
2. Concentration of microorganism in trated water outlet flowrate not significant
3. Ideal perfect mixed aeration tank
4. Constant density of inlet/outlet streams
5. Monod/Michaelis-Menten kinetics
6. Complete convertion from soluble substrate to biomass
7. Decay of biomass results only in inerts formation
8. $C_S >> K_S$

Equations for the unit model

Global mass balance: $Q_0=Q_u+Q_f$

Global mass balance of microorganisms: $Q_0 \cdot C_{M,0} + V \cdot (r_1-r_2)=Q_u \cdot c_{M,u} + Q_F \cdot c_{M,F}$

Microorganisms growth rate: $r_1=k \cdot c_M \cdot c_S/(K_S+c_S)$

Microorganisms decay rate: $r_2=k_d \cdot c_M$

Inlet clarifier microorganisms concentration:

$$c_M = \frac{Y \cdot (c_{S,0} - c_S)}{1 + k_d \cdot \theta_C} \cdot \frac{\theta_C}{\tau}$$

Sludge microorganisms concentration:

$$c_{M,F} = \frac{V}{Q_F} \cdot (r_1 - r_2) = \frac{(Q_0 + Q_r) \cdot c_M - V \cdot (r_1 - r_2)}{Q_r}$$

Other Parameters

Reflux ratio: $r = \frac{Q_r}{Q_0}$

Residence time: $\tau = V/Q_0$

Sludge age: $\theta_C = \frac{1}{\frac{k \cdot c_S}{K_S + c_S} - k_d}$

Sludge Volume Index: $SVI = \frac{c_{M,F}}{c_M}$

Removal global efficiency: $\eta = \frac{c_{S,0} - c_S}{c_{S,0}}$

Belt and sand filters

Simple holistic models for belt and sand filters were developed by SSSA. Both Excel-based models have the same input and outputs. Different assumptions were done for the two unit operations. Figure H5 shows the whole model for belt filters.

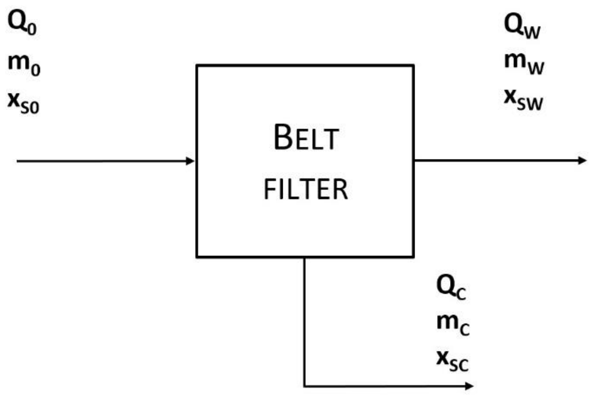


Figure H5: Belt filter holistic model

Input data for both models are:

- the initial volumetric flowrate;
- the inlet flow density;
- the filtration area;
- the initial solids mass concentration;
- the solids removal efficiency;
- the cake moisture.

The models outputs are:

- the filtration velocity;
- the inlet mass flowrate;
- the mass inlet solids flowrate;
- the mass inlet water flowrate;
- the mass outlet cake flowrate;
- the solids mass concentration in cake stream;
- the solids mass flowrate in cake stream;
- the water mass flowrate in cake stream;
- the mass outlet liquid flowrate;
- the solids mass concentration in liquid stream;
- the water mass concentration in liquid stream;
- the solids mass flowrate in liquid stream;
- the water mass flowrate in liquid stream.

Assumptions for belt filters

- Typical mass concentration of solids in liquid outlet stream: 20 ppm
- Typical mass concentration of solids in cake outlet stream: 35%
- No losses were considered

Assumptions for sand filters

- independence of the filtration velocity by time
- Typical mass concentration of solids in cake outlet stream: 15%
- Typical mass concentration of solids in liquid outlet stream: 20 ppm
- No losses were considered

Equations for the unit model

Global mass balance: $m_0 = m_W + m_C$

Global mass balance on solids: $m_0 \cdot x_{S0} = m_W \cdot x_{SW} + m_C \cdot x_{SC}$

Venturi gas scrubbing with water

Related to the unit operations which water is used in, for a few of case studies a Venturi gas scrubber is of interest. SSSA developed a simplified model taking into account the expected increase in terms of solids contaminants concentrations. Figure H6 shows the block diagram of the model.

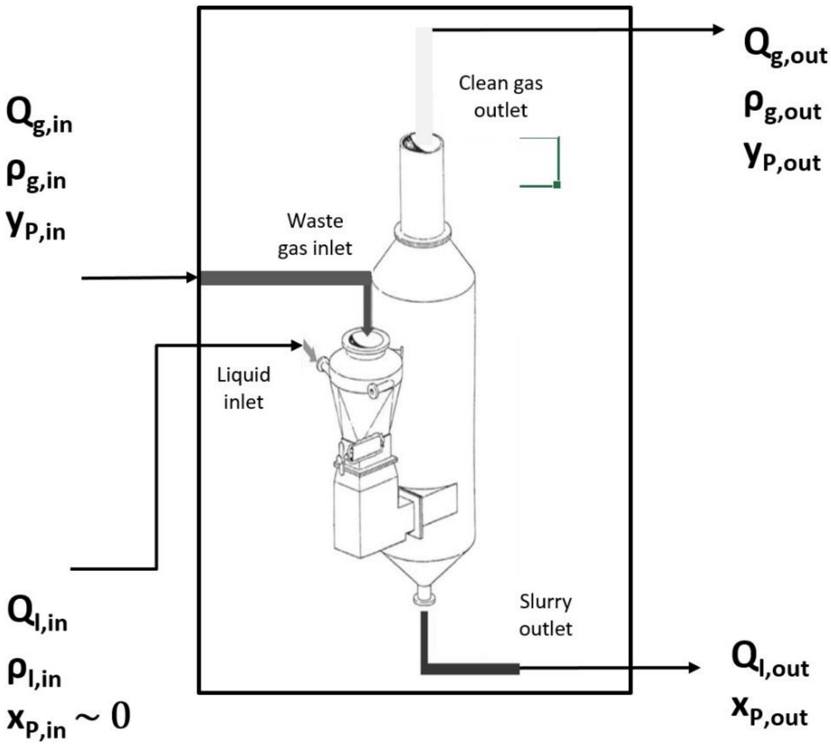


Figure H6: Venturi scrubber scheme

The input data for the model are:

- the volumetric flowrate of liquid inlet;
- the volumetric flowrate of gas inlet;
- the mass density of liquid inlet;
- the mass density of gas inlet;
- the mass concentration of particles in gas inlet;
- the gas velocity;
- the throat area;
- the throat lenght;
- the inlet gas absolute temperature;
- the mean particle size;
- the mean particle density;
- the gas dynamic viscosity;
- the correlation coefficient.

The models outputs are:

- the mass flowrate of gas inlet;
- the mass flowrate of particles in gas inlet;
- the mass flowrate of liquid inlet;
- the liquid mean droplet size;
- the throat velocity;
- the liquid-to-gas ratio;
- the Cunningham slip correction factor;
- the inertial impaction parameter;
- the collection efficiency;
- the mass flowrate of particles in gas outlet;
- the mass concentration of particles in gas outlet;
- the mass flowrate of gas outlet;
- the mass flowrate of liquid outlet;
- the mass flowrate of particles in slurry outlet;
- the mass concentration of particles in slurry outlet.

Assumptions

- Evaporation losses not significant (demister before gas outlet)
- Validity of Boll et. al correlation
- Gas velocity much higher than liquid velocity
- k correlation coefficient between 0.1 and 0.2

Equations for the unit model

Liquid mean droplet size:

$$d_l = \frac{\left[0.042 + 0.00565 \cdot (1000 \cdot \frac{Q_l}{Q_g})\right]}{v_r^{1.602}}$$

with

$\nu_r = \nu_g - \nu_l \simeq \nu_g$ [m/s]

Q_l, volumetric flowrate of liquid [m^3/s]

Q_g, volumetric flowrate of gas [m^3/s]

d_l, liquid mean droplet size [m]

Throat velocity: $v_T = Q_g/A_T$
with A_T = throat area [m^2] and v_T = throat velocity [m/s]
Liquid-to-gas-ratio: Q_l/Q_g
Cunningham slip correction factor: $C=1+0.000621 \cdot T_g/(d_p \cdot 10^6)$
with T_g=inlet gas absolute temperature [K], d_p= particle diameter [m].
Inertial impaction parameter:

$$\Psi = \frac{d_P^2 \cdot C \cdot \rho_P \cdot v_T}{18 \cdot \mu_g \cdot d_l}$$

with d_p=particle diameter [m], C = Cunningham slip correction factor, ρ_P=particle density [kg/m^3], v_T=throat velocity [m/s], μ_g=gas viscosity [Pa·s], d_l=liquid mean droplet size[m].
Collection efficiency:

$$\eta = 1 - \exp(k \cdot R \cdot \sqrt{\Psi})$$

with k=correlation coefficient tipically 0.1÷0.2 and R=liquid-to-gas ratio [$m^3/1000 \cdot m^3$].

Reverse osmosis

The Excel-based SSSA model for RO is presented in detail in Appendix C and summarized in Figure H7, where it is possible to recognize the input variables (in yellow cells) from the outputs parameters (in white cells).

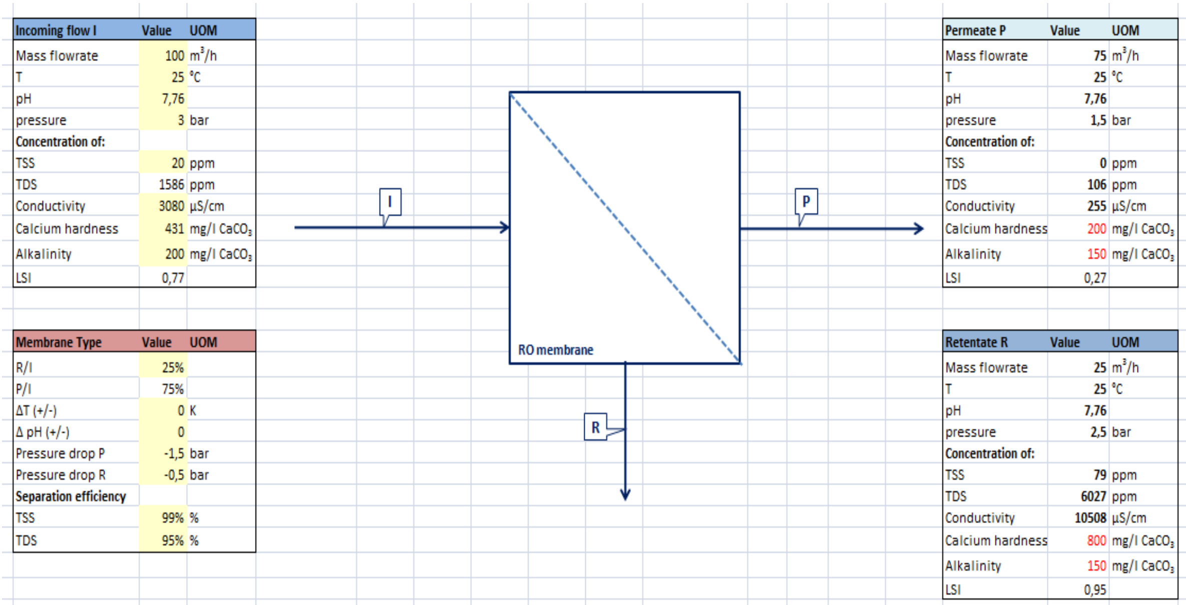


Figure H7: Reverse osmosis holistic model

Oil separator

Several process in a steelmaking plant use oil as lubricant (e.g. pipe mill, pipe forming, etc.). Oil removal from water is carried out by means of an oil separator prior to water reuse or discharge.
SSSA developed a simplified excel-based model referring to API (American Petroleum Institue) Stokes based relationship to evaluate "oil particle" ascensional rate [8]. The model considers an oil "particle" diameter d_{oil}>0.15 mm. Figure H8 shows the model diagram.

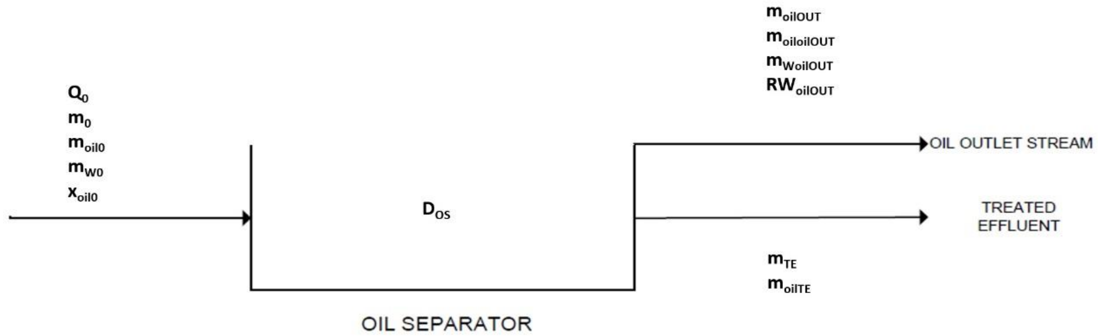


Figure H8: Oil separator holistic model

The input data for the model are:

- the inlet volume flowrate Q_0;
- the inlet flow density ρ_{Q0};
- the oil relative density ρ_{oil};
- the water relative density ρ_W;
- the water viscosity μ_W;
- the initial oil mass concentration x_{oil0};
- the oil stream residual water RW_{oilOUT};
- the oil separator diameter D_{OS};
- the separation zone-oil separator tank area ratio A_{sz}/A;
- the oil particle diameter d_{oil} (reference data).

The models outputs are:

- the inlet mass flowrate m_0;
- the inlet oil mass flowrate m_{oil0};
- he inlet water mass flowrate m_{W0};
- the oil separator tank area A;
- the separation zone A_{sz};
- the surface loading rate v_{sl};
- the ascensional rate v_{oil};
- the ascensional rate-surface loading rate ratio $|v_{oil}/v_{sl}|$;
- the oil removal efficiency η;
- the outlet oil stream oil oil mass flowrate $m_{oiloilOUT}$;
- the outlet oil stream water mass flowate $m_{WoilOUT}$;
- the outlet oil stream mass flowrate m_{oilOUT};
- the treated effluent oil mass flowrate m_{oilTE};
- the treated effluent water mass flowrate m_{WTE};
- the treated effluent mass flowrate m_{TE}.

Equations for the unit model

Surface loading rate $v_{sl}=Q_0/A_{sz}$

With v_{sl}=surface loading rate [m/h], Q_0=inlet volume flowrate [m^3/h], A_{sz}=separation zone (fraction of flotation tank area A) [m^2]

Oil ascensional rate $v_{oil}=0.443\cdot(\rho_{oil}-\rho_W)/\mu_W$

with v_{oil} =oil ascensional rate [m/h], ρ_{oil}=oil relative density, ρ_W=water relative density, μ_W=water viscosity [poise].

Balance equation $h=|v_{oil}/v_{sl}|$

With v_{oil}=oil ascensional rate [m/h] and v_{sl}=surface loading rate [m/h].

Balance equations

$$m_0=m_{TE}+m_{SF}$$

With m_0=inlet mass flowrate [kg/h], m_{TE}=treated effluent mass flowrate [kg/h] and m_{SF}=outlet stream mass flowrate [kg/h].

$$m_{oil0}=m_{oilTE}+m_{SF}$$

With m_{oil0}=inlet oil mass flowrate [kg/h], m_{oilTE}=treated effluent oil mass flowrate [kg/h] and m_{oilOUT}=outlet oil stream mass flowrate [kg/h].

Floation unit

Some water treatments in iron and steel plant use flotation to enhance suspended solid removal [8]. SSSA developed a model of flotation unit using Excel. The model is based on literature contour plots of particle removal fraction (see Figure H9-1, H9-2, H9-3) [9], which depends on bubbles and solid particles diameters for different surface loading rate ($v_{fsl}=0.05\div0.75$ cm/s). A schematic description of the holistic model is depicted in Figure H10.

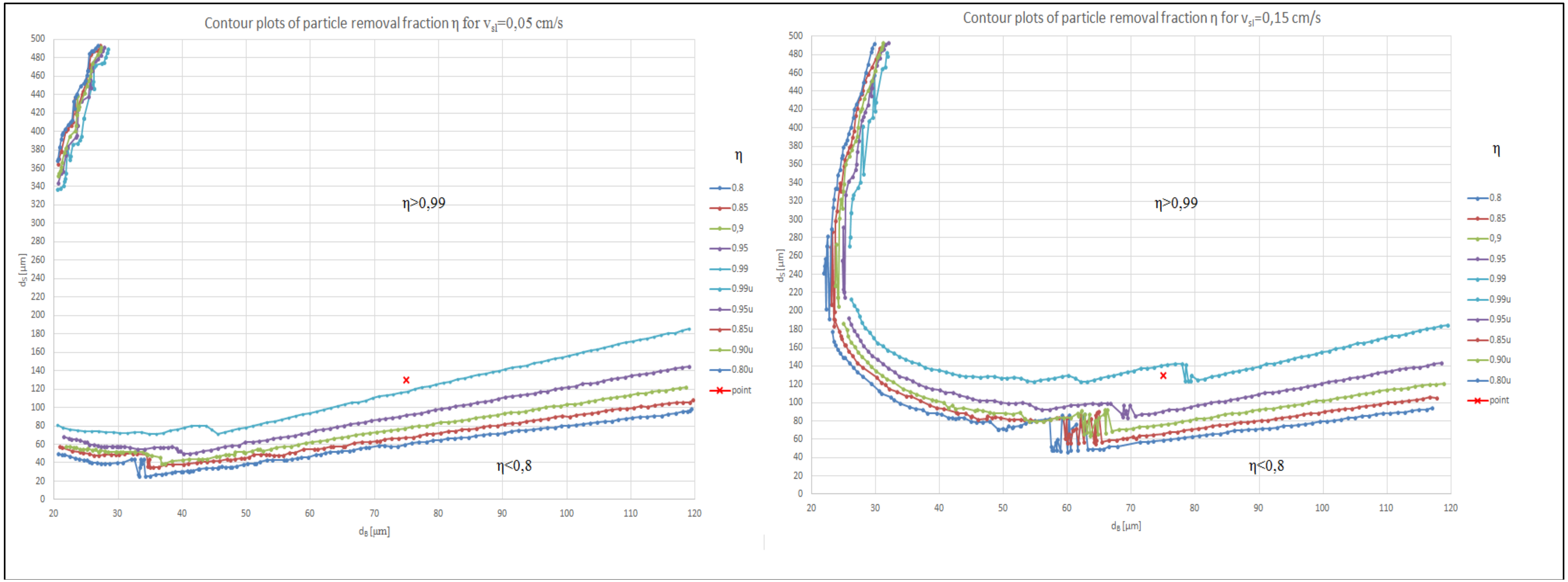


Figure H9-1: Contour plots of particle removal fraction (part1)

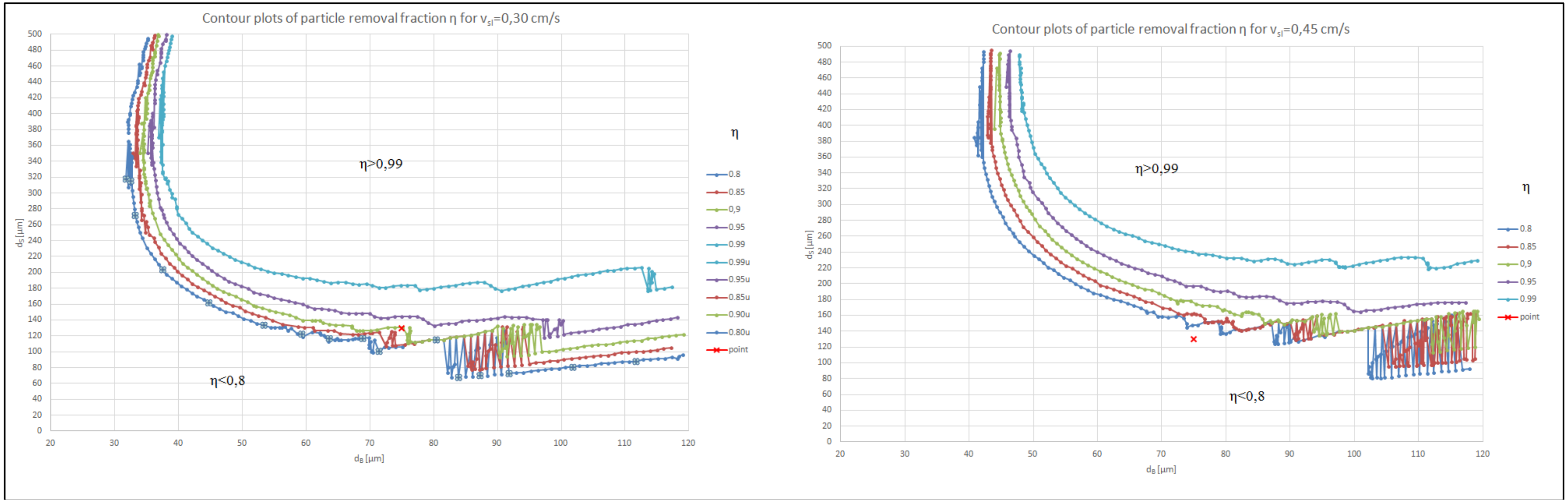
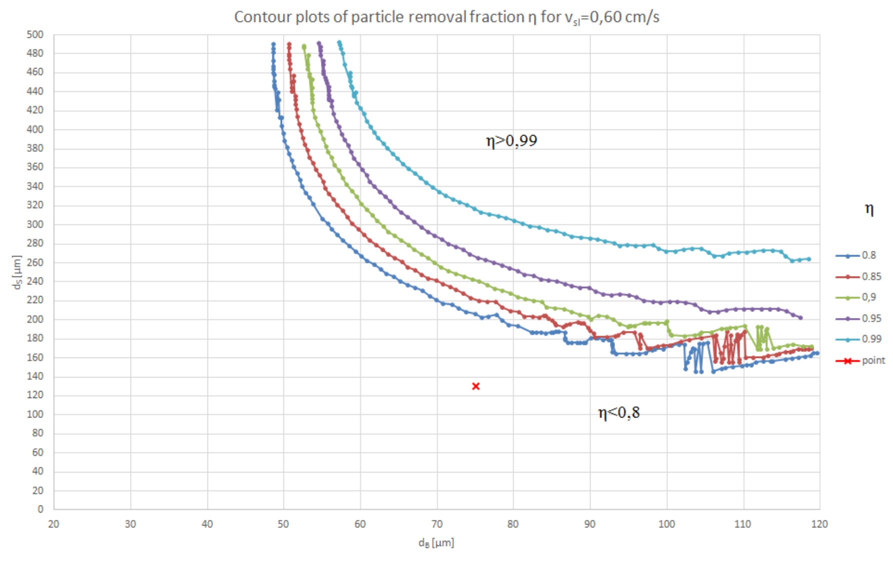


Figure H9-2: Contour plots of particle removal fraction (part2)



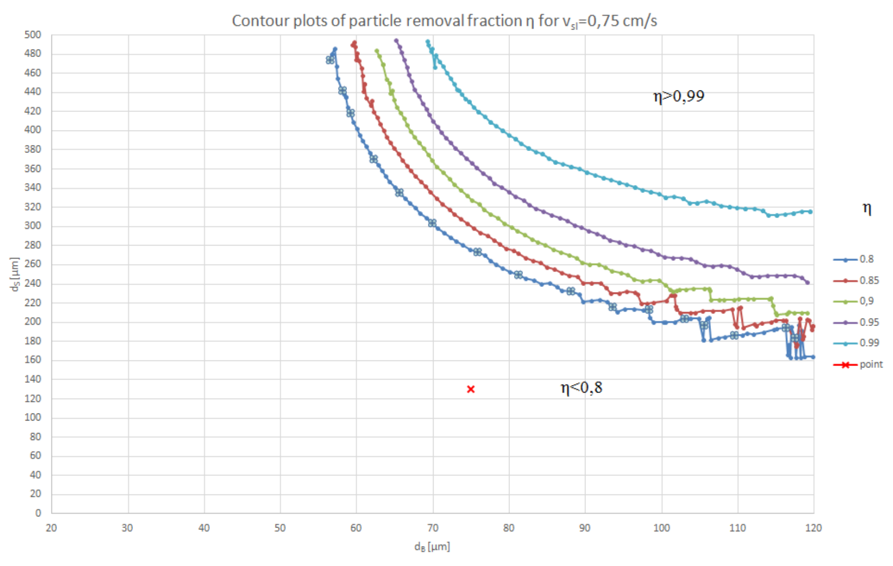
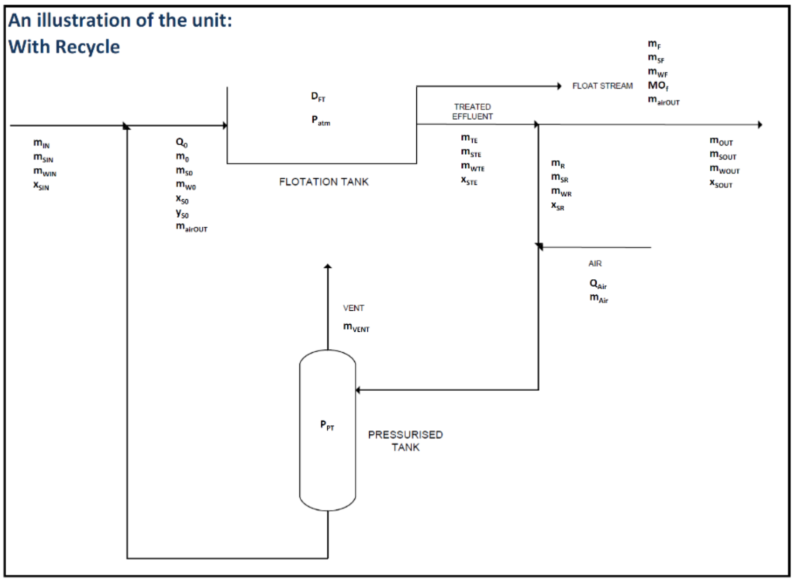


Figure H9-3: Contour plots of particle removal fraction (part3)



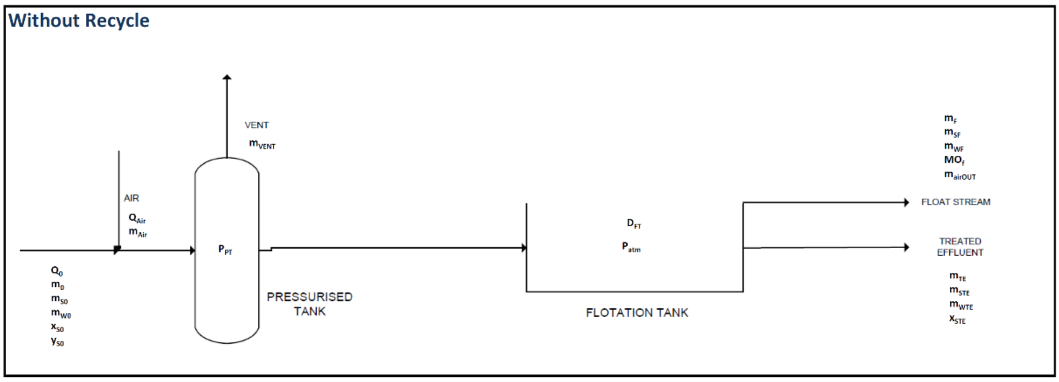


Figure H10: Flotation unit holistic model

The operating principle of the flotation model is as follows: given a flotation tank diameter and inlet volume flow rate, the model estimates the surface loading rate in the flotation tank. A selection of the correct contour plot (Figure H9) is carried out to be used for the calculation of particle removal fraction. Then the inverse distance weighting (*IDW*) multivariate interpolation method allows evaluating an approximation of removal efficiency depending on input data of d_b and d_p.

Input data for the model are:

- the inlet voume flowrate Q_{IN};
- the mean density of stream to treat ρ_Q;
- the initial solids mass concentration x_{SIN};
- the float stream moisture MO_F;
- the flotation tank diameter D_{FT};
- the bubbles mean diameter d_{B_mean};
- the particles mean diameter d_{S_mean};
- the separation zone-flotation tank area ratio A_{sz}/A;
- the pressurised tank pressure P_{PT};
- the atmospheric pressure P_{atm};
- the air volume flowrate Q_{Air};
- the recycle ratio $r=m_R/m_{IN}$;
- the water density ρ_W;
- the air solubility in water Sol_{air};
- air-bubble density $\rho_{bubble\text{-}air}$ (reference data);
- solid particles density ρ_S (reference data).

The models outputs are:

- the inlet mass flowrate m_{IN};
- the mass flowrate of solid inlet to flotation tank m_{SIN};
- the mass flowrate of water inlet to flotation tank m_{WIN};
- the recycle mass flowrate m_R;
- the inlet mass flowrate to flotation tank m_0;
- the inlet volume flowrate to flotation tank Q_0;
- the float stream mass flowrate m_F;
- the outlet mass flowrate m_{OUT};

- the treated effluent mass flowrate m_{TE};
- the solid concentration in inlet stram to flotation tank x_{S0};
- the solid concentration in outlet stream x_{SOUT};
- the solid concentration in treated effluent x_{STE};
- the solid concentration in recycle x_R;
- the mass flowrate of solid in inlet stream to flotation tank m_{S0};
- the mass flowrate of water in inlet stram to flotation tank m_{W0};
- the mass flowrate of solid in outlet stram m_{SOUT};
- the mass flowrate of water in outlet stream m_{WOUT};
- the mass flowrate of solid in recycle m_{SR};
- the mass flowrate of water in recycle m_{WR};
- the mass flowrate of solid in treated effluent m_{STE};
- the mass flowrate of water in treated effluent m_{WTE};
- the mass flowrate of solid in float stream m_{SF};
- the mass flowrate of water in float stream m_{WF};
- the flotation tank surface area A;
- the separation zone area A_{sz};
- the surface loading rate v_{sl};
- the flotation separation efficiency η;
- the air mass flowrate m_{Air};
- the air solubility in water G_{atm};
- the air per recycle water volume flowrate G_{Air};
- the air solubility in water at P_{PT} G_{satP};
- the air saturation level f;
- the solubilized air at P_{PT} G_P;
- the air mass flowrate in float stream m_{airOUT};
- the vent mass flowrate m_{VENT};
- the released air er recycle water volume flowrate G_{RelAir};
- the initial solids mass/volume concentration y_{S0};
- the released air-initial solids ratio G_{RelAir}/y_{S0} (0.005÷0.060).

Assumptions

- The model is based on literature contour plots of particle removal fraction η which depends on bubbles and solid particles diameters for different surface loading rate (v_{SL} = 0.05÷0.75 cm/s).
- Data are referred to surface loading rate v_{SL}=0.05÷0.75 cm/s, bubbles diameter d_B=20÷120 µm and particle diameter d_P =20÷500 µm.
- The model has good accuracy for particle removal fraction η>0,8.
- Simplified approach considers mean bubbles diameter and mean solid particles diameter (possibility to upgrade to PSD).
- Given flotation tank diameter and inlet volume flowrate, first the model estimates the surface loading rate in the flotation tank and selects the correct sheet to be used for the calculation of particle removal fraction η, then the inverse distance weighting (IDW) multivariate interpolation method allows to evaluate an approximation of η depending on input data of d_B and d_P.
- Air- bubble density = 0.0012 kg/dm^3.
- Solid particle density = 1.05 kg/dm^3
- Accepted air saturation level >0,6.
- Reccomended ratio of (G_{RelAir}/y_{S0}) = 0,005÷0,060.

Main equations of the model unit

Surface loading rate $v_{sl}=Q_0/A_{sz}$

With v_{sl}=surface loading rate [cm/s], Q_0=inlet volume flowrate [cm^3/s], A_{sz}=separation zone (fraction of flotation tank area A) [cm^2]

Recycle ratio m_R/m_{IN}

with m_R=recycle mass flowrate [kg/h] and m_{IN}=inlet mass flowrate [kg/h].

Solubilized air at P_{PT} $G_P=G_{atm}\cdot P_{PT}/P_{atm}$

with G_P=solubilized air at P_{PT} [g/m^3], P_{PT}=pressurized tank pressure [bar] and P_{atm}=atmospheric pressure [bar].

Released air per recycle water volume flowrate: $G_{relair}=G_P-G_{air}$

with G_{relair}=released air per recycle water volume flowrate [g/m^3] and G_{air}= solubilized air at P_{atm} [g/m^3].

Balance equations $m_{IN}=m_{OUT}+m_F$

with m_{IN}=inlet mass flowrate [kg/h], m_{OUT}=outlet mass flowrate [kg/h] and m_F=flow stream mass flowrate [kg/h].

$$m_{IN}\cdot x_{SIN}=m_{OUT}\cdot x_{SOUT}+m_F\cdot(1-MO_F)$$

with x_{SIN}=initial solid mass concentration [kg/kg], x_{SOUT}=solid concentration in outlet stream [kg/kg] and MO_F=float stream moisture [kg/kg]

$$m_0\cdot x_{S0}=m_{TE}\cdot x_{STE}+m_F\cdot(1-MO_F)$$

with m_0=inlet mass flowrate to flotation tank [kg/h], x_{S0}= solid concentration in inlet stream to flotation tank [kg/kg], m_{TE}=treated effluent mass flowrate [kg/h], x_{STE}=solid concentration in treated effluent [kg/kg].

$$x_{STE}=x_{SOUT}=x_{SR}$$

with x_{SR}=solid concentration in recycle [kg/kg]

$$m_0=m_{TE}+m_F$$

$$m_F\cdot(1-MO_F)=\eta\cdot m_0\cdot x_{S0}$$

with η=flotation separation efficiency.

$$m_{VENT}=m_{air}-m_{airOUT}$$

with m_{VENT}=vent mass flowrate [kg/h], m_{air}=air mass flowrate [kg/h] and m_{airOUT}=air mass flowrate in float stream [kg/h].

Inverse Distance Weighting (IDW) $\eta=\Sigma w_i\cdot \eta_i / \Sigma w_i$

with η=interpolated value of removal efficiency, η_i=sample values of removal efficiency and w_i=weights.

$$w_i=1/d_i$$

with d_i=distance between i-th given value and sample value.

14.2 Holistic simulation models - by-products and wastes

Cooling stage

Before some waste/by-product treatments, a cooling stage is necessary, such as in the case of BOF slag. SSSA developed an Excel-based model of a possible cooling stage. The main sheet of the model is shown in Figure H11 and basic equations of the model are listed in Figure D.4.1.17.

INPUT VARIABLES			
F	kg	2000000,00	Slag mass
Tin	°C	1600,00	Initial slag temperature
Ta	°C	25,00	Ambient temperature
h	m	2,00	Height of slag heap
t	min	1440,00	Cooling time

REFERENCE AND AUXILIARY DATA			
PM	g/mol	1,82E+02	Mean molar weight of slag
rho	kg/m^3	3,30E+03	Slag density
ε	-	7,50E-01	Slag emissivity
c	J/(mol*K)	5,97E+01	Slag specific heat
kslag	J/(m*K*s)	1,50E+00	Slag conductivity
K	J/(m*K*s)	1,00E-02	Air thermal conductivity
σ	W/(m2*K^4)	5,68E-08	Stefan-Boltzmann constant
δ	m	5,00E-03	Thickness of the conductive layer in external fraction of slag
s	m	0,10	Thickness of each conductive layer in internal fraction of slag

CALCULATED VARIABLES			
Tin	K	1873,15	Initial slag temperature
Ta	K	298,15	Ambient temperature
V	m^3	606,06	Slag Volume
L	m	17,41	Lenght of slag heap
S	m2	442,29	External area of slag heap
t	s	86400,00	Cooling time
c	J/(kg*K)	327,93	Slag specific heat
Vrad	m^3	43,46	Volume of the external radiant layer of the slag
Fext	kg	143407,88	Mass of the external radiant layer of the slag
n	-	9,00	Maximum number of conductive layers in internal part of slag

OUTPUT VARIABLES			
Tcore	°C	920,24	Final temperature of core slag
Text	°C	25,00	Final temperature of external slag
Qloss	GJ	487,93	Heat Losses

Figure H11: Main sheet of Cooling stage holistic model

The model is based on simplified solutions of Newton's law of cooling [10] and discrete solution of Fourier equation for conductivity. In particular, the Newton's law is used to take into account heat losses for convection and radiation: each time the model calculates transfer heat coefficient (convective/conductive and radiant) in an iterative way and estimates temperature of the external cooling phase. On the other hand, after the calculation of conductive heat transfer coefficient the model estimates the temperature of each conductive fraction of the waste for each time.
The global operating principle of the cooling stage model is as follows: given an initial temperature of hot waste (i.e. BOF slag) and ambient temperature the model first divides the waste heap in several layers and then estimates the temperature of external layer and the temperature of the internal core after a fixed cooling time. The model allows to calculate heat losses due to the cooling.

Due to its aim, the model can be used to monitor the slag temperature during the time e to evaluate possibilities of energy recovery.
Input data for the model are:

- the inlet mass *F_>1;*
- the initial slag temperature *Tin* ;
- the ambient temperature *Ta* ;
- the height of slag heap *h*;
- the cooling time *t*;
- the mean molar weight of slag *PM (reference data)*;
- the slag density *rho (reference data)*;
- the slag emissivity *ε (reference data);*
- the slag specific heat *c (reference data)*;
- the slag conductivity *kslag (reference data);*
- the air thermal conductivity *K (reference data)*;
- the Stefan-Boltzmann constant *σ (reference data)*;
- the thickness of the conductive layer in external fraction of slag *δ (reference data)*;
- the thickness of each conductive layer in internal fraction of slag *s (auxiliary data)*;

Models outputs are:

- the final temperature of core slag *Tcore*;
- the final temperature of external slag *Text*;
- the heat losses *Qloss*.

Main equations of the model unit

Newton's law of cooling $dT(t)/dt=-h[T(t)-T_a]$

with h=heat transfer coefficient [1/s], T(t)=temperature of the slag surface at time t [K] and T_a=room temperature [K]

Solution of theNewton's law of cooling $T(t)=T_a+[T(t-1)-T_a]\cdot e^{h\cdot t}$

Global heat transfer coefficient $h=h_{rad}+h_{conv/cond}$

with h_{rad}=radiative heat transfer coefficient [1/s] and $h_{conv/cond}$=convective-conductive heat transfer coefficient [1/s].

Radiative heat transfer coefficient: $h_{rad_i} = \frac{S}{F_{ext} \cdot c} \cdot \epsilon \cdot \sigma \cdot \left(\left(\frac{T_i + T_i}{2} \right)^2 + T_a^2 \right) \cdot \left(\frac{T_{i-1} + T_i}{2} + T_a \right)$

With S=external area of slag heap [m^2], c=slag specific heat [J/(kg·K)], ε=slag emissivity, σ= stefan-Boltzmann constant [W/(m^2·K)], T_i= temperature of the slag surface at time t_i [K].

Convective-conductive heat transfer coefficient: $h_{conv/cond}=k/(F_{ext}\cdot c\cdot \delta)$

With k= air thermal conductivity [J/(m·K·s)], δ=thickness of the conductive layer in external fraction of slag [m].

Fourier equation for conductivity: $dT/dt=[k_s/(c\cdot\rho)]d^2T/dx^2$

with T=temperature of the conductive layers of the slag [K], k_s=slag thermal conductivity [J/(m·K·s)], ρ=slag density [kg/m^3], x=thickness of conductive layers [m].

Discrete solution of Fourier equation:

$$T_{i,j} = T(x_i, t_j) = T_{i,j-1} + \frac{k}{c \cdot \rho} \cdot \frac{\Delta t}{\Delta x}^2 \cdot (T_{i+1,j-1} - 2 \cdot T_{i,j-1} + T_{i-1,j-1})$$

with $T_{i,j}$=temperature in the layer i and at the time j [K], Δt=magnitude of discretized time period [s] and Δx=thickness of each conductive layer in internal fraction of slag [m].

Grinding and Sieving

Common waste or by-product treatments in steelworks are grinding and sieving. SSSA developed a holistic model of grinding and sieving stage ad-hoc for BOF slag treatment but customizable for other type of waste/by-products. Main sheet of the model is shown in Figure H12.

Starting from initial PSD and compositions of the slag (minerals and other components), the model reduces waste particle size (by 3,9,27 or 241 times as specific factors) using fixed grinding grade efficiency for each reduction grade and allocates each compounds using fixed distribution efficiency.

In the case of not-normalized analyses data, the model first step is an internal computation of normalization.

Grinding grade and distribution efficiencies are based on PSD and mineral grindability, which take into account of particle size and literature information about tenacity, hardness (Mohs scale) and work index of each slag compounds [11-13]. The model also provides the composition of each particle size fraction and an estimation of mill energy consumption based on Bond's law of comminution [14-16].

Input data for the model are:

- the inlet mass *F*;
- the composition;
- the initial PSD;
- the grinding grade efficiency (auxiliary data);
- the distribution efficiency (auxiliary data).

Models outputs are:

- the output PSD (fraction);
- the output PSD (mass);
- the composition of each particle size fraction;
- the mass of each particle size fraction.

Equations for the unit model

Bond's equation of comminution:

$$W = 10 \cdot W_i \cdot \left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \right)$$

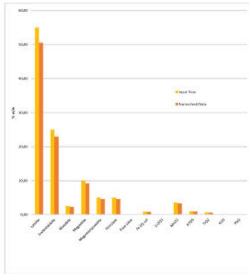
with W=predicted mill energy consumption [kWh/shortton], W_i=work index[kWh/shortton], P_{80}=80% passing size in μm of product and F_{80}=80% passing size in μm of feed.

INPUT VARIABLES

	F	kg	2000000,00	BOF slag mass (inserted or from previous stage)
	Wi	kWh/ton	27,00	Bond Work Index

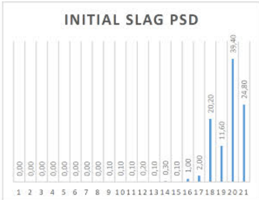
Mineral and other oxydes Content

Larnite	% w/w	55,00
Srebodolskite	% w/w	25,00
Wuestite	% w/w	2,50
Magnetite	% w/w	10,00
Magnesiowuestite	% w/w	5,00
Periclase	% w/w	5,00
Free Lime	% w/w	0,00
Fe tot	% w/w	0,00
Fe tot cal	%w/w	19,89
Fe (0)	% w/w	0,89
Fe (0) cal	% w/w	0,89
Cr_2O_3	% w/w	0,13
MnO_2	% w/w	3,57
P_2O_5	% w/w	1,00
TiO_2	% w/w	0,66
K_2O	% w/w	0,01
PbO	% w/w	0,00



Initial PSD (mm)

1	<	0,063	% w/w	0,00
2	0,063	0,106	% w/w	0,00
3	0,106	0,125	% w/w	0,00
4	0,125	0,15	% w/w	0,00
5	0,15	0,212	% w/w	0,00
6	0,212	0,25	% w/w	0,00
7	0,25	0,5	% w/w	0,00
8	0,5	1	% w/w	0,00
9	1	1,4	% w/w	0,10
10	1,4	2	% w/w	0,10
11	2	2,36	% w/w	0,10
12	2,36	2,8	% w/w	0,20
13	2,8	3,35	% w/w	0,10
14	3,35	4	% w/w	0,30
15	4	4,75	% w/w	0,10
16	4,75	6,3	% w/w	1,00
17	6,3	8	% w/w	2,00
18	8	9,5	% w/w	20,20
19	9,5	10	% w/w	11,60
20	10	16	% w/w	39,40
21	>	16	% w/w	24,80



REFERENCE AND AUXILIARY DATA

	grinding grade	1	3	9	27	81	243
		grinding grade efficiency					
PSD grindability	1	0,50	0,50	0,00	0,00	0,00	0,00
	2	0,00	0,02	0,34	0,18	0,28	0,18
	3	0,02	0,16	0,05	0,50	0,02	0,25
	grinding grade	1-3	81-243				
		% of distribution					
Mineral grindability	1	0,20	0,43				
	2	0,25	0,42				
	3	0,55	0,16				

OUTPUT VARIABLES

Output PSD (mm)

1	<	0,045	% w/w	6,38	<	0,045	kg	127640,00
2	0,045	0,063	% w/w	7,20	0,045	0,063	kg	144080,00
3	0,063	0,09	% w/w	7,04	0,063	0,09	kg	140800,00
4	0,09	0,125	% w/w	8,92	0,09	0,125	kg	178440,00
5	0,125	0,25	% w/w	11,78	0,125	0,25	kg	235600,00
6	0,25	0,5	% w/w	13,40	0,25	0,5	kg	267920,00
7	0,5	0,8	% w/w	13,52	0,5	0,8	kg	270400,00
8	0,8	1	% w/w	6,97	0,8	1	kg	139360,00
9	>	1	% w/w	24,79	>	1	kg	495760,00

Mass of each particle size fraction

Composition of each particle size fraction

	Output PSD (mm)			Larnite	Srebodolskite	Wuestite	Magnetite	Magnesiowuestite	Periclase	Free Lime	Fe (0)	Cr_2O_3	MnO_2	P_2O_5	TiO_2	K_2O	PbO
1	<	0,045	% w/w	39,31	33,82	2,11	8,45	9,25	3,57	0,00	1,23	0,11	0,17	1,39	0,57	0,01	0,00
2	0,045	0,063	% w/w	39,31	33,82	2,11	8,45	9,25	3,57	0,00	1,23	0,11	0,17	1,39	0,57	0,01	0,00
3	0,063	0,09	% w/w	39,31	33,82	2,11	8,45	9,25	3,57	0,00	1,23	0,11	0,17	1,39	0,57	0,01	0,00
4	0,09	0,125	% w/w	39,36	33,78	2,11	8,44	9,25	3,58	0,00	1,23	0,11	0,17	1,39	0,57	0,01	0,00
5	0,125	0,25	% w/w	39,80	33,40	2,10	8,41	9,22	3,62	0,00	1,22	0,11	0,17	1,37	0,57	0,01	0,00
6	0,25	0,5	% w/w	61,58	14,39	1,77	7,10	7,78	5,60	0,00	0,53	0,09	0,07	0,59	0,48	0,01	0,00
7	0,5	0,8	% w/w	61,40	14,41	1,79	7,18	7,86	5,58	0,00	0,53	0,09	0,07	0,59	0,49	0,01	0,00
8	0,8	1	% w/w	61,04	14,43	1,83	7,33	8,02	5,55	0,00	0,53	0,09	0,07	0,59	0,50	0,01	0,00
9	>	1	% w/w	49,25	15,30	3,06	12,24	13,41	4,48	0,00	0,56	0,16	0,08	0,63	0,83	0,01	0,00

Composition of each particle size (Mass)

	Output PSD (mm)			Larnite	Srebodolskite	Wuestite	Magnetite	Magnesiowuestite	Periclase	Free Lime	Fe (0)	Cr_2O_3	MnO_2	P_2O_5	TiO_2	K_2O	PbO
1	<	0,045	kg	50176,51	43172,89	2695,14	10780,56	11807,01	4561,50	0,00	1575,38	139,23	223,03	1770,09	729,30	8,42	0,94
2	0,045	0,063	kg	56639,24	48733,55	3042,27	12169,09	13327,75	5149,02	0,00	1778,29	157,16	251,76	1998,08	823,24	9,50	1,06
3	0,063	0,09	kg	55349,84	47624,12	2973,02	11892,06	13024,34	5031,80	0,00	1737,80	153,59	246,03	1952,59	804,50	9,28	1,03
4	0,09	0,125	kg	70228,93	60284,10	3766,48	15065,93	16500,40	6384,45	0,00	2199,77	194,58	311,43	2471,65	1019,21	11,78	1,31
5	0,125	0,25	kg	93770,38	78690,66	4956,42	19825,66	21713,32	8524,58	0,00	2871,42	256,05	406,52	3226,32	1341,21	15,73	1,75
6	0,25	0,5	kg	164997,37	38563,99	4755,24	19020,94	20831,98	14999,76	0,00	1407,20	245,66	199,22	1581,12	1286,77	27,67	3,07
7	0,5	0,8	kg	166014,35	38958,62	4852,43	19409,74	21257,80	15092,21	0,00	1421,60	250,68	201,26	1597,30	1313,07	27,85	3,09
8	0,8	1	kg	85062,66	20115,47	2552,83	10211,31	11183,56	7732,97	0,00	734,01	131,88	103,92	824,73	690,80	14,27	1,59
9	>	1	kg	244171,49	75871,68	15170,67	60682,67	66460,44	22197,41	0,00	2768,56	783,72	391,95	3110,74	4105,18	40,95	4,55

W	MWh	17,42	Predicted mill energy consumption

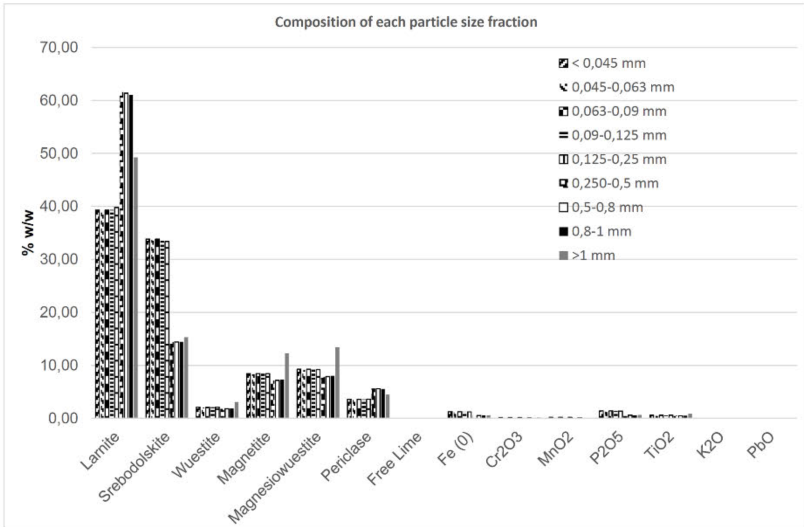
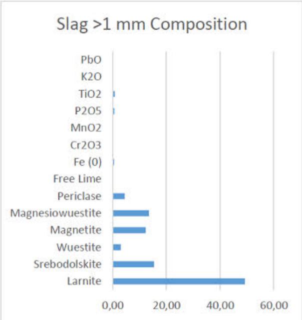


Figure H12: Main sheet of Grinding and Sieving holistic model

Magnetic Separation

The recovery of magnetic fraction to be recycled in the steel process is a common stage of waste/by-product treatment. SSSA developed a model of the magnetic separation ad-hoc for BOF slag but customizable for other waste. Main model sheet is shown in Figure H13. The model is based on separation efficiencies between magnetic and non-magnetic fractions. These efficiencies are fixed taking into account literature information about magnetic properties of compounds of the slag [12-13]. Model results are mass and composition of magnetic and non-magnetic fractions.

INPUT VARIABLES			
F_>1	kg	495760,00	BOF slag mass (inserted or from orevious stage)
Mineral and other oxydes content			
Larnite	% w/w	49,25	
Srebodolskite	% w/w	15,30	
Wuestite	% w/w	3,06	
Magnetite	% w/w	12,24	
Magnesiowuestite	% w/w	13,41	
Periclase	% w/w	4,48	
Free Lime	% w/w	0,00	
Fe (0)	% w/w	0,56	
Cr_2O_3	% w/w	0,16	
MnO_2	% w/w	0,08	
P_2O_5	% w/w	0,63	
TiO_2	% w/w	0,83	
K_2O	% w/w	0,01	
PbO	% w/w	0,00	

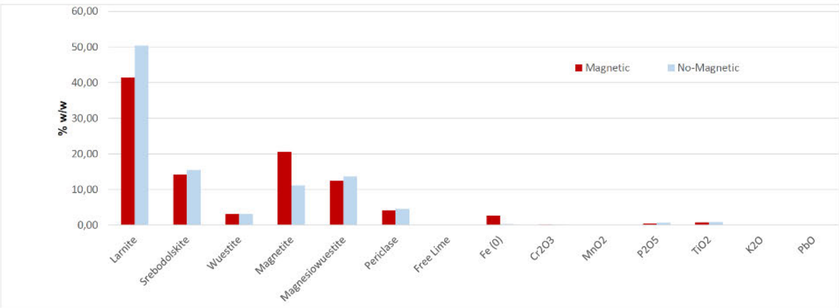


REFERENCE AND AUXILIARY DATA			
		magnetic fraction	no-magnetic fraction
		separation efficiency	
magnetic grade	0	0,10	0,90
	1	0,11	0,89
	2	0,12	0,88
	3	0,20	0,80
	4	0,57	0,43

OUTPUT VARIABLES			
MAG	% w/w	11,89	Magnetic fraction
NOMAG	% w/w	88,11	No- Magnetic fraction
FMAG	kg	58935,29	Mass of Magnetic Fraction
FNOMAG	kg	436824,71	Mass of No-Magnetic Fraction

Composition of magnetic and no-magnetic fraction

		Larnite	Srebodolskite	Wuestite	Magnetite	Magnesiowuestite	Periclase	Free Lime	Fe (0)	Cr_2O_3	MnO_2	P_2O_5	TiO_2	K_2O	PbO
MAG	% w/w	41,43	14,16	3,09	20,59	12,40	4,14	0,00	2,68	0,13	0,07	0,53	0,77	0,01	0,00
NO MAG	% w/w	50,31	15,46	3,06	11,11	13,54	4,52	0,00	0,27	0,16	0,08	0,64	0,84	0,01	0,00



Composition of magnetic and no-magnetic fraction

		Larnite	Srebodolskite	Wuestite	Magnetite	Magnesiowuestite	Periclase	Free Lime	Fe (0)	Cr_2O_3	MnO_2	P_2O_5	TiO_2	K_2O	PbO
MAG	kg	24417,15	8345,89	1820,48	12136,53	7310,65	2441,71	0,00	1578,08	78,37	39,20	311,07	451,57	4,10	0,50
NO MAG	kg	219754,34	67525,80	13350,19	48546,13	59149,79	19755,69	0,00	1190,48	705,34	352,76	2799,67	3653,61	36,86	4,05

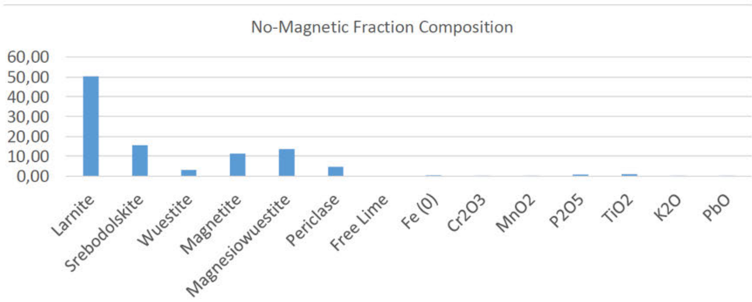


Figure H13: Main sheet of Magnetic separation model

The input data of the model are:

- the inlet mass *F*;
- the composition;
- magnetic separation efficiency (auxiliary data).

Models outputs are:

- the magnetic fraction *MAG*;
- the non-magnetic fraction *NOMAG*;
- the magnetic fraction mass *FMAG;*
- the non-magnetic fraction mass *FNOMAG;*
- the composition of magnetic fraction;
- the composition of non-magnetic fraction.

15 APPENDIX I - Site-specific PI-based solutions for resource efficiency (D4.2)

15.1 PI-based solutions - water

The following case studies for ILVA plant were simulated by SSSA:

- reuse of blowdown water from the CC No 1 (CCO1) for the off-gas cleaning of the BOF No 1 (BOF1);
- reuse of the CCs No 2/3/4 blowdown (CCO2/3/4) in the BOF No 2 (BOF2);
- reuse of pipe coating No 1 blowdown (RIV1) in pipe mill No 1 (TUL1);
- alternative use of process water streams for off gas cleaning (contaminants reduction and water reuse of coke-making area wastewater).

Such case studies are presented in detail in the following subsections 19.1.1-4.
Four case studies concerning the Tata Steel water network were considered and analysed by PIL for the implementation phase:

- Lagoon 1 water reuse in BF Gas Wash Circuit
- Pond A water reuse in BF Gas Wash Circuit
- Recycling of the BF GW HC overflow water with suitable treatment
- HPM-Ancholme System Water Recovery & Control

The details of these four case studies and the corresponding site-specific PI-based solution can be found in the following subsections 19.1.5-8.
Two complex case studies concerning the SSAB water network were considered and analysed by MEFOS:

- efficient usage of the spray-on water used at the CC
- improving water efficiency of the BF gas treatment system

Such case studies are presented in detail in the following subsections 19.1.9-10.

15.1.1 CASE STUDY No1: reuse of CCO1 blow down water for off-gas cleaning of BOF1

SSSA Aspen Plus simulation of ILVA water network for the gas washing system of BOF No1 is shown in Figure I1. The main unit operations are highlighted with labels; it is possible to see that in few cases one equipment is represented by two or more blocks.

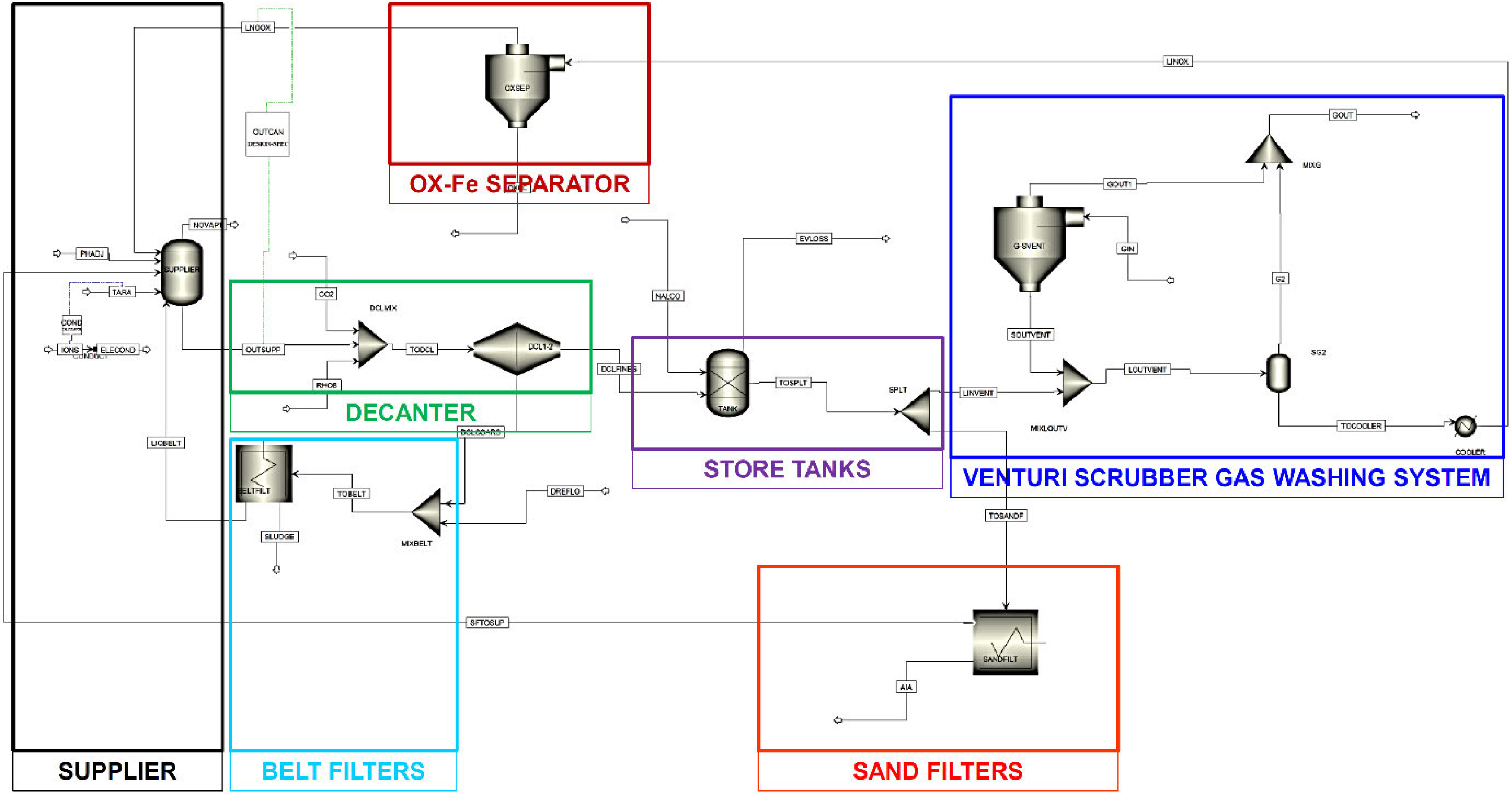


Figure I1 Water network for the gas washing system of BOF No1 simulation flowsheet

The system is composed by a supplier, where all the recirculated water streams are mixed together with fresh water (Tara river) and are charged at the decanter. Most relevant fraction of the overflow is the stream used to wash BOF gases in Venturi scrubbers; wastewater from the scrubber is sent to a separation unit to remove iron oxides and then again to the supplier. The remaining quantity of overflow is filtered in sand filters and then recirculated. Sludge from the decanter is treated in a belt filter where the water is recovered. Chemical addictives are used to promote and increase separation efficiency and CO_2 is added to adjust pH value.
The results for standard operating conditions for inlet, intermediate and outlet streams are show in Tables I1, I2 and I3, respectively. The values reported in red represent the main parameters of interest, which allow understanding the feasibility and convenience of the proposed solution. The pH and electrical conductivity values give an idea of the water contamination.

	Units	TARA		CO2		RHOB		DREFLO		NALCO		PHADJ		GIN	
		Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output
From															
To			SUPPLIER		DCLMIX	DCLMIX	DCLMIX		MIXBELT		TANK		SUPPLIER		G-SVENT
GLOBAL															
Mass Flow	**KG/HR**	35000	35000	58.2	2.1	23333	23333	7000	7000	8.71	8.71	-	30		184826
Temperature	**C**	27	27	27	27	30	30	25	25	25	25	-	30		200
Pressure	**BAR**	2	2	4	4	2	2	1.2	1.2	1.2	1,2	-	1		1
Mass Density	**KG/CUM**		998.15		7.19		997.52		997.15		1046.68	-	1441.92		0.70
Phase: Liquid												-			
pH		**7.9**	**7.92**			**8.5**	**9.26**		7		12	-	16.9		
Electrical conductivity	**µS/cm**	**3100-3300**	**3365**			**~4500**	**4746**								
SOLIDS															
Mass Flow	**KG/HR**	0.07	0.073		0	4.67	4.67		0		0	-	0		8143
Mass Density	**KG/CUM**		2648.28				5464.39					-			5464,39

Table I1: comparison of real data and simulation results for inlet streams for the gas washing system of ILVA BOF No1

	Units	OUTSUPP		TODCL		DCLFINES		DCLCOARS		TOBELT		LIQBELT		TOSPLT	
		Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output
From			SUPPLIER		DCLMIX		DCL1-2		DCL1-2		MIXBELT		BELTFILT		TANK
To			DCLMIX		DCL1-2		TANK		MIXBELT		BELTFILT		SUPPLIER		SPLT
GLOBAL															
Mass Flow	**KG/HR**	500000	501350	523391.2	524685	478308	474078	45083	50607.1	52083	57607.1	41667	47231	472690	468459
Temperature	**C**		35		34.78		34.78		34,78		33.48		33.48		34.79
Pressure	**BAR**		2		2		2		2		1.2		1.2		1.2
Mass Density	**KG/CUM**		995.46		995.55		995,5		995.92		996.11		995.82		995.49
Phase: Liquid															
pH			**10.42**		**10.26**	**10**	**10.26**		**10.26**		**10.24**		**10.24**		**10,27**
Electrical conductivity	**µS/cm**					**<4800**	**3764**								
SOLIDS															
Mass Flow	**KG/HR**		9515.40		9520.07		3242,73		6277.34		6277.34		1113.29		3242.73
Mass Density	**KG/CUM**		5464.32		5464.32		5464.32		5464.32		5464.32		5464.32		5464.32

Table I2: comparison of real data and simulation results for intermediate streams for the gas washing system of ILVA BOF No1

	Units	SLUDGE		EVLOSS		GOUT		OXFE		AIA	
		Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output
From			BELTFILT		TANK		MIXG		OXSEP		SANDFILT
To											
GLOBAL											
Mass Flow	**KG/HR**	10420	10376.1	5627	5627	176683	177489	2500	3074.16	55000	53780.3
Temperature	**C**		33.48		34.79342		65		35.00		34.79
Pressure	**BAR**		1,2		1,2		1		0.75		1.2
Mass Density	**KG/CUM**		998.71		994.21		0.98		997.60		995.48
Phase: Liquid											
pH			**10,24**		**6,85**				**9,76**	**11**	**10.27**
Electrical conductivity	**µS/cm**									**<6000**	**3810**
SOLIDS											
Mass Flow	**KG/HR**	5210	5164.05		0	814	814.29	2125	2160.97	0,44	0.435
Mass Density	**KG/CUM**		5464.32				5464.39		5464.37		5464.32

Table 13: comparison of real data and simulation results for outlet stream for the gas washing system of ILVA BOF No1

Irrelevant gaps between real and simulated values allow to validate the model for the normal operating conditions. By exploiting the validated model and by assuming a constant global mass balance, which means to respect the gas/liquid ratio for BOF gas washing process in Venturi scrubbers, the use of blow down water from CC No 1 was investigated (see an overall scheme in Figure 12).
In order to respect the global mass balance it is necessary to continue supplying fresh water to the system, but reducing the amount of required freshwater. Tables 14, 15 and 16 show the results for this option for inlet, intermediate and outlest streams, respectively. In particular, where available, the features of the Tara water and of the CCO1 blowdown water are compared in order to show analogies and differences.
The quality of water blowdown appears almost the same, with irrelevant changes in pH value and electrical conductivity with respect to the standard situation. Therefore the simulation results reveal that this option can be a promising on-line application, involving reuse of blowdown stream with the consequent reduction fresh water drawing.

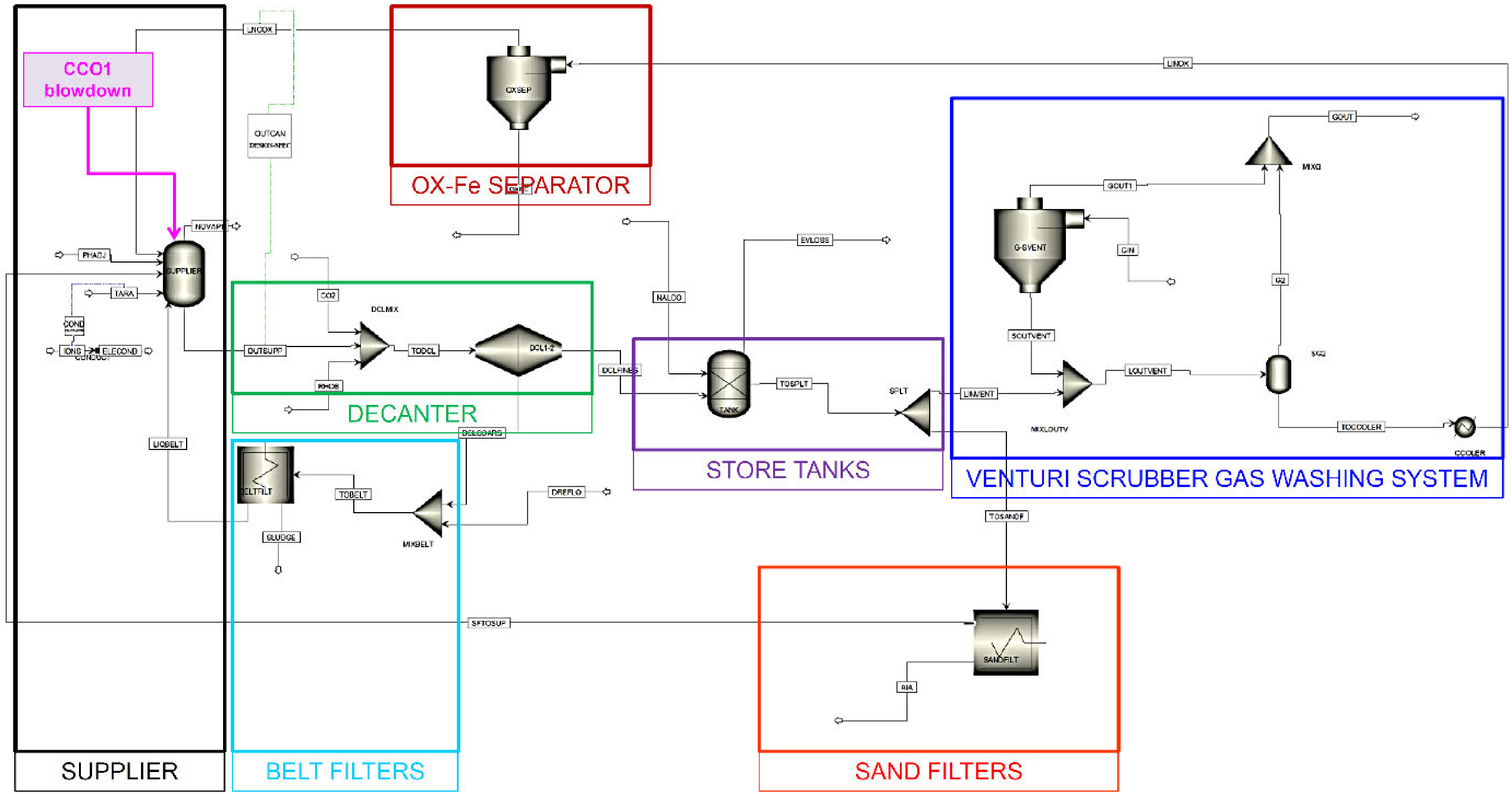


Figure I2: Water network for the gas washing system of BOF No1 simulation flowsheet for the option of CCO1 blowdown reuse

	Units	CCO1		TARA		CO2		RHOB		DREFLO		NALCO		PHADJ		GIN	
		CCO1	Tara	CCO1	Tara	CCO1	Tara	CCO1	Tara	CCO1	Tara	CCO1	Tara	CCO1	Tara	CCO1	Tara
From																	
To					SUPPLIER		DCLMIX	DCLMIX	DCLMIX		MIXBELT		TANK		SUPPLIER		G-SVENT
GLOBAL																	
Mass Flow	KG/HR	15000	-	20000	35000	2.1	2,1	23333	23333	7000	7000	8,71	8,71	30	30	184826	184826
Temp.	C	27	-	27	27	27	27	30	30	25	25	25	25	30	30	200	200
Pressure	BAR	2	-	2	2	4	4	2	2	1.2	1,2	1.2	1.2	1	1	1	1
Mass Density	KG/CUM	997.12	-	998.15	998.15	7.19	7.19	997.52	997.52	997.2	997.2	1046.7	1046.7	1441.9	1441.9	0.70	0.70
Phase: Liquid			-														
pH		8,07	-	7,92	7,92			9,26	9,26	7	7	12	12	16,87	16,87		
Electrical conductivity	µS/cm	1207	-	3365	3365			4746	4746								
SOLIDS																	
Mass Flow	KG/HR	0,15	-	0.0735	0.0735	0	0	4,67	4,67	0	0	0	0	0	0	8143	8143
Mass Density	KG/CUM	5464.4	-	2648.3	2648.3			5464.4	5464.4							5464.4	5464.4

Table 14: Simulation results for inlet streams for CCO1 blowdown reuse

	Units	OUTSUPP		TODCL		DCLFINES		DCLCOARS		TOBELT		LIQBELT		TOSPLT	
		CCO1	Tara	CCO1	Tara	CCO1	Tara	CCO1	Tara	CCO1	Tara	CCO1	Tara	CCO1	Tara
From			SUPPLIER		DCLMIX		DCL1-2		DCL1-2		MIXBELT		BELTFILT		TANK
To			DCLMIX		DCL1-2		TANK		MIXBELT		BELTFILT		SUPPLIER		SPLT
GLOBAL															
Mass Flow	KG/HR	501362	501350	524697	524685	474095	474078	50602.1	50607.1	57602.1	57607.1	47237.4	47231	468477	468459
Temp.	C	35	35	34.78	34.78	34.78	34.78	34.78	34.78	33,48	33.48	33.48	33.48	34.79	34.79
Pressure	BAR	2	2	2	2	2	2	2	2	1.2	1.2	1.2	1.2	1.2	1.2
Mass Density	KG/CUM	995.25	995.45	995.35	995.55	995.33	995.51	995.64	995.92	995.87	996.11	995.64	995.82	995.30	995.49
Phase: Liquid															
pH		10.58	10.42	10.46	10.26	10.46	10.26	10.46	10.26	10.45	10.24	10.45	10.24	10.47	10.27
El. con.	µS/cm					3255	3764								
SOLIDS															
Mass Flow	KG/HR	9515.7	9515.4	9520.4	9520.0	3242.8	3242.7	6277.5	6277.3	6277.5	6277.3	1113.4	1113,3	3242.8	3242.7
Mass Density	KG/CUM	5464.32	5464.32	5464.32	5464.32	5464.32	5464.32	5464.32	5464.32	5464.32	5464.32	5464.32	5464.32	5464,32	5464,32

Table 15: Simulation results for intermediate streams for CCO1 blowdown reuse

	Units	SLUDGE		EVLOSS		GOUT		OXFE		AIA	
		CCO1	Tara	CCO1	Tara	CCO1	Tara	CCO1	Tara	CCO1	Tara
From			BELTFILT		TANK		MIXG		OXSEP		SANDFILT
GLOBAL											
Mass Flow	KG/HR	10364.7	10376.1	5627	5627	177489	177489	3073.9	3074.1	53783.6	53780.3
Temperature	C	33.48	33,48	34.79	34.79	65	65	35.00	35,00	34.79	34.79
Pressure	BAR	1.2	1.2	1.2	1.2	1	1	0.755	0.755	1.2	1.2
Mass Density	KG/CUM	997.8	998.7	994.2	994.2	0,981	0,981	997.25	997.60	995.3	995.5
Phase: Liquid											
pH		10.45	10.24	6.85	6,85			10.20	9.76	10.47	10.27
Electrical conductivity	µS/cm									3296	3810
SOLIDS											
Mass Flow	KG/HR	5164.1	5164.0	0	0	814.3	814.3	2161	2161	0,435	0,435
Mass Density	KG/CUM	5464.3	5464.3			5464.4	5464.4	5464.37	5464.37	5464.32	5464.32

Table 16: Simulation results for outlet streams for CCO1 blowdown reuse

15.1.2 CASE STUDY No2: reuse of blow down water from CCO2/3/4 for the off-gas cleaning of the BOF2

SSSA developed with an analogous approach a model with Aspen Plus® to represent ILVA area of interest.

Figure I3 shows ILVA water network for the gas washing system of BOF No2. The main intake of fresh water comes from Sinni river, which is a high quality freshwater source.

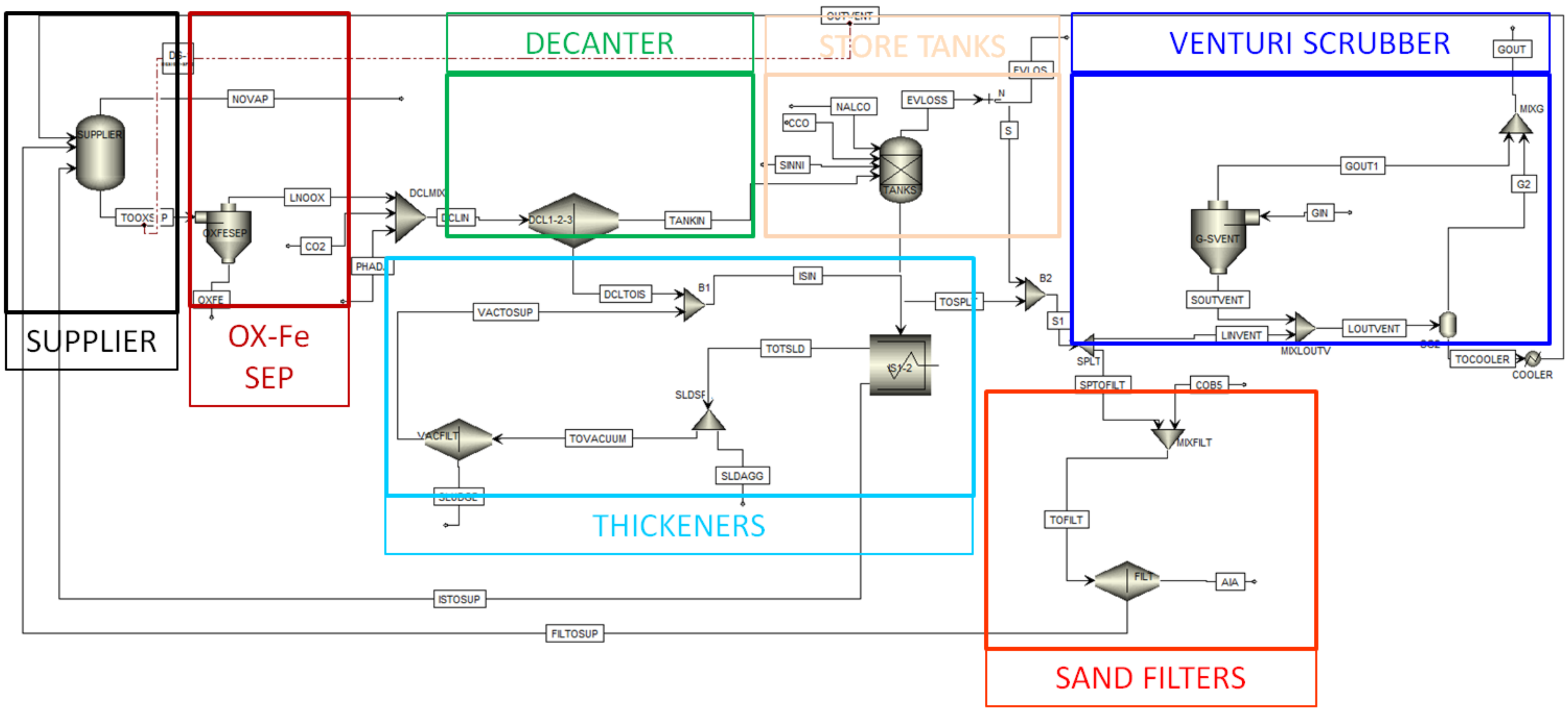


Figure I3 BOF2 gas washing simulation flowsheet

There is a supplier, where all the recirculated process water streams are mixed together and sent to a separator to eliminate iron oxides. Water outlet is the charge for the clarifier unit, where the overflow is recovered and sent to mixing tanks with freshwater. Most of the amount of water from tanks is used to wash gases coming from BOF2 area while the remaining fraction is filtered, together with wastewater coming from another ILVA area (COB5), to be discharged. Course outlet is sent back to the supplier. Sludge from the decanter is treated in belt filters, where the water is recovered and thickened fraction is in part sent to agglomeration area. The remaining fraction is the charge for vacuum filters, where sludge are separated from water to recover.
The results for standard operating conditions for inlet and outlet streams are show in Tables I7 and I8, respectively. The values reported in red represent the main parameters of interest with respect to water quality. Little gaps allow validating the model.
Analogously to the previous case study, fixing the global mass balance, the option of reusing the wastewater coming from the CC areas (CCO2/3/4) was evaluated. Part of the freshwater has been replaced by this stream and results related to streams features for inlets and outlets are shown in Tables I9 and I10.
The quality of water blowdown appears almost the same in terms of pH value with respect to the standard situation. Therefore the simulation results reveal that this option can be a promising on-line application to obtain a reduction in fresh water drawing.

	Units	SINNI		CO2		COB5		NALCO		GIN	
		Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output
GLOBAL											
Mass Flow	**KG/HR**	42000	42000	58.2	58.2	206000	206000	2.28	2.28	210314	210314
Temperature	**C**	27	27	27	27	30	30	25	25	900	900
Pressure	**BAR**	2	2	4	4	2	2	1.2	1.2		
Phase: Liquid											
pH		**8.4**	**8.1**			**8.5**	**8.1**				
Electrical conductivity	**µS/cm**	**350**	**387**			**500-1000**	**1082**				
SOLIDS											
Mass Flow	**KG/HR**	0.35	0.35			2.06	2.06			9762	9762

Table I7: comparison of real data and simulation results for inlet streams for the gas washing system of ILVA BOF No2

	Units	SLUDGE		SLUDGE TO AGG		EVLOSS		GOUT		OXFE		AIA	
		Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output
GLOBAL													
Mass Flow	**KG/HR**	2500	2508	33333	33323	180000	183443	200550	201297	2542	2878	39583	40569
Temperature	**C**	35	35	35	35			65	65	35	35	32	32.3
Pressure	**BAR**	1	1	1	1			1	1	1.5	1.89	1	1
Phase: Liquid													
pH													**9.15**
Electrical conductivity	**µS/cm**												
SOLIDS													
Mass Flow	**KG/HR**	1000	849	5000	5436.6				780.95	2288	2697	0.4	0.52

Table I8: comparison of real data and simulation results for outlet stream for the gas washing system of ILVA BOF No1

	Units	SINNI		CCO WATER		CO2		COB5		NALCO		GIN	
		CCO + Sinni	Sinni	CCO + Sinni	Sinni	CCO + Sinni	Sinni	CCO + Sinni	Sinni	CCO + Sinni	Sinni	CCO + Sinni	Sinni
GLOBAL													
Mass Flow	**KG/HR**	24360	42000	17640	-	58.2	58.2	206000	206000	2.28	2.28	210314	210314
Temperature	**C**	27	27	30	-	27	27	30	30	25	25	900	900
Pressure	**BAR**	2	2	2	-	4	4	2	2	1.2	1.2		
Phase: Liquid					-								
pH		**8.1**	**8.1**		-			**8.1**	**8.1**				
Electrical conductivity	**µS/cm**	**387**	**387**	**1310**	-			**1082**	**1082**				
SOLIDS					-								
Mass Flow	**KG/HR**	0.35	0.35	0.1	-			2.06	2.06			9762	9762

Table I9: comparison of simulation results with and without the reuse of CCO2/3/4 wastewater for inlet streams

	Units	SLUDGE		SLUDGE TO AGG		EVLOSS		GOUT		OXFE		AIA	
		CCO + Sinni	Sinni	CCO + Sinni	Sinni	CCO + Sinni	Sinni	CCO + Sinni	Sinni	CCO + Sinni	Sinni	CCO + Sinni	Sinni
GLOBAL													
Mass Flow	**KG/HR**	2511	2508	33360	33323	185015	183443	201287	201297	2882	2878	40710	40569
Temperature	**C**	35	35	35	35			65	65	35	35	32.3	32.3
Pressure	**BAR**	1	1	1	1			1	1	1.89	1.89	1	1
Phase: Liquid													
pH												**8.6**	**9.15**
Electrical conductivity	**µS/cm**												
SOLIDS													
Mass Flow	**KG/HR**	849	849	5436.64	5436.6			780.95	780.95	2698	2697	0.52	0.52

Table I10: comparison of simulation results with and without the reuse of CCO2/3/4 wastewater for outlet streams

However, according to ILVA staff position, the differences in the current quality of CCO wastewater with respect to the past year are such that this solution is no more promising, therefore it was not selected for the experimental trials to be developed in WP5.

15.1.3 CASE STUDY No3: reuse of blow down water from RIV1 in TUL1

SSSA developed an Aspen Plus® model of ILVA pipe mill washing water network.

Three main water users and a complex treatment system compose the real network. Indeed, water is exploited in washing systems of pipe forming and pipe finishing and in hydraulic press to make tests on pipe. During these processes, water contamination occurs mainly by oil and suspended solids. Water is treated in a complex system before its recirculation and/or discharge in order to make it suitable to the internal reuse and to comply with discharge contaminants limits.

A circuit for pipe forming process and a distinct circuit for the finishing one constitute the water treatment arrangement because of the greater use of lubricant oil in forming process. Several equipments compose each circuit: homogenization and storage tanks (water, rainwater, oil), circular and longitudinal decanters, sand and carbon filters, an oil separator and a sludge thickener. The addition of chemicals (e.g. NaOH, NaClO) enhances water treatment efficiency and control pH value.

Nowadays Sinni river is the main supplier of make-up water; rainwater and water used in welding are also added to the system.

The model development required some assumptions and simplifications: for istance similar unit operations were grouped and represented in one single block and the washing processes were considered as oil and SS producers. Some adjustments were needed, such as the addition of a stream to consider salt contamination in finishing washing system and to target the EC value in the water stream; the concentration of NaClO and NaOH has been also set to have a pH of 8,5-9,5 in the whole water network. Figure I4 shows the flowsheet of the developed «virtual plant»: despite of its complexity, it represents a simplified representation of the real scenario, as the number of units is lower than the number of units that are present in the real plant. The main unit operations are delimited with coloured squares and the labels highlits which real unit operations were assembled. In some cases (e.g. in the thickener modelling), one real equipment is depicted using different Aspen Plus® unit operations.

In the model representation, continuous arrows stand for material streams and dotted lines are auxiliary streams for calculator blocks and design specs operations. Calculator blocks allow the calculation of water electrical conductivity. On the other hand, design spec block is used to set a moisture content of the outlet sludge. Models of make-up water streams are based on real data and consider a simplified ionic representation of industrial wastewater.

The results for standard operating conditions are shown in Tables I11, I12 and I13, for inlet, intermediate and outlet streams, respectively: real data and simulation results are compared.

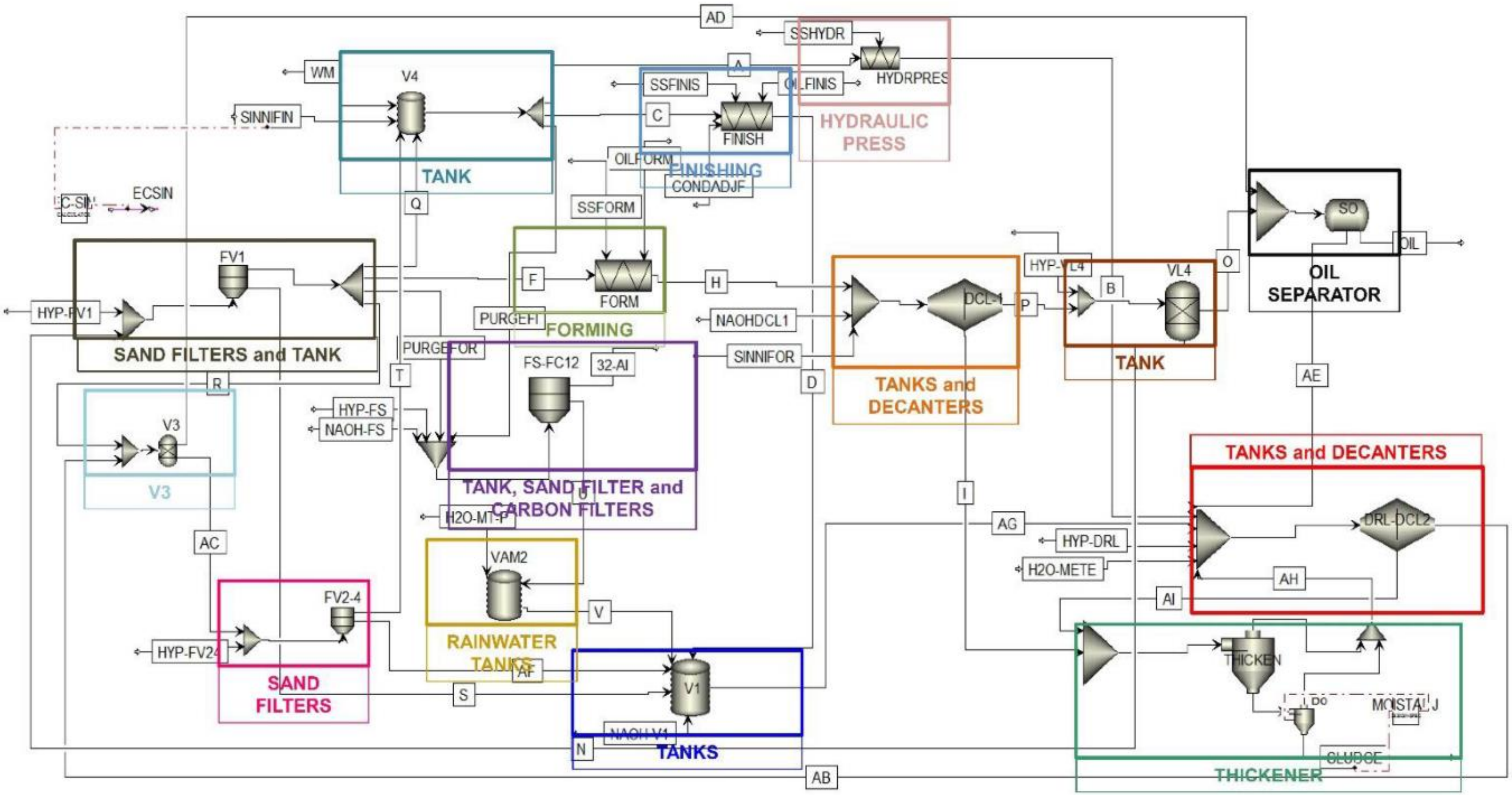


Figure 14: TUL1 simulation flowsheet.

	Streams	Sinni_Fin		WM		Hyp_FV1		SS_Fin		Oil_Fin		Condadj	
		Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output
From													
To			V-4		V-4		FV-1		Finishing		Finishing		Forming
Mass Flow	**kg/h**	2580	2580	60	60	1.32	1.32	2.33	2.33	0.07	0.07	-	4
T	**°C**	27	27	40	40	25	25	40	40	40	40	-	40
pH		8.3	8.1	n.a.	7.8	n.a.	8.9	-	-	-	-	-	-
EC	**µCa**	358	387	n.a.	386	-	-	-	-	-	-	-	-
SS	**g/h**	20	22	-	-	-	-	2329	2329	-	-	-	-
SS Conc	**mg/kg**	8.4	8.4	-	-	-	-	-	-	-	-	-	-
Oil	**g/h**	-	-	-	-	-	-	-	-	68	68	-	-
Oil Conc	**mg/kg**	-	-	-		-	-	-	-	-	-	-	-

	Streams	SS_hydr		SS_form		Oil_Form		Sinni_Form		NaOH_DCL1		Hyp_VL4	
		Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output
From													
To			Hyd. Press		Forming		Forming		DCL-1		DCL-1		VL-4
Mass Flow	**kg/h**	0.95	0.95	0.25	0.25	0.07	0.07	3500	3500	2.44	2.43	3.1	3.1
T	**°C**	40	40	40	40	40	40	27	27	25	25	25	25
pH		-	-	-	-	-	-	8.3	8.1	n.a.	8.8	n.a.	8.9
EC	**µC/cm**	-	-	-	-	-	-	358	387	-	-	-	-
SS	**g/h**	954	954	252	252	-	-	29	29	-	-	-	-
SS Conc	**mg/kg**	-	-	-	-	-	-	8.4	8.4	-	-	-	-
Oil	**g/h**	-	-	-	-	75	75	-	-	-	-	-	-
Oil Conc	**mg/kg**	-	-	-	-	-	-	-	-	-	-	-	-

	Streams	Hyp_FS		NaOH_FS		Hyp-FV24		NaOH_V1		H2O_mete		Hyp_DRL	
		Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output
From													
To			FS-FC-1-2		FS-FC-1-2		FV-2-4		V-1		DRL-DCL-2		DRL-DCL-2
Mass Flow	**kg/h**	1.32	1.32	8.31	8.28	2.63	2.63	2.44	2.43	30	30	10.8	10.8
T	**°C**	25	25	25	25	25	25	25	25	25	25	25	25
pH		n.a.	8.9	n.a.	8.8	n.a.	8.9	n.a.	8.8	n.a.	8.1	n.a.	8.9
EC	**µS/cm**	-	-	-	-	-	-	-	-	n.a.	387	-	-
SS	**g/h**	-	-	-	-	-	-	-	-	n.a.	0.3	-	-
SS Conc	**mg/kg**	-	-	-	-	-	-	-	-	-	-	-	-
Oil	**kg/h**	-	-	-	-	-	-	-	-	-	-	-	-
Oil Conc	**mg/kg**	-	-	-	-	-	-	-	-	-	-	-	-

Table I11: comparison of real data and simulation results for inlet streams at ILVA TUL1.

	Streams	A		B		c		D		F	
		Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output
From			V4		Hyd. Press		V-4		Finishing		FV-1
To			Hyd. Press		DRL-DCL-2		Finishing		V1		Forming
Flow	kg/h	2719	2966	2720	2967	33984	35920	33987	35926	2625	2666
T	°C	n.a.	27	n.a.	27	n.a.	27	n.a.	27	n.a.	27
pH		n.a.	8.2	n.a.	8.2	n.a.	8.2	n.a.	8.2	n.a.	8.2
EC	µS/cm	n.a.	1774	1622	1774	n.a.	1774	n.a.	2012	n.a.	388
SS	g/h	150	277	1100	1230	1870	3350	4190	5679	93	89
SS Conc	mg/kg	54.9	93.3	405.5	414.6	54.9	93.3	123.4	158.1	35.5	33.5
Oil	g/h	13.0	2.3	13.0	2.3	170.0	27.3	169	9.5	5.2	57.1
Oil Conc	mg/kg	5.0	0.8	5.0	0.8	5.0	0.8	7.0	2.6	2.0	21.4

	Streams	H		N		ac		Purgefi		Purgefor	
		Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output	Data	Model Output
From			Forming		VL-4		V-3		V-4		FV-1
To			DCL-1		FV-1		FV2-4		FS-FC-1-2		FS-FC-1-2
Flow	kg/h	2625	2666	6130	6171	40694	43237	6805	7100	94	96
T	°C	n.a.	27	n.a.	27	n.a.	27	n.a.	27	n.a.	27
pH		n.a.	8.2	n.a.	8.2	n.a.	8.2	n.a.	8.2	n.a.	8.2
EC	µS/cm	n.a.	390	297	388	2401	1916	n.a.	1774	n.a.	388
SS	g/h	345	341	356	351	8710	14383	370	662	3	3
SS Conc	mg/kg	131.4	127.9	58.0	56.9	214.0	332.6	54.4	93.3	35.5	33.5
Oil	g/h	80.0	132.2	70.0	132.2	n.a.	0.1	33.0	5.4	0.2	2.0
Oil Conc	mg/kg	30.6	49.6	11.6	21.4	n.a.	0.0	4.8	0.7	2.0	21.4

Table I12: comparison of real data and simulation results for intermediate streams at ILVA TUL1.

	Streams	32-AI		Oil		Sludge	
		Data	Model Output	Data	Model Output	Data	Model Output
From			FS-FC-1-2		Oil Separator		Thickener
Flow	kg/h	6193	6144	0.14	0.14	12.7	11.1
T	°C	-	27	n.a.	30	-	27
pH		-	8.2	-	-	-	-
EC	µS/cm	<4500	1754	-	-	n.a.	-
SS	g/h	124	139	n.a.	-	3558	3084
SS Conc	mg/kg	20.0	22.6	n.a.	-	0.3 (kg/kg)	0.3 (kg/kg)
Oil	g/h	0.5	6.3	142.7	136.3	0.0	0.0
Oil Conc	mg/kg	0.08	1.03	n.a.	-	0.0	0.0

Table I13: comparison of real data and simulation results for outlet streams at ILVA TUL1.

The comparison between real data and model results show some small gaps, which are irrilevant for model purpose. The global mass balance is verified with an overall error lower than 0.1%. This fact represents a validation of the developed model.

By assuming a costant global mass balance and exploiting the developed model, the partial replacement of the freshwater source with blowdown from RIV1 was simulated. Figure I15 shows a scheme of the plant where the addition of RIV1 blowdown stream is considered.

Tables I14, I15 and I16 show the results for this option for inlet, intermediate and outlest streams, respectively. In particular, where available, the features of the Sinni water and of the mixed RIV1 and Sinni water are compared in order to show analogies and differences.

Due to the high quality of RIV1 water blowdown, irrelevant variations in the qualities of all the water during the whole process (e.g. pH, EC and SS); also the quality of the water blowdown (32-AI) appears almost the same.

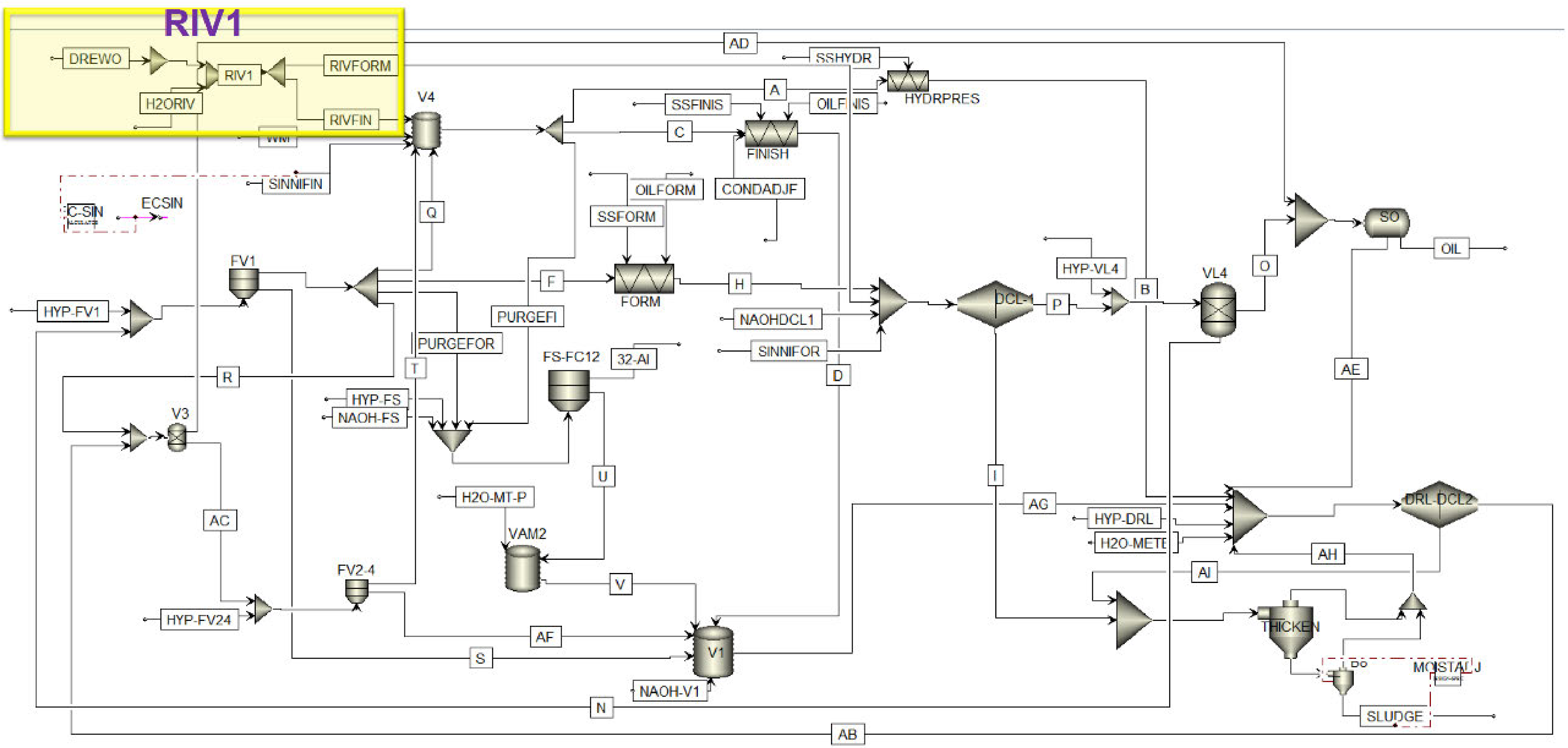


Figure I15: TUL1 simulation flowsheet with RIV1 blowdown reuse.

	Streams	Sinni_Fin		WM		Riv_Fin		Sinni_Form		NaOH_DCL1		Riv_Form	
		Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni
From													
To			V-4		V-4		V-4		DCL-1		DCL-1		DCL-1
Mass Flow	kg/h	2580	2050	60	60		530	3500	2780	2,4	2,4		720
pH		8.1	8.1	7.8	7.8		7.0	8.1	8.1	8.8	8.8		7.0
EC	µC/cm	387	387	386	386		407	387	387				407
SS	g/h	22	17				0	29	23				0.0
SS Conc	mg/kg	8.4	8.4				0.0	8.4	8.3				0.0
Oil	kg/h						0.0						0.0
Oil Conc	mg/kg						0.0						0.0

Table I14: Simulation results for inlet streams of TUL1 for RIV1 blowdown reuse

	Streams	A		b		c		d		f	
		Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni
From			V4		Hyd. Press		V-4		Finishing		FV-1
To			Hyd. Press		DRL-DCL-2		Finishing		V1		Forming
Mass Flow	kg/h	2966	3155	2967	3156	35920	38211	35926	38217	2666	2685
pH		8.2	8.4	8.2	8.4	8.2	8.4	8.2	8.4	8.2	8.3
EC	µC/cm	1774	1781	1774	1781	1774	1781	2012	2004	388	394
SS	g/h	277	468	1230	1422	3350	5671	5679	8000	89	88
SS Conc	mg/kg	93.3	148.4	414.6	450.5	93.3	148.4	158.1	209.3	33.5	32.9
Oil	g/h	2.3	2.3	2.3	2.3	27	27	95	95	57	57
Oil Conc	mg/kg	0.8	0.7	0.8	0.7	0.8	0.7	2.6	2.5	21.4	21.4
	Streams	H		n		ac		Purgefi		Purgefor	
		Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni
From			Forming		VL-4		V-3		V-4		FV-1
To			DCL-1		FV-1		FV2-4		FS-FC-1-2		FS-FC-1-2
Mass Flow	kg/h	2666	2686	6171	6191	43237	46718	7100	7553	96	96
pH		8.2	8.4	8.2	8.3	8.2	8.4	8.2	8.4	8.2	8.3
EC	µS/cm	390	395	388	394	1916	1914	1774	1781	388	394
SS	g/h	341	340	351	344	14382	23263	662	1121	3.2	3.2
SS Conc	mg/kg	127.9	126.6	56.9	55.6	332.6	497.9	93.2	148.4	33.5	32.9
Oil	g/h	132	133	132	133	0.1	0.1	5.4	5.4	2.0	2.1
Oil Conc	mg/kg	49.6	49.4	21.4	21.4	0.0	0.0	0.8	0.7	21.4	21.4

Table I15: Simulation results for intermediate streams of TUL1 for RIV1 blowdown reuse

	Streams	32-AI		Oil		Sludge	
		Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni	Sinni	RIV1 + Sinni
From		FS-FC-1-2	FS-FC-1-2	Oil Separator	Oil Separator	Thickener	Thickener
Mass Flow	kg/h	6144	6132	0,14	0,14	11.2	12.1
pH		8.2	8.4	-	-	-	-
EC	µS/cm	1754	1761	-	-	-	-
SS	g/h	139	152	-	-	3083.6	3296.0
SS Conc	mg/kg	22.6	24.8	-	-	0.3 (kg/kg)	0.3 (kg/kg)
Oil	g/h	6.3	6.0	136.3	136.8	0.0	0.0
Oil Conc	mg/kg	1.0	1.0	-	-	0.0	0.0

Table I16: Simulation results for outlet streams of TUL1 for RIV1 blowdown reuse

In addition, the partial replacement of the freshwater from the Sinni river with the blowdown water if RIV21 can lead to a reduction of about 20% of fresh water intake for this plant , with a total mass flowrate of 4830 kg/h instead of 6080 kg/h. Therefore the simulation results suggests that partial fresh water replacement with RIV1 blowdown can be a promising on-line application.

15.1.4 CASE STUDY No4: contaminants reduction and water reuse of coke-making area wastewater

SSSA used WATER software to evaluate if the solution of proposed water reuse was possible. Initial suggestion related with the necessity of treatments were aquired.

According to the actual ILVA operations, the possibility to reuse wastewater blowdown coming from ammonia stripping area, which is currently discharged, was investigated.

Starting from the water features in terms of contaminants concentrations and hypothesizing to have available different water sources and options of water use and treatments, with their own charateristics of addition or remotion of specific contaminants and operating costs, WATER generated an automatic water network design to minimize operating costs (Figure I16). As highlighted, it is preferable to treat the wastewater coming from ammonia strippers instead of high quality fresh water. The impossibility to impose to the solver to guarantee a discharge, which is always necessary because of contaminants inert increasing concentrations in the reuse cycles, even in cases of very high quality, with the subsequential requirement of make up water, justifies the following considerations. Simulations results show that wastewater can reach a high level of purity if treated by ultrafiltration and reverse osmosis, to be used in the main process as fresh water. In addition it is possible to see that water coming from RO has very high quality because also an addition of "lower" quality water can be carried out without exceeding the required process water properties. Conceptually, WATER suggests evaluating a real option of reuse, as shown only for a better understanding in Figure I17, where SSSA extrapolated the preliminary advices and prompted a real implementation for ILVA plant.

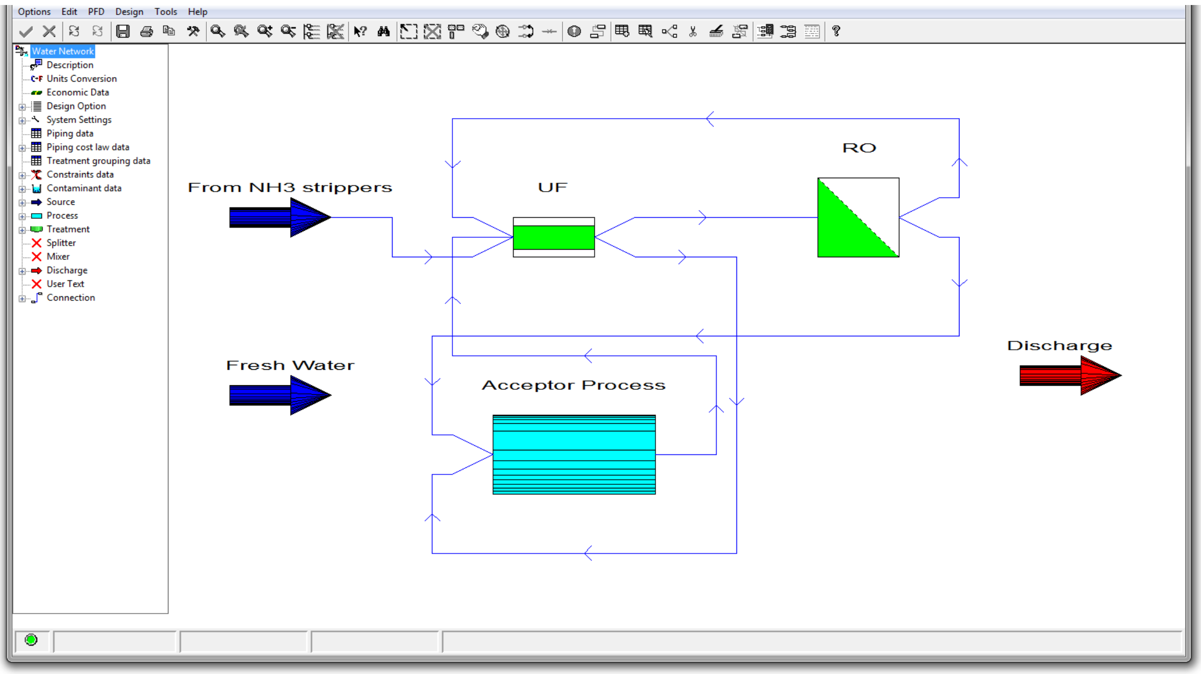


Figure I16: WATER preliminary results for case study no. 4

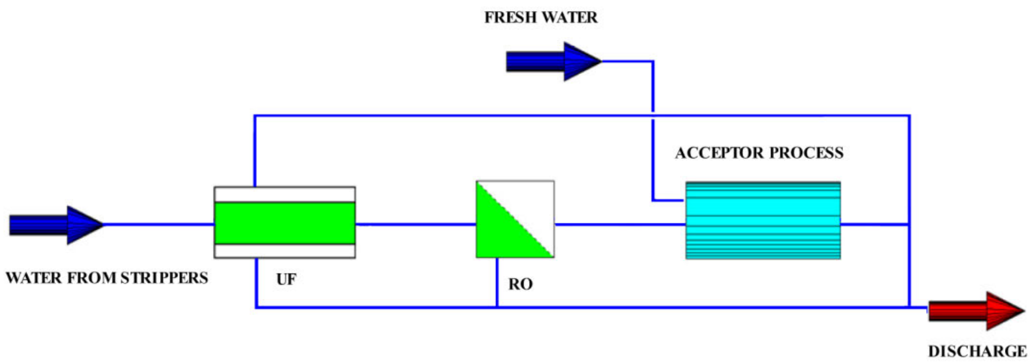


Figure I17: Feasible implementation of WATER proposed solution

With this main result, further investigations was carried out, starting from an economical point of view. Process analyses in terms of capital and operating costs, depending on contaminants concentrations and interested flowrates, together with economical concept like depreciation, were carried out using literature data and engineering information, as well as some of the outcomes of a concluded RFCS project entitled *"Selective salt elimination and valorisation for sustainable water*

and facility management in the steel industry" (Ref. SELSA). In this project RO was applied coupled to a preliminary UF stage, although for the treatment of a different water stream, i.e. the blowdown of a HRM direct cooling system. In particular, the analysis of the PayBack Period (PBP) was pursued concerning the application at industrial scale of a RO plant for the treatment of the considered stream at varying prices of the recovered permeate stream (which is a high-quality water suitable to replace part of the external freshwater intake and/or increase the availability for quality demanding water consuming processes) and of the concentrate stream, whose quality needs to be evaluated as it might be suitable for less demanding water using processes.
The PBP measures the number of the years required to recover an investment i.e. the period of time required for the investment to pay its cost by accumulating savings and gains [9]. Among different investments alternative, usually the investment which has the shortest period of capital recovery is preferred. There are two ways to calculate the PBP: the Simple PBP (SPBP) and the Discounted PBP (DPBP). The SPBP is calculated as the ratio between the investment and the Gross Operating Profit (the gross operating result before the taxes, but after the interest). The SPBP is easy to compute and gives a preliminary evaluation of the level of risk related to an investment, but does not take into account cash flows after the project's payback period and it neglects the time value of the money [18-19]. Therefore a more accurate PBP analysis is usually made through the DPBP, which corresponds to the period by which the accumulated present value of the cash flows covers the initial investment outlay [20]. Clearly the DPBP of the considered option depends on the prices of permeate and retentate streams. The results from the preliminary economic evaluation showed promising advantages in implementing the selected solution. Threfore a real pilot experimental phase has been developed within WP5 in order to obtain realistic data for the evaluation of the technical and economic feasibility of this option (see Appendix N Section 22.1 for the results of the on site trials and Appendix O Section 24.1 for the economic evaluation)

15.1.5 CASE STUDY No 5: Lagoon 1 Water Reuse in BF Gas Wash Systems

In the Tata Steel UK plant, the lagoons are large settlement ponds which act as a collection site for all the major process blowdowns before discharging them as wastewater to a small river stream (Beck). Also they collect large amounts of rainwater due to their low drainage location. Thus, simplistically saying, a lagoon settles suspended solids and dilutes the dissolved solids with the collected rainwater. At Tata Steel UK site, the Lagoon 1 discharge point (to Beck) happens to be in close proximity of nearby settlement areas. Thus there are public and environmental pressures to discharge relatively good quality water at all times. However depending upon the amount of rainwater collected, the discharge water quality varies significantly and hence the site is configured in such a way that it can cope the extreme cases. However this means that Lagoon 1 water quality is well below the environmental limits during the period of high rainfall.

On the other hand the BF gas wash (BF GW) system represents one of the biggest water users on the site and has relatively higher process limits as compared to the Lagoon 1 environmental discharge limits. Thus a significant reduction in fresh water demand can be achieved by using the Lagoon 1 water in the BF GW systems.

However fresh water abstraction limits cannot be reduced if Lagoon 1 water is used intermittently. Hence the idea is to consider average contaminant levels and understand the treatment needs in order not to exceed the discharge water quality levels.

The objective of the optimisation by PIL consists of minimising the sum of treatment, pumping and fresh water cost. And the constraints would be to maintain the water quality in the gas wash water circuit and lagoon 1 discharge the same as that of prior to the Lagoon 1 water reuse.

Based on the collected data, an average case scenario was simulated for the lagoons. The simulations were first achieved in spreadsheets and later transferred to the Water-int™ software as a base case for optimisation. Figure I18 illustrates the base case simulation results for the combined system BF GW and Lagoons.

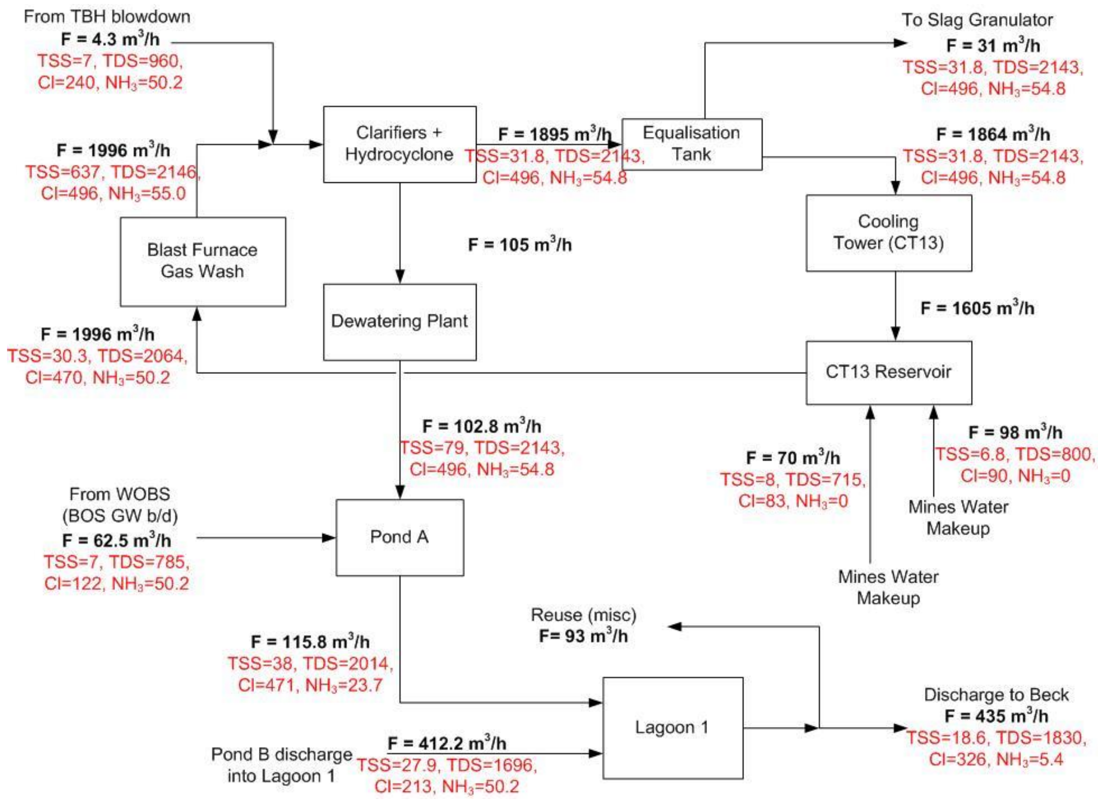


Figure I18: Base case simulation results for the combined system BF GW and Lagoons.

Figure I19 shows the snapshot of WATER-int™ software simulation for RO treatment option considered along with lagoon 1 water reuse.

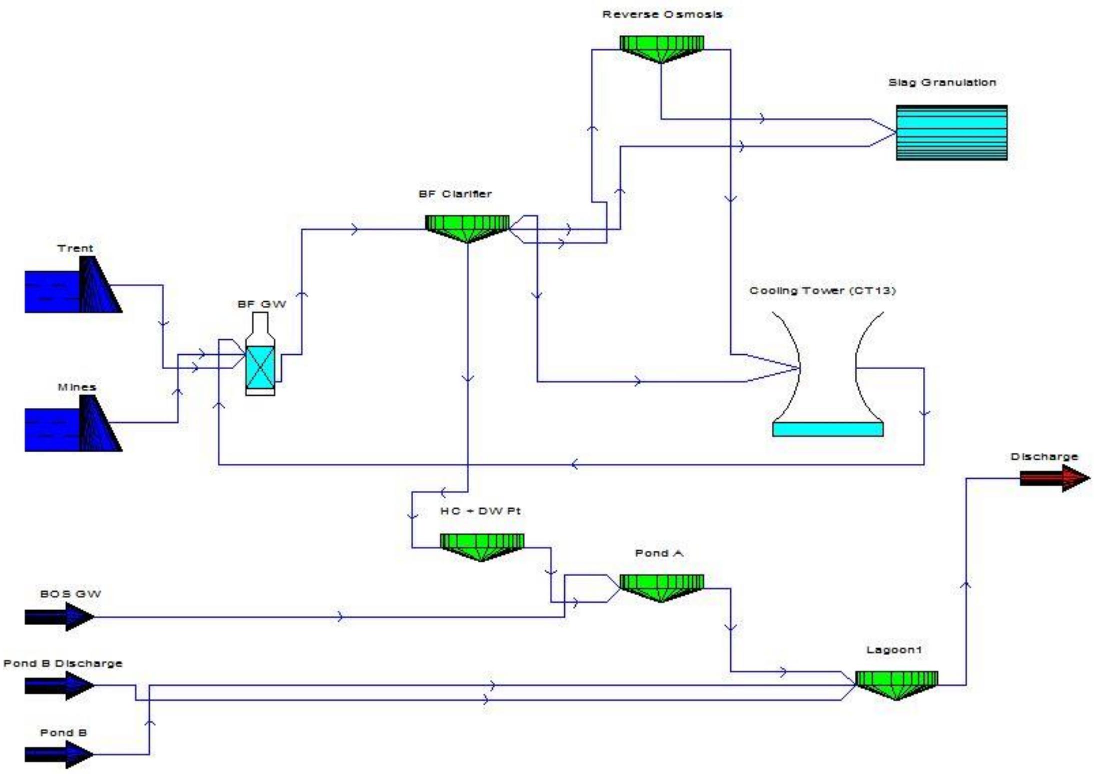


Figure I19: Simulation snapshot of Lagoon 1 water reuse + RO treatment

If lagoon 1 water quality is well within the discharge limits, it is recommended to directly reuse Lagoon 1 water as makeup source for BF GW system. In this case, there is a cost involved in pumping water from Lagoon 1 to the BF GW system. Also such reuse possibilities require an increase in blowdown flowrate. Thus there is a cost involved in pumping the blowdown stream to Lagoon 1. Figure I20 illustrates the trade-offs between reduction in fresh water demand as makeup and the combined cost of pumping Lagoon 1 reuse water and blowdown streams.

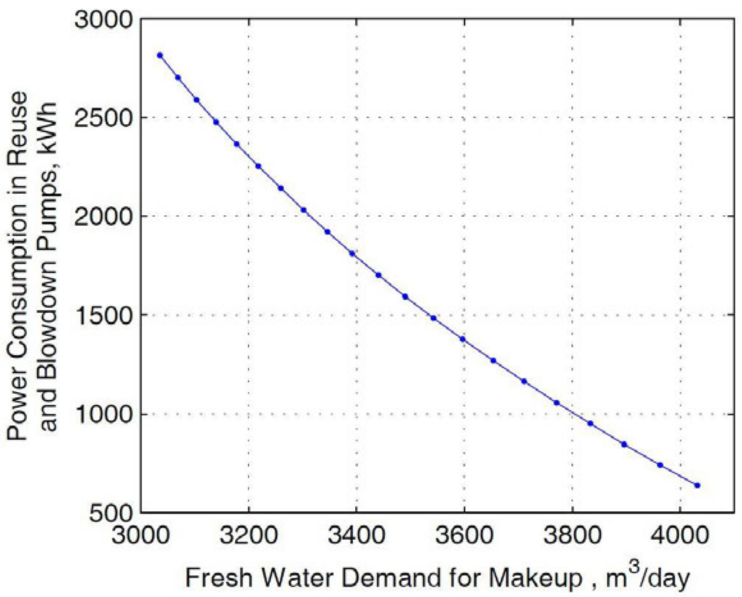


Figure I20: Pareto Front for Lagoon 1 Reuse without Treatment

However one of the major bottlenecks identified with this reuse proposal was that more reuse means more blowdown which in turn significantly increases the ammonia content in Lagoon 1 discharge water. This is because BF GW system is the dominant contributor of ammonia and more blowdown means less ammonia could be disposed through the fixed flow rate sent towards the slag granulation unit. However considering the high potential of water savings, the following 3 treatment options were proposed to mitigate increased ammonia levels:

a. Air Stripping
b. Chlorination
c. RO

Table I17 summarises the comparison among these three treatment options. While Table I18 provides the payback period analysis for these options.

	Air Stripping	Chlorination	RO
CAPEX k£[1]	456	152	915
OPEX, k£/yr[1]	42	104	268
% Contaminant Removal	NH_3 - 99%	NH_3 - 99%, Cyanides - 100%	NH_3 - 91-94%, TDS - 96 - 98% Cl = 92 - 96%
% Water Recovery	100%	100%	70%
Pros	Lowest Operating Cost	Lowest capital cost; Takes care of Legionella issue;	Comprehensively tackles all contaminants in a single step
Cons	Relatively high CAPEX; Need pH adjustment step;	Adds chloramines which can be decomposed & thereby increase chloride content of water; Relatively high operating cost;	Need pre-filtration step; Highest Capital and Operating cost

[1]CAPEX and OPEX estimates listed above are for a treatment unit flowrate of 50 m^3/h and inlet ammonia concentration of 65 mg/L.

Table I17: Comparison between Ammonia Treatment Options

		Air Stripping	Chlorination	RO
CAPEX (k£)	Treatment Unit1	456	152	915
	Pumps	84	84	63
	Piping	26	26	26
	Total	567	262	1005
OPEX (k£/yr)	Treatment Unit1	42	104	268
	Pumping Cost	230	230	248.2
	Water Savings	-541	-541	-1168
	Total	-269	-207	-652
	Payback Period (yr)	2.1	1.3	1.5

Table I18: Payback period analysis for Ammonia Treatment Options

NOTE:

1. CAPEX and OPEX estimates for treatment units are based on treatment unit flowrate of 50 m^3/h and inlet ammonia concentration of 65 mg/L.
2. CAPEX and OPEX estimates for pumps are based on water reuse flowrate.
3. CAPEX estimates for pipings are based on 4" Sch 40 pipe of 2 km length.
4. OPEX estimate for water savings are based on value of treated water as 2 £/m^3
5. It is assumed that air stripping and chlorination options can be operated for 50% of the time.

As can be seen from these tables, all three treatment options provide reasonable payback period (<2 years). However, the first two options (air stripping and chlorination) only deal with Ammonia, and hence the concentration of other contaminants (TSS, TDS and Cl) increases in the final discharge water. Chlorination in particular further increases the chloride levels in the final discharge water. This might be acceptable during periods of high rainwater collection in the lagoons (assumed to be 50% of the time). While RO removes all the concerned contaminants (TSS, TDS, Cl, NH_3) from the system and hence is the preferred treatment choice for this application.
The following advantages can be listed of RO-based treatment approach:

a. Enables water savings and an overall water quality improvement together
b. If placed between the clarifier and cooling tower, it improves the cooling tower inlet water quality. (This improves the reliability of the system since operating issues related to water quality have been reported in the past.)

Figure I21 illustrates Pareto-front for RO-based Lagoon 1 water reuse case study. In this case there are two conflicting objectives namely economical (i.e. minimise RO treatment cost) and environmental (i.e. minimise fresh water demand / wastewater discharge).

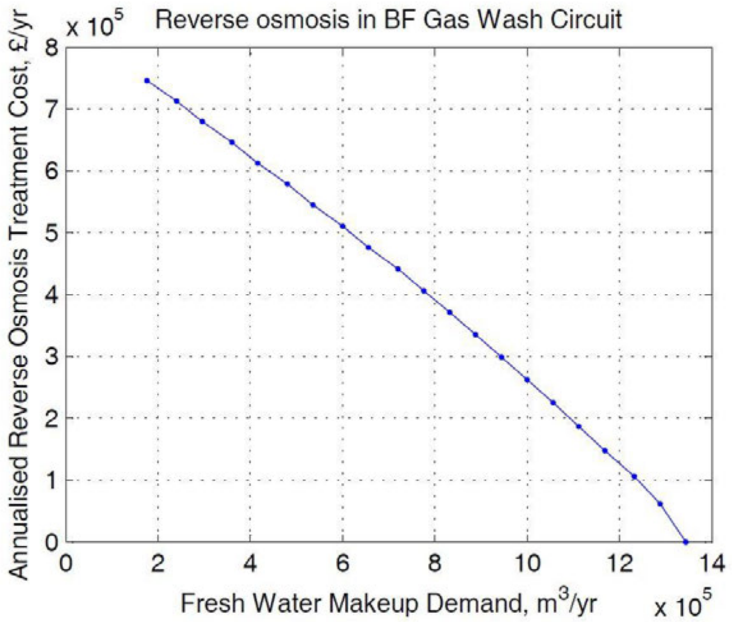


Figure I21: Pareto Front for Lagoon 1 water reuse with RO treatment

Based on such multi-objective optimisation analysis, it was decided to propose a final solution consisting of 50 m^3/h capacity of RO unit. This solution reduces treatment cost through economy of scale and results in a fresh water demand reduction of 71 m^3/h. Both of these objectives are achieved within approximately 1 million £ capital investment target (see Table I18 above).
Figure I22 illustrates the proposed solution in this regard. While Table 33 illustrates the water quality improvements in BF GW water and final discharge water. Also the final discharge amount gets reduced by 16% in this case.

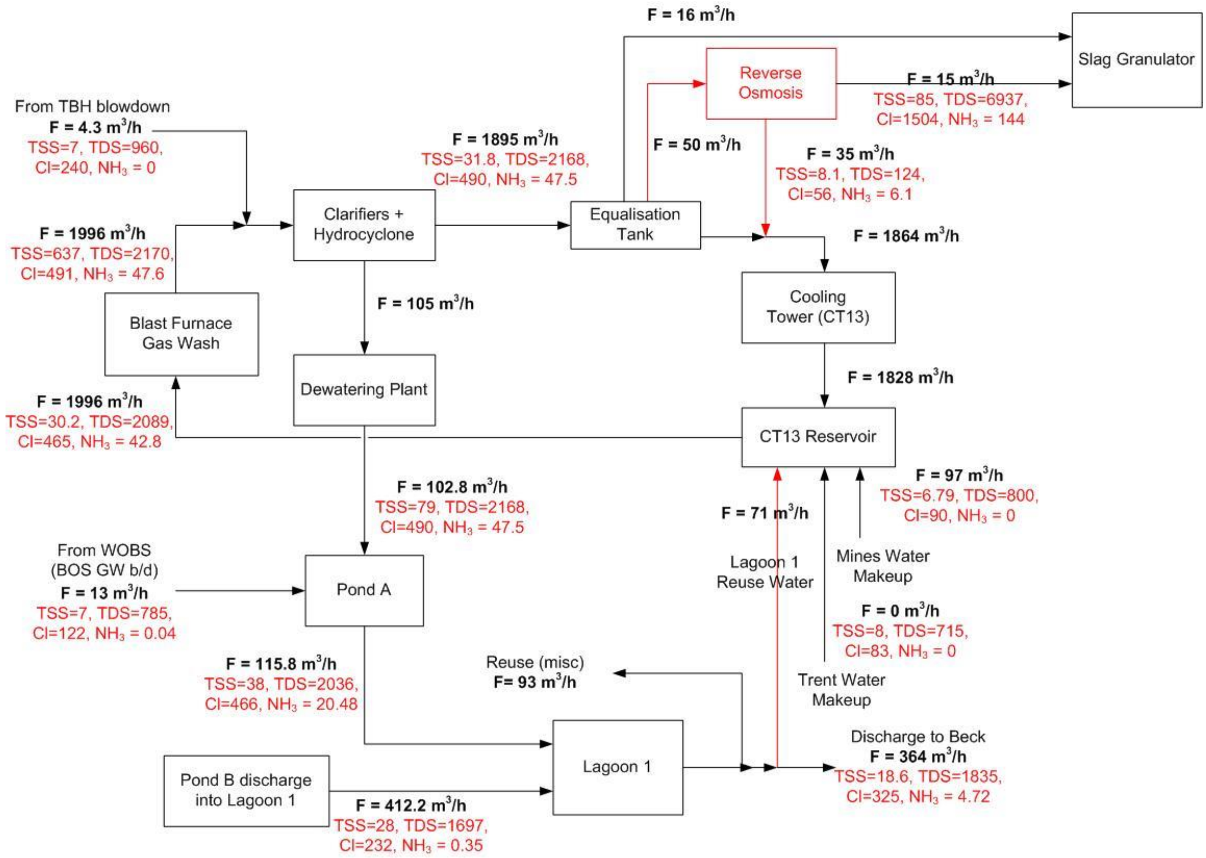


Figure I22: Lagoon 1 water reuse for RO processing capacity of 50 m^3/h

15.1.6 CASE STUDY No 6: Pond A Water Reuse in BF Gas Wash Systems

Lagoon 1 water reuse (discussed above in Case Study No 5) would maintain ammonia concentration or at best reduce it by 10-15%. However this may not be enough for future environmental legislation which may limit ammonia concentration in the final discharge from 4 mg/L to 2 mg/L. In this regard, Pond A water reuse is proposed as a low-cost alternative solution which could specifically achieve substantial reduction in ammonia levels in final discharge water.

In the Tata Steel plant, Pond A represents a large settlement pond which acts as a collection site for the blowdowns from gas wash sections of both BF and BOS plants. Water reuse from Pond A has the following advantages:

a. Due to a large difference in pH values of both of these blowdown streams and associated electrolytic & biological separation involved, a substantial amount of ammonia reduction (30-50%) is observed in Pond A. Thus Pond A can act as a natural sink for ammonia by repeated circulation of the BF gas wash water across it.
b. The BF Gas Wash water accounts for more than 80% of the ammonia contribution towards the final discharge water. Thus Pond A water reuse in the BF GW reduces the amount of the BF GW blowdown reaching the final discharge lagoon and hence results in a substantial reduction in ammonia levels.

Figure 57 illustrates how Pond A is placed in between the BF GW and Lagoon 1 and how the reuse connection can be configured between Pond A and BF GW.

As discussed in the earlier case study, these water reuse schemes result in an increase of contaminant concentrations for a fixed amount of blowdown. However contaminant concentration in this case can be maintained relatively the same by increasing the blowdown amount. This additional blowdown can be taken directly from BF GW recirculation water and used by other users on-site which do not need high quality water. One such potential user would be the bowsering tanks which spray water for dust suppression purposes. Currently bowsering tanks use 93 m^3/h of water from Lagoon 1 and potentially part of their water demand can be satisfied by the additional BF GW blowdown.

Table I19 illustrates the simulation results for Pond A reuse in the exiting configuration wherein overflow from one of the HC is being recycled. In this case the BF GW blowdown to Pond A is limited to 69 m^3/h and the total amount of water available from Pond A is 81 m^3/h. Thus maximum reuse in multiples of 25 would be 75 m^3/h. As can be seen from the results, ammonia reduction of up to 85% can be achieved for Pond A reuse = 75 m^3/h.

Case No.	Pond A Water Reuse m^3/h	Increase in b/d flow m^3/h	BF GW Water Quality TDS mg/L	TSS mg/L	Cl mg/L	NH_3 mg/L	pH -	Lagoon 1 Water Quality TDS mg/L	TSS mg/L	Cl mg/L	NH_3 mg/L	pH -
Base Case	0	0	2089	26.8	482	53.6	7.30	1801	19.8	308	4.11	8.44
1	25	25	2071	27.1	474	48.0	7.38	1787	19.0	296	2.83	8.42
2	50	50	2028	27.4	464	43.4	7.45	1773	18.3	283	1.68	8.41
3	75	75	1987	27.7	454	39.6	7.51	1760	17.5	270	0.61	8.38
			% change vs current case					% change vs current case				
1	25	25	-1%	1%	-2%	-10%	1%	-1%	-4%	-4%	-31%	0%
2	50	50	-3%	2%	-4%	-19%	2%	-2%	-7%	-8%	-59%	0%
3	75	75	-5%	3%	-6%	-26%	3%	-2%	-12%	-13%	-85%	-1%

Table I19: Pond A water reuse results for one HC overflow recycle

However, as it was pointed out above, there are recycles in this case i.e. one from HC overflow and second from Pond A reuse. It might be better to consolidate all the recycle flows through Pond A and thereby take advantage of suspended solids and ammonia separation happening in Pond A. In this case BF GW blowdown to Pond A would be 104 m^3/h and the total amount of water available from Pond A is 116 m^3/h.

Table I20 illustrates the simulation results for Pond A reuse with zero recycle from HC overflow. As can be seen from the results, an improvement in BF GW and Lagoon 1 water quality in terms of NH_3, TDS & Cl are similar to one HC overflow recycle case (see Table I19) if compared on the correct basis of the same blowdown flow. Only the suspended solids numbers are improved, but that too without selective separation of useful components (e.g. iron). Since the approach of avoiding local recycling across the HC involves higher pumping and dewatering plant costs without any substantial benefits, this idea was discarded.

Case No.	Pond A Water Reuse m^3/h	Increase in b/d flow m^3/h	BF GW Water Quality TDS ppm	TSS ppm	Cl ppm	NH3 ppm	pH -	Lagoon 1 Water Quality TDS ppm	TSS ppm	Cl ppm	NH3 ppm	pH -
Base Case	0	0	2089	26.8	482	53.6	7.30	1801	19.8	308	4.11	8.44
1	50	15	2063	25.3	474	43.9	7.45	1800	18.8	303	3.11	8.43
2	75	40	2034	25.5	468	40.1	7.51	1783	18.3	290	2.01	8.41
3	100	65	2007	25.8	463	36.9	7.57	1767	17.7	276	0.97	8.39
			% change vs current case					% change vs current case				
1	50	15	-1%	-6%	-2%	-18%	2%	0%	-5%	-2%	-24%	0%
2	75	40	-3%	-5%	-3%	-25%	3%	-1%	-8%	-6%	-51%	0%
3	100	65	-4%	-4%	-4%	-31%	4%	-2%	-11%	-11%	-76%	-1%

Table I20: Pond A water reuse results for zero HC overflow recycle

Figure I23 illustrates the Pareto-front for Pond A water reuse case study. In this case there are two conflicting objectives namely environmental (i.e. minimise ammonia in discharge water) and operational (i.e. minimise BF GW blowdown to other users e.g. bowsering tanks since it may increase corrosion in this new user).

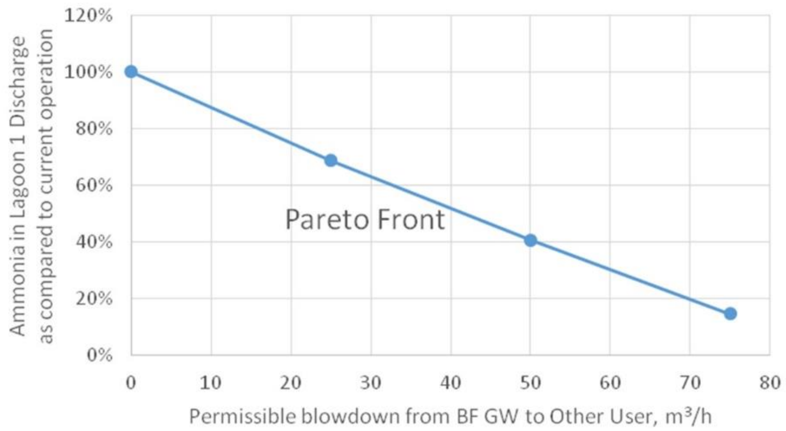


Figure I23: Pareto front for Pond A water reuse case study

Based on this MOO analysis, final recommendation for this case study is to recycle 75 m^3/h of Pond A water with the existing configuration of recycle from one the HC overflow streams. Blowdown to the identified user would be the same amount. This proposal involves installation of 75 m^3/h pump and 1 km long piping of 5" Sch 40 carbon steel pipes. Overall capital expenditure for this proposal would be £21,000. While operating cost of recycling 75 m^3/h of Pond A water is estimated to be around 63,000 £/yr. However, it is difficult to quantify benefits from discharge water quality improvements especially in terms of reduction in ammonia levels. Thus the PBP is not reported in this case, which is acceptable since it is purely a solution to the problem of breaching the environmental limit for ammonia concentration in Lagoon 1 discharge water, and the requirement by plant personnel to deal with the problem.

As discussed, Pond A water reuse is a low cost solution for achieving a substantial reduction in ammonia levels in the final discharge water (85%). However major hurdle in implementation of this case study is the identification of suitable user for this additional blowdown from BF GW and then getting approval from site for such utilisation of gas wash blowdown water. As discussed one such potential destination could be the bowsering tanks, however agreement for implementation by Tata Steel management was not granted due to the current financial situation and further investigations may be required in order to encourage such proposed usage.

15.1.7 CASE STUDY No 7: Recycling of BF GW HC overflow water with suitable treatment

A combination of clarifiers, HCs and pressure filters are used to separate suspended solids from the BF gas wash water. In particular, HCs are low cost, compact classification devices which can concentrate the clarifier slurry directly into sludge without any further dewatering treatment. Furthermore, HC classification separates unwanted metals i.e. Zn and Pb from iron and thus the collected sludge can be directly recycled back to the BFs via the sinter plant process. Thus it was decided to analyse the separations around the HCs more closely in order to achieve suspended solids reduction and to recover iron-rich sludge for reuse purposes.

Figure I24 depicts the suspended solids separation section of the BF GW system.

The following objectives were targeted while performing this case study:

1. Optimise HC separation
   - based on initial measurements and comparison with operating manual performances, it was speculated that the HC operations are far off from optimum performance
2. Need to verify if the current practice of recycling HC1 overflow to clarifier 3 is optimum. (HC behaviour is not well understood by operators since it hardly requires operator's attention)
3. Improve gas washing water quality
   - HC system has contaminants (such as metals and other suspended solids) in more concentrated form and thus can be separated more easily. Strategically placing other treatment units can improve the overall BF GW water quality and thereby reduce maintenance issues.
4. Reduction in dewatering plant treatment and pumping cost
   - Dewatering plant is owned and operated by a third party who are charging per unit mass load of contaminants separated. Also there is a significant pumping cost associated with sending the blowdown from the BF GW system to the Lagoons. Both of these costs will be reduced by decreasing the BF GW system blowdown.
5. Improved Lagoon 1 discharge water quality
   - BF GW blowdown water is a major source of contaminants in the lagoon 1 water. Thus any reduction achieved in its blowdown flow rate will translate into improvement in the discharge water quality.
6. Opportunity to recover more metals
   - As discussed HCs separate valuable iron from Zn and Pb. Thus more recycling means more recovery of iron sludge which in turn can improve profitability.

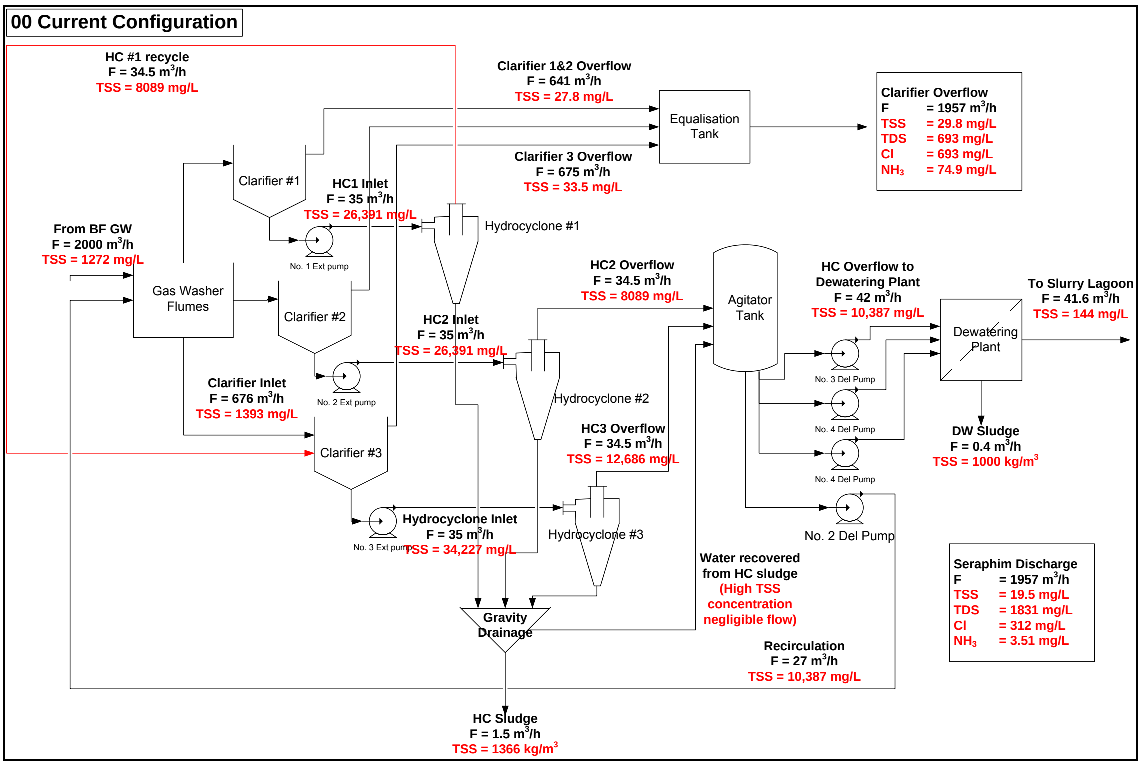


Figure I24: HC Rearrangement - Current configuration

Two kinds of analysis were carried out in this case study. The first one is recycle-reuse analysis wherein recycle connections can be directly added/modified without any interim treatments while the second one is regeneration-recycling wherein strategic location and optimum capacity of treatment units were identified. Optimisation objective for both of these analyses would be to minimise the total cost, and the constraints would be to not exceed the existing contaminant levels.

Recycle-Reuse Analysis

The following six flowschemes were studied for the possibility of direct reuse:

a. Current Configuration
   - Water recycled back from HC#1 overflow and agitator tanks
b. Base Case Configuration
   - No recycle either from HC#1 overflow or agitator tanks
c. Existing – HC#1 Overflow recycle to Gas Wash Flumes
   - Increased mass load from HC#1 overflow recycle is distributed equally among all 3 clarifiers by sending it to gas wash flumes instead of clarifier 3
d. One HC recycle
   - HC#1 overflow recycled but no recycle from agitator tanks
e. Two HCs recycle
   - HC#1 & HC#2 overflow recycled but no recycle from agitator tanks
f. Three HCs recycle
   - HC#1, HC#2 and HC#3 overflow recycled; no recycle from agitator tanks

Table I21 compares the change in water quality in the BF GW circuit and final discharge point in the lagoon system for these 6 cases.

Case #	Case Description	Water Savings m^3/h	Cooling Tower Inlet				Lagoon 1 Discharge			
			TSS mg/l	TDS mg/l	Cl mg/l	NH3 mg/l	TSS mg/l	TDS mg/l	Cl mg/l	NH_3 mg/l
1	Current Operation	62	29.8	2649	649	71	19.5	1832	308	3.37
2	No Recycle Case	0	25.3	1808	398	46	19.7	1953	303	4.57
3	Recycle to Flumes	62	29.3	2649	649	71	19.4	1832	308	3.37
4	1 HC Recycle	35	27.6	2145	501	57	19.8	1801	308	4.12
5	2 HC Recycle	69	31.0	2822	707	77	19.2	1821	305	3.05
6	3 HC Recycle	104	38.8	4870	1333	115	16.8	1729	262	0.33

Table I21: BF GW HC Recycling Without Treatment – Water Quality Analysis

Table I22 shows the sludge metal contents for the HC and dewatering plant (DW) for these 6 cases.

Case #	Case Description	HC Sludge			DW Plant Sludge		
		Fe wt%	Zn wt%	Pb wt%	Fe wt%	Zn wt%	Pb wt%
1	Current Operation	35.0%	0.25%	0.03%	28.6%	6.8%	0.5%
2	No Recycle Case	34.5%	0.18%	0.02%	35.2%	4.7%	0.4%
3	Recycle to Flumes	35.9%	0.33%	0.04%	29.7%	7.2%	0.5%
4	1 HC Recycle	35.5%	0.23%	0.03%	32.7%	5.7%	0.4%
5	2 HC Recycle	36.0%	0.38%	0.04%	28.6%	7.9%	0.6%
6	3 HC Recycle	35.1%	1.44%	0.12%	-	-	-

Table I22: BF GW HC Recycling Without Treatment – Sludge Analysis

NOTE: Typical compositions of BF GW sludge in EU steelmaking plants are Fe: 7-35 wt%, Zn: 1-10 wt% and Pb: 0.8-2.0 wt%, and Zn content of HC sludge is 0.2-0.6 wt% [20]. At the Tata Steel site typical compositions of HC sludge are Fe: ~35 wt%, Zn: 0.2-0.3 wt% and Pb: 0.02-0.04 wt% and is being reused in the BF via the sinter plant. However, unlike the HC sludge, the DW plant sludge cannot be reused in the BF due to its high Zn content.

The following inferences can be made from Table I21 and Table I22:

a. Lower blowdown improves the lagoon water quality but at the same time degrades the GW water quality;
b. Increasing the recycling increases the sludge (and iron) recovery;
c. Increasing the recycling leads to less blowdown from BF GW circuit and hence lower freshwater makeup demand.
d. Connecting the recycles to the gas flumes (which equally distribute water across the three clarifiers) instead of directly to the clarifiers, slightly improves TSS in both cooling tower and lagoon, compared to the current operation. Hence it is recommended to send the recycle streams to the flumes for better distribution across the clarifiers and HCs.

Since the BF GW water quality deteriorates due to the increase in contaminants concentration from recycling, some form of treatment was deemed necessary in this case study. This led to the investigation of regeneration-reuse solutions as discussed below. In general, RO (for the treatment of BF GW cooling tower inlet) and magnetic filtration (for the treatment of HC overflow) were identified as suitable treatment options as discussed below.

Treatment Unit Selection

a. RO

It was decided to add a RO unit on side-stream of the BF GW cooling tower inlet stream (see Figure I25) in order to control the concentration of dissolved solids (TDS, Chlorides and Ammonia) which would otherwise increase due to the water reuse schemes. A RO unit concentrates the contaminants in a reject stream which can be sent directly to a low grade water application such as the slag granulation unit or the bowsering tanks mentioned above, while the permeate stream (i.e. purified water) is sent back to the GW circuit, hence the improvement in gas wash water quality. Such application of a RO unit in BF GW circuit was reported in the past by Terril and Neufied [21]. Calculated values of contaminant concentrations for the permeate and the reject streams of a typical RO unit are shown in Figure I25.

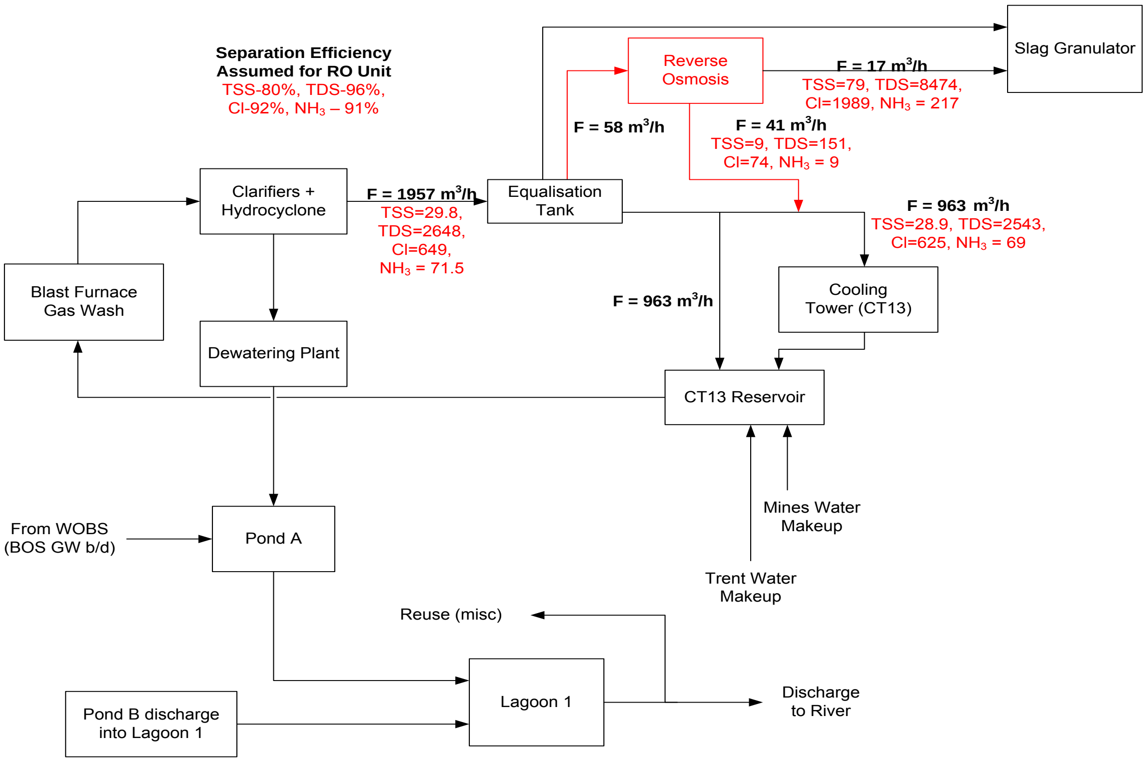


Figure I25: RO Unit Location in BF GW water circuit

b. Magnetic Filtration

It was decided to add a filtration unit on HC overflow in order to control the suspended solids concentrations. This location was selected because suspended solids are in relatively higher concentration here and also resulting the sludge recovery can be recycled back to the BF if Zn and Pb are selectively separated.

Magnetic filtration had previously been used as part of a different research project at a Tata Steel rolling mill [22] and hence was identified as a promising technique in this application. However, this technique had not previously been tested for the BF GW water application and it was decided to carry out a field trial to evaluate the effectiveness of this option. Details of the magnetic field trials can be found in Section 3.5 (WP5 – Task 5.1). Table I23 represents the separation factors for individual metals (Fe, Zn, Pb) that are calculated based on the magnetic filtration trial results.

MF Separation Efficiency (η)			
Overall	Fe	Zn	Pb
10%	17%	8%	6%
50%	84%	40%	28%
90%	100%	47%	33%
99%	100%	47%	33%

Table I23: Estimated separation efficiency based on the magnetic filtration trials

Regeneration-Recycle Analysis

Even after the trials, there was high uncertainty around what size of filter and what separation efficiency should be targeted for this service. Hence it was decided to carry out a scenario-based sensitivity analysis study in order to understand the incremental benefits of filtration capacity and separation efficiency.

In this sensitivity analysis, the recycle flowrate was varied in a stepwise manner from 33% to 100% of blowdown flowrate. Here 33% corresponds to one HC recycle while 100% corresponds to all three HC overflows being recycled back to the GW water flumes. Also separation efficiency of the proposed filter was varied between 10%, 50%, 90% and 99%. Overall a total of 12 different scenarios were generated in this analysis.

Table I24 shows the improvements in the BF GW circuit (cooling tower inlet) and Lagoon 1 discharge water quality when two or more HC overflows are recycled back to the GW water flumes.

#	Case Description	MF η	Water Saving m^3/h	Filter Flow m^3/h	RO Flow m^3/h	BF GW Cooling Tower Inlet TSS mg/l	TDS mg/l	Cl mg/l	NH_3 mg/l	Lagoon 1 Discharge TSS mg/l	TDS mg/l	Cl mg/l	NH_3 mg/l
1	Current	-	62	0	0	29.8	2649	649	71	19.5	1832	308	3.37
2	No Recycle	-	0	0	0	25.3	1808	398	46	19.7	1953	303	4.57
7	1 HC Recycle	10%	35	35	0	27.3	2145	501	57	19.3	1801	308	4.12
8		50%				26.2	2145	501	57	18.4	1801	308	4.12
9		90%				25.3	2145	501	57	18.4	1801	308	4.12
10		99%				25.1	2145	501	57	16.8	1801	308	4.12
11	2 HC Recycle	10%	69	69	13	29.8	2486	628	71	19.0	1801	299	2.86
12		50%				26.9	2486	628	71	18.4	1801	299	2.86
13		90%				24.9	2486	628	71	18.0	1801	299	2.86
14		99%				24.5	2486	628	71	18.0	1801	299	2.86
15	3 HC Recycle	10%	104	104	58	34.1	2205	625	74	16.8	1729	262	0.33
16		50%				27.5	2205	625	74	16.8	1729	262	0.33
17		90%				24.1	2205	625	74	16.8	1729	262	0.33
18		99%				23.5	2205	625	74	16.8	1729	262	0.33

Table I24: BF GW HC Recycling with RO & Filter – Water Analysis

NOTES:

i. Cases 3, 4, 5 and 6 (related to the recycle-reuse scenario) do not involve any additional treatment, and hence are not included in this Table.

ii. RO treatment flow rate was decided based on the requirement to maintain relatively the same water quality in the blast furnace cooling tower inlet.

iii. RO treatment flow is set to zero for 1 HC recycle case since its water quality is already better than current operation.

iv. RO treatment flow rate is fixed at 13 m^3/h for 2 HCs recycle cases (#11-14) and at 58 m^3/h for 3 HCs recycle cases (#15-18).

Table I25 shows the sludge metal contents (Fe, Zn and Pb) for the sludge collected from HC, DW plant and MF for these 12 cases (#7-18).

#	Case Description	MF η	HC Sludge Fe wt%	Zn wt%	Pb wt%	DW Plant Sludge Fe wt%	Zn wt%	Pb wt%	Filtration Sludge Fe wt%	Zn wt%	Pb wt%
1	Current	-	35.0%	0.25%	0.03%	28.6%	6.8%	0.5%	-	-	-
2	No Recycle	-	34.5%	0.18%	0.02%	35.2%	4.7%	0.4%	-	-	-
7	1 HC Recycle	10%	35.1%	0.23%	0.03%	32.8%	5.6%	0.4%	55%	4.4%	0.2%
8		50%	33.9%	0.21%	0.03%	33.1%	5.3%	0.4%	55%	4.1%	0.2%
9		90%	34.4%	0.21%	0.03%	34.8%	5.5%	0.4%	38%	2.8%	0.2%
10		99%	34.6%	0.21%	0.03%	35.3%	5.6%	0.4%	35%	2.6%	0.1%
11	2 HC Recycle	10%	35.4%	0.34%	0.04%	29.1%	7.4%	0.5%	49%	5.8%	0.3%
12		50%	33.1%	0.26%	0.03%	30.6%	6.2%	0.5%	51%	4.9%	0.3%
13		90%	34.1%	0.26%	0.03%	34.3%	6.7%	0.6%	38%	3.5%	0.2%
14		99%	34.5%	0.26%	0.04%	35.3%	6.9%	0.6%	35%	3.2%	0.2%
15	3 HC Recycle	10%	34.8%	0.58%	0.07%	-	-	-	38%	7.9%	0.4%
16		50%	32.1%	0.19%	0.03%	-	-	-	46%	3.4%	0.2%
17		90%	33.9%	0.18%	0.03%	-	-	-	37%	2.4%	0.2%
18		99%	34.5%	0.19%	0.03%	-	-	-	35%	2.3%	0.2%

Table I25: BF GW HC Recycling with RO & Filter – Sludge Analysis

A substantial amount of Fe (up to 244 kg/h or 5.86 tons per day) can be recovered in the MF sludge which can potentially be reused in a BF. However, the Zn content in the MF sludge was estimated to be around 6-10% (based on results from MF trials). It should be noted that, as stated in the BREF Document [2], recycled HC sludge typically contains 0.2–0.6 wt% Zn and thus the current Zn content in the MF sludge is considered unacceptable for reuse in a BF.
However, there exists a large difference in the magnetic properties of Fe and Zn. Also the trials were conducted on a small scale, and with a MF unit which was not purpose-built for such application. Thus there is a need for further research on how to improve the design of the MF for this application. It is expected that a better designed customised MF should be able to recover high quality sludge which can be reused in a BF.

Cost-benefit Analysis

Table I26 summarises the cost information used for calculating the capital and operating costs of the above discussed regeneration-reuse scenarios.

Operating Cost of Treatment Units		
Hydrocyclone	£/kg	0
Magnetic Filter	£/kg	0.0078
Dewatering	£/kg	0.0155
Reverse Osmosis	(£/yr)/(m³/h)	5380

Capital Cost of Treatment Units		
Magnetic Filter		
Base Size (Sludge)	kg	5.23
CAPEX	£	30000
Reverse Osmosis		
Base Size (Flowrate)	m³/h	13
CAPEX	£	407760

Other Cost Parameters		
Cost of Electricity	£/kWh	0.074
Cost of Freshwater	£/m³	0.12
Value of Recovered Iron	£/kg	0.4
Operating Hours	h/yr	8000

Specific Power Consumption of Pumps		
Extraction Pumps	kWh/m³	0.2857
Agitator Tank Pumps	kWh/m³	0.1609
Delivery Pumps	kWh/m³	1.4286

Table I26: Cost Information

Table I27 represents the operating costs breakdown for the proposed regeneration reuse analysis scenarios. The following conclusions can be drawn from this table:

a. Motor and pumping represents a major cost in the system due to agitation needs and the large distance between the blast furnace and lagoon systems.
b. RO treatment is not required for the 1 HC recycle cases, and a relatively small size (13 m^3/h) is required for the 2 HCs recycle cases. It is only when all 3 Hcs are recycled that the unit size and the cost of RO treatment become substantial, but this is offset by the cost savings and other benefits.
c. Total operating cost reduces with increase in recycle flow due to the reduced pumping and dewatering costs.
d. For a given recycle flow, the operating cost slightly increases with increase in filtration efficiency requirement. However, this can be easily overcome by the benefits of improved water quality and increased sludge recovery.

Case #	Case Description	Treatment		Operating Cost				
		RO Flow	MF Flow	RO	MF	DW Plant	Pumping Cost	Total Cost
		m^3/h	m^3/h	k£/yr	k£/yr	k£/yr	k£/yr	k£/yr
1	Current Operation	0	0	0	0	53	690	743
2	No Recycle Case	0	0	0	0	85	1668	1752
7	1 HC Recycle (η = 10%)	0	34.5	0	2	66	1118	1186
8	1 HC Recycle (η = 50%)	0	34.5	0	8	62	1118	1187
9	1 HC Recycle (η = 90%)	0	34.5	0	13	58	1118	1189
10	1 HC Recycle (η = 99%)	0	34.5	0	14	57	1118	1189
11	2 HC Recycle (η = 10%)	10	69	70	4	41	568	683
12	2 HC Recycle (η = 50%)	10	69	70	17	34	568	689
13	2 HC Recycle (η = 90%)	10	69	70	27	29	568	694
14	2 HC Recycle (η = 99%)	10	69	70	29	28	568	695
15	3 HC Recycle (η = 10%)	62	103.5	312	9	0	18	338
16	3 HC Recycle (η = 50%)	54	103.5	312	29	0	18	359
17	3 HC Recycle (η = 90%)	49	103.5	312	41	0	18	371
18	3 HC Recycle (η = 99%)	49	103.5	312	43	0	18	373

Table I27: BF GW HC Recycling with RO & Filter – Operating Cost Analysis

Table I28 represents the trade-offs between capital investment and operating costs. The Table indicates the potential PBPs for the different scenarios studied compared to both the current operation and no recycle cases.

#	Case Description	MF η	Operating Cost				Capital Cost			PBP	
			Total Op. Cost	Savings ΔFe	Savings ΔWater	Net Op. Cost	RO Unit	MF	Total CAPEX	wrt Current Operatn	wrt No Recycle Case
			k£/yr	k£/yr	k£/yr	k£/yr	k£	k£	k£	yr	yr
1	Current Operation	-	743	0	0	743	0	0	0	-	-
2	No Recycle Case	-	1753	-182	-59[a]	1995	0	0	0	-	-
7	1 HC Rcy	10%	1186	34	-26[a]	1178	0	81	81	-0.2[b]	0.1
8		50%	1187	70	-26[a]	1143	0	203	203	-0.5[b]	0.2
9		90%	1189	78	-26[a]	1136	0	277	277	-0.6[b]	0.3
10		99%	1189	78	-25[a]	1136	0	291	291	-0.7[b]	0.3
11	2 HC Rcy	10%	683	290	7	385	408	139	546	1.5	0.3
12		50%	689	331	7	351	408	325	733	1.9	0.4
13		90%	694	339	7	348	408	424	832	2.1	0.5
14		99%	695	339	7	349	408	442	849	2.2	0.5
15	3 HC Rcy	10%	338	600	40	-301	1000	216	1216	1.2	0.5
16		50%	359	600	40	-281	1000	443	1443	1.4	0.6
17		90%	371	600	40	-269	1000	547	1547	1.5	0.7
18		99%	373	600	41	-268	1000	564	1564	1.5	0.7

Table I28: BF GW HC Recycling with RO & Filter – Payback Period Analysis

NOTE:

a. Water savings are shown in negative because 1 HC recycle case needs more makeup water than current case. This is because current case already has one HC overflow being recycled in addition to recycle from agitator tanks.
b. Case 7-10 (for 1 HC recycle) have negative PBPs wrt current operation because both capital cost and operating cost are higher in these cases with respect to current operation. This is because 1HC Recycle case needs additional investment in MF while amount of recycle is less than current operation and hence higher pumping and freshwater costs.

As can be seen from Table I28, the PBP is less than one year if compared against the no recycle case which was the original design case for the system. The PBP varies from 1.2 to 2.2 years if compared against the current operation. It should be noted that these PBP calculations are sensitive to the economic value assigned to the recovered iron and water savings, and hence need to be considered further before a final investment decision is made.

Overall it can be concluded that the BF GW HC overflow recycling with appropriate treatment has numerous environmental and economic benefits. The most effective treatment identified in this research was RO in side-stream of the clarifier overflow stream, and magnetic filtration for the HC overflow recycled water.

The implementation of HC overflow recycling with the above treatment in the BF GW water circuit has the potential to achieve the following benefits:

- Improvement in final lagoon water quality due to reduced blowdown,
- Improvement of water quality in BF GW circuit from treatment,
- Increased sludge (iron) recovery from HC and new MF,
- Lower pumping and agitation costs,
- Lower third-party dewatering plant costs,

- Lower freshwater makeup demand due to reduced blowdown.

Table I29 below summarises the range of potential improvements that can be achieved in the water system studied.

Parameter		Unit	Current Operation	Number HC Overflows Recycled			% Improvement vs zero HC Recycle		
				1	2	3	1 HC	2 HC	3 HC
RO Flow		m^3/h	0	0	13	58	-	-	-
MF Flow		m^3/h	0	34.5	69	103.5	-	-	-
Lagoon 1 Water	TSS	mg/L	19.5	19.0	18.0	16.8	3%	8%	14%
	TDS	mg/L	1832	1801	1796	1729	1%	1%	5%
	Chlorides	mg/L	308	308	299	262	0%	3%	15%
	Ammonia	mg/L	3.37	4.12	2.86	0.33	-22%	15%	90%
Cooling Tower Inlet	TSS	mg/L	29.8	25.3	24.9	24.1	15%	16%	19%
	TDS	mg/L	2648	2145	2486	2205	19%	6%	17%
	Chlorides	mg/L	649	501	628	625	23%	3%	4%
	Ammonia	mg/L	72	57	71	74	20%	1%	-4%
Iron Recovery in HC & MF		kg/h	677	701	783	864	4%	42%	28%
Pumping Energy		kWh	1165	1888	959	30	-62%	66%	97%
Total Op. Cost		k£/yr	743	1189	694	371	60%	-7%	-50%

Table I29: Summary of potential improvements from HC overflow recycling

NOTE:
1. HC recycle cases presented above are based on 90% separation efficiency of MF.
* Assuming that the MF is well designed to produce reusable sludge.

At the time of this research, the Tata Steel site was undergoing difficult economic conditions and the proposed capital investment for the project had to be put on-hold. However, when economic conditions improve, the following two options are recommended for implementation:

- Three HCs overflows recycled back to flumes with the overflow stream treated by magnetic filtration with 90% separation efficiency and side-stream from clarifier overflow treated in a 58 m3/h RO unit. This will achieve significant improvements as mentioned above with a payback period of 1.5 years.
- Two HCs overflow recycled back to flumes with the overflow stream treated by MF with 90% separation efficiency, and side-stream from clarifier overflow treated in a 13 m3/h RO unit. This will achieve the benefits mentioned above with a payback period of 2.1 years.

Table I30 summarises the costs, savings and benefits associated with both these options. The Table shows that option "3 HC Recycle" apart from the initial capital investment, and potential increase in Zn content of sludge, provides greater advantages. However, if the capital investment or sludge Zn content becomes a concern then option "2 HC Recycle" will be a good alternative.
Further field trials and discussions with RO and MF vendors are recommended before finalising the design for implementation. The new MF should be designed for this application such that the Fe content in the sludge is maximised, while the Zn and Pb contents are minimised to enable recovery of high quality sludge which can be reused in BF.

Case Description	Units	1 HC Recycle **(η = 90%)**	2 HC Recycle **(η = 90%)**	3 HC Recycle **(η = 90%)**
RO Treatment Flow	m^3/h	0	13	58
Filtration Flow	m^3/h	34.5	69	103.5
Capital Investment	Million £	0.28	0.83	1.55
Net Operating Cost[a]	Million £/yr	1.13	0.35	-0.27[b]
Payback Period	yr	-0.7	2.1	1.5
Water Savings	km^3/yr	-216	56	336
Δ Iron Recovery	tons/yr	196	847	1499
Suspended Solids in Cooling Tower Inlet[c]	mg/L	25.3	24.9	24.1
NH_3 Reduction in Lagoon 1 Discharge[c]	%	-22%	15%	90%

Table I30: Summary of recommended options

Note:
a. Assuming that the magnetic filter is well designed to produce reusable sludge.
b. Net operating cost is negative in this case because reduction in pumping cost is more than operating cost of magnetic filter.
c. Under the current BF GW water operation configuration, water (make-up) consumption is 107 m^3/h, cooling tower water TSS is 29.8 mg/L, and lagoon 1 NH_3 is 3.4 mg/L.

15.1.8 CASE STUDY No 8: HPM-Ancholme System Water Recovery & Control

Figure I26 represents the schematics of the combined HPM-Ancholme system. As shown, there are two systems (HPM and Ancholme) which are linked together by storm pumps. Starting with the Ancholme water system, it supplies water to the two Coke Ovens, BFs, Rod Mill 2 and serves as a backup to Rod Mill 1. The system has two water sources namely Ancholme river water and excess HPM water which is supplied by river pumps and storm pumps respectively. The flowrate of both of these sets of pumps are larger than the process demand and hence excess water is being diverted towards a storage reservoir. The storage reservoir supports the system during periods when both river pumps and storm pumps are off via manual pressure control and level control mechanisms. The HPM harvests site drainage and excess water from the BOC plant to meet internal mill demand with the additional water pumped into the Ancholme system reducing the abstracted river water demand.

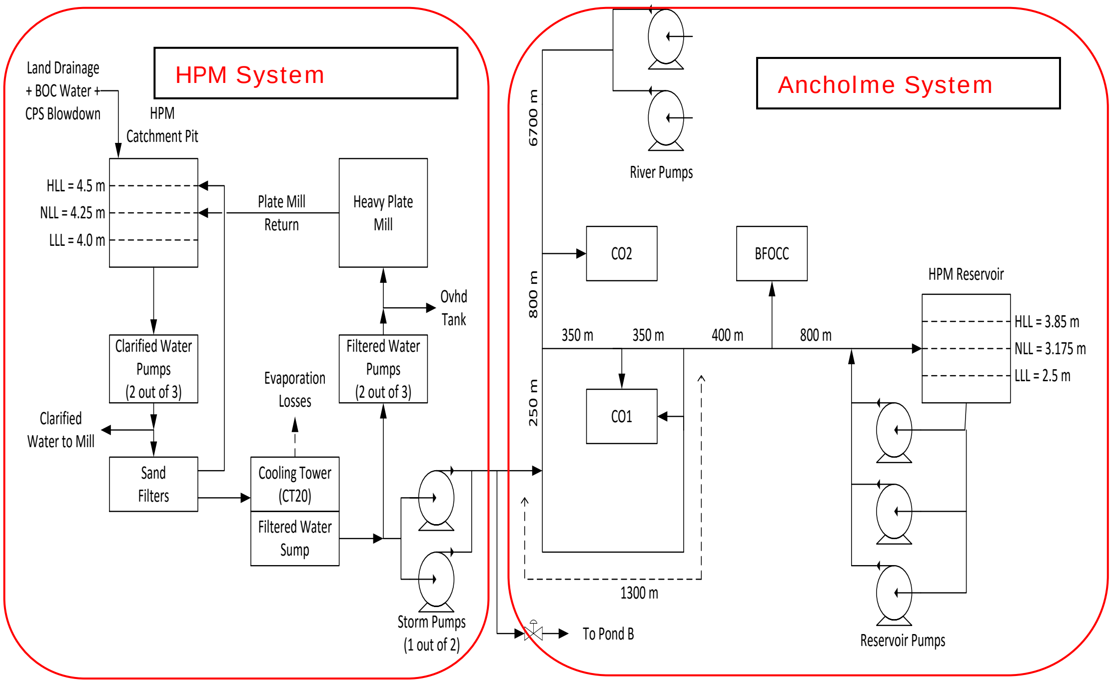


Figure I26: Schematics of HPM-Ancholme System

The following problems/opportunities are being observed in the present set-up:

a. Pressure below 4 bar near the Fire Hydrant supply point

Water is supplied to the fire hydrants near Coke Oven 1 and hence it is critical to maintain the pressure above 4 bar at all times from safety point of view. However, system pressure frequently drops below 4 bar due to switching among river pumps, storm pumps and reservoir pumps.

b. Drainage of good quality HPM water to Pond B

Excess HPM water cannot be sent to Ancholme network due to high pressure when other pumps are operating at the same time due to the current sub-optimal manual control scheme. Thus good quality HPM water is being drained down to Pond B and subsequently discharged from the site.

c. Excess pumping energy consumption

Flow capacity of the fixed speed pumps are 2-5 times larger than the average process demand in the Ancholme network. Thus excess water (i.e. difference between flow capacity and process demand) gets pumped twice i.e. first by river pumps or storm pumps and then by reservoir pumps. Thus flow reduction can eliminate the double pumping of the excess water. Also VSD feature helps to control the discharge pressure in a more energy efficient manner instead of throttling the pressure across the discharge valve. Overall it helps the system to be maintained at a relatively stable pressure of 4 bar.

The following two solutions were proposed in this regard:

a. Installation of a control system linking the pumps and valves to strategic pressure points
b. Upgrade of pumps with variable speed drives

Figure I27 illustrates Pareto-front for VSD capacity optimisation in HPM-Ancholme Water Reuse case study. In this case there are two conflicting objectives namely environmental (i.e. minimise electricity consumption in pumps) and economical (i.e. minimise capital investment required for VSD installation). Based on initial estimates for variable speed drive (VSD) option, payback period was high (>3 years) and hence was not deemed unattractive for this particular application.

Since then the option of control system upgrade is the major focus of this case study. Here the objective is to study the trade-offs between capital investment required for control system upgrade and the benefits achieved in terms of water savings and energy savings. And the constraint would be to maintain the Ancholme water mains system pressure at 4 bar.

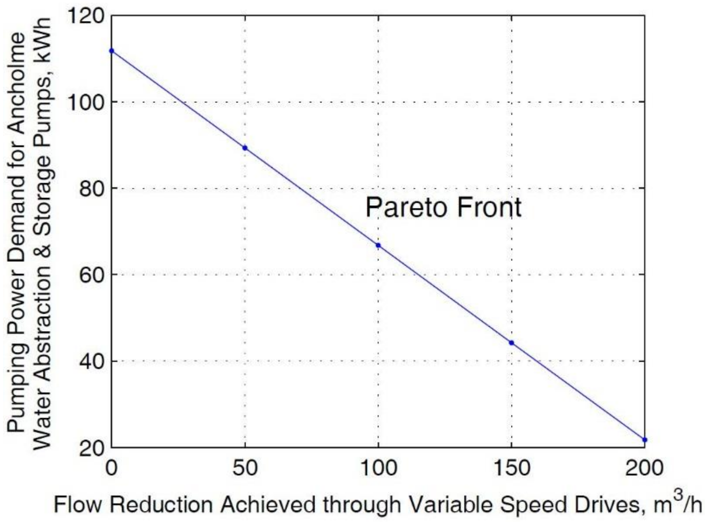


Figure I27: Pareto front for the case study related to HPM-Ancholme Water Reuse

Base Case

Figure I28 represents the simplified system configuration considered for this study. The following simplifications were made in this study:

a. Heavy Plate Mill section was simplified as consisting of just HPM Catchment Pit which receives a net excess water that is discharged either to the Ancholme system or to Pond B under level control. The net water received by HPM Catchment Pit is assumed as constant.
b. All process users are combined together and are assumed to be located near Coke Oven 1 which is where the fire hydrants are also located.
c. It is assumed that each set of service can be represented by a single pump with a combined capacity of multiple pumps which are supposed to be operating simultaneously in these services.
d. An Excel based simulation model was developed wherein pressure variations, pond levels and corresponding water recovery potential are predicted. Figure I29 provides a snapshot of the base case simulation.

An Excel based simulation model was developed wherein pressure variations, pond levels and corresponding water recovery potential are predicted. Figure I29 provides a snapshot of the base case simulation.

The following operating philosophy is considered while developing the simulation of current operation i.e. base case:

a. Storm Pump is activated when HPM Catchment Pit level reaches its upper limit (HLL) i.e. 4.5 m and continues its operation until the level reaches its lower limit i.e. 4 m.
b. River Pump is activated when Ancholme Reservoir level reaches its lower limit (LLL) i.e. 2.5 m and continues its operation until the level reaches its normal liquid level of 3.175 m. (Note: HLL = 3.85 m)
c. Reservoir Pumps do not operate when any of these two pumps are in operation. And vice versa, it is in operation when neither of the two pumps are activated.

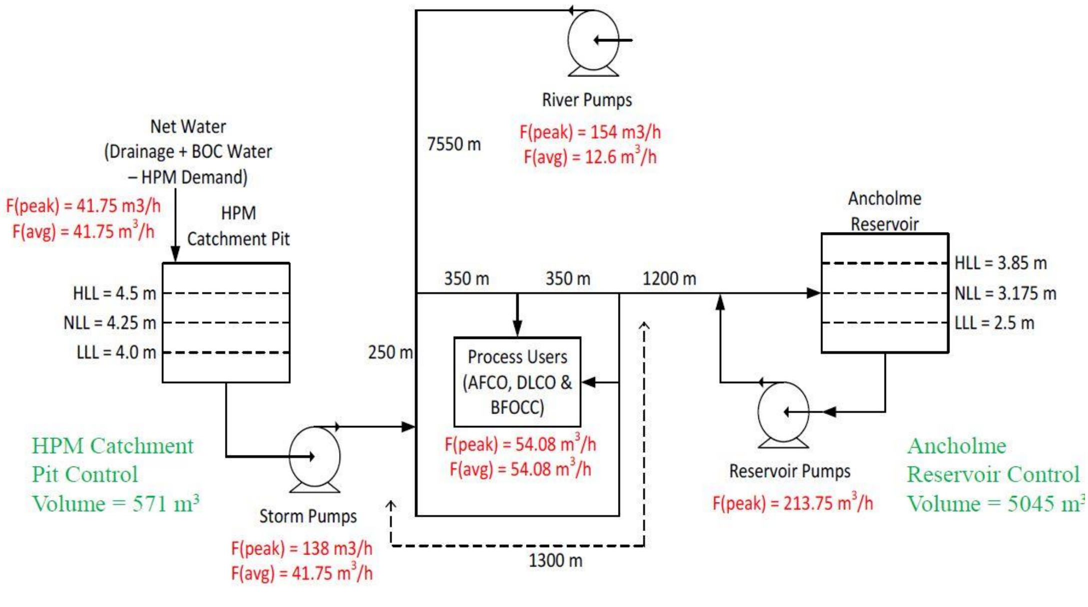


Figure I28: Simplified Flowscheme used for Optimisation Studies

RESULTS		Operational Frequency			Operational Frequency			Total Power Consumption			4 bar	3 bar
		1518	4380	9069	3814	566		91.5	kW		14262	139
		10.1%	29.3%	60.6%	87%	13%		HPM Water drained to Pond B			99.03%	0.97%
		Power Consumption (kW)			Flow (m^3/h)			5.40	m^3/h			
		9.7	9.6	72	36.35	5.40		% of time pressure loss near AFCO				
								0.97%	=14 minutes per day			
INPUTS	Start Date								Cross-sectional Area			
	01/04/2015 00:00								1143	3738		
	End Date								Reservoir HLL (m)			
	31/05/2015 00:00								4.5	3.85		
	Time Interval	Pump Flow (m^3/h)					Average Flow (m^3/h)		Reservoir LLL (m)			
	00:06:00	154	138.38	213.75			41.75	54.07	4	2.5		
	6											
Sr No	Date & Time	Pumps ON/OFF Info			Storm Pump Destination		Flowrate (m3/h)		Liquid Level (m)			Coke Oven 1 Pressure (bar)
		River Pumps	Storm Pumps	Reservoir Pumps	To Ancholme	To Pond B	HPM Excess	Process Demand	Catchment Pit	Ancholme Reservoir		
1	01/04/2015 00:00	0	1	0	1	0	41.75	54.07	4.5	3.175		4
2	01/04/2015 00:06	0	1	0	1	0	41.75	54.07	4.492	3.177		4
3	01/04/2015 00:12	0	1	0	1	0	41.75	54.07	4.483	3.180		4
4	01/04/2015 00:18	0	1	0	1	0	41.75	54.07	4.475	3.182		4
5	01/04/2015 00:24	0	1	0	1	0	41.75	54.07	4.466	3.184		4
57	01/04/2015 05:36	0	1	0	1	0	41.75	54.07	4.027	3.301		4
58	01/04/2015 05:42	0	1	0	1	0	41.75	54.07	4.018	3.304		4
59	01/04/2015 05:48	0	1	0	1	0	41.75	54.07	4.010	3.306		4
60	01/04/2015 05:54	0	1	0	1	0	41.75	54.07	4.001	3.308		3
61	01/04/2015 06:00	0	0	1	0	0	41.75	54.07	3.993	3.310		4
62	01/04/2015 06:06	0	0	1	0	0	41.75	54.07	3.996	3.309		4
63	01/04/2015 06:12	0	0	1	0	0	41.75	54.07	4.000	3.307		4
64	01/04/2015 06:18	0	0	1	0	0	41.75	54.07	4.004	3.306		4
14398	30/05/2015 23:42	0	0	1	0	0	41.75	54.07	4.060	2.723		4
14399	30/05/2015 23:48	0	0	1	0	0	41.75	54.07	4.064	2.722		4
14400	30/05/2015 23:54	0	0	1	0	0	41.75	54.07	4.067	2.720		4
14401	31/05/2015 00:00	0	0	1	0	0	41.75	54.07	4.071	2.719		4

Figure I30: Base Case Simulation

As shown in Figure I29, the Ancholme supply pressure drops below 4 bar for 0.97% of the time (i.e. 14 minutes per day or 77 hours per year). Frequency of such pressure loss for a week's time is depicted in Figure I30. Also 13% of the excess HPM water (5.4 m^3/h) is being lost to Pond B.

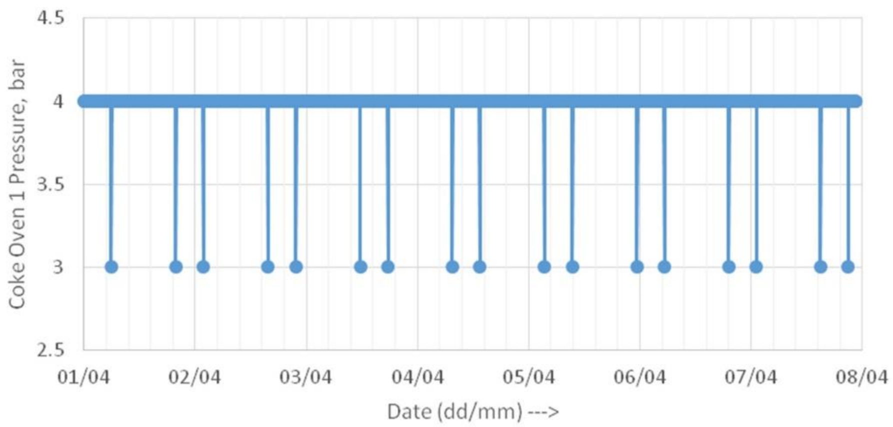


Figure I30: Depiction of coke oven 1 pressure loss due to pump switching

<u>Optimised Case</u>

However, based on analysis the following modifications were suggested:

a. When the Ancholme Reservoir level reaches its lower limit (LLL) i.e. 2.5 m, storm pumps shall be activated first and continue to operate until the HPM Catchment Pit level reaches its lower limit of 4 m. River pump gets activated after that when both Ancholme Reservoir and Catchment Pit reach their lower liquid levels.

b. Ancholme Reservoir level's lower limit updated to 2.875 m instead of 2.5 m in order to match operation time of the River and Storm Pumps.

c. Second pump shall be activated in advance prior to closing the first pump. This is to adjust for the time lag in the pressure wave propagation after pump activation.

As shown in Figure I31, the proposed control scheme recovers almost all the HPM water and also pressure loss situation is eliminated.

RESULTS		Operational Frequency			Operational Frequency			Total Power Consumption			4 bar	3 bar
		1130	4232	9049	4359	20		79.6	kW		14401	0
		8%	29%	63%	100%	0%		HPM Water drained to Pond B			100.00%	0.00%
		Power Consumption (kW)			Flow (m^3/h)			0.2	m^3/h			
		7.5	9.7	62	41.6	0.2		% of time pressure loss near AFCO				
								0.00%				
INPUTS	Start Date								Cross-sectional Area			
	01/04/2015 00:00								1143	3738		
	End Date								Reservoir HLL (m)			
	31/05/2015 00:00								4.5	3.475		
	Time Interval	Pump Flow (m^3/h)					Average Flow (m^3/h)		Reservoir LLL (m)			
	00:06:00	154	138.38	213.75			41.75	54.07	4	2.875		
	6											
Sr No	Date & Time	Pumps ON/OFF Info			Storm Pump Destination							
		River Pumps	Storm Pumps	Reservoir Pumps	To Ancholme	To Pond B	HPM Excess	AFCO Demand	Catchment Pit	Ancholme Reservoir		AFCO Pressure (bar)
1	01/04/2015 00:00	0	1	0	1	0	41.75	54.07	4.5	3.175		4
2	01/04/2015 00:06	0	1	0	1	0	41.75	54.07	4.492	3.177		4
3	01/04/2015 00:12	0	1	0	1	0	41.75	54.07	4.483	3.180		4
4	01/04/2015 00:18	0	1	0	1	0	41.75	54.07	4.475	3.182		4
5	01/04/2015 00:24	0	1	0	1	0	41.75	54.07	4.466	3.184		4
57	01/04/2015 05:36	0	1	0	1	0	41.75	54.07	4.027	3.301		4
58	01/04/2015 05:42	0	1	0	1	0	41.75	54.07	4.018	3.304		4
59	01/04/2015 05:48	0	1	0	1	0	41.75	54.07	4.010	3.306		4
60	01/04/2015 05:54	0	1	0	1	0	41.75	54.07	4.001	3.308		4
61	01/04/2015 06:00	0	1	1	1	0	41.75	54.07	3.993	3.310		4
62	01/04/2015 06:06	0	0	1	0	0	41.75	54.07	3.984	3.313		4
63	01/04/2015 06:12	0	0	1	0	0	41.75	54.07	3.988	3.311		4
64	01/04/2015 06:18	0	0	1	0	0	41.75	54.07	3.992	3.310		4
14398	30/05/2015 23:42	0	1	0	1	0	41.75	54.07	4.120	3.169		4
14399	30/05/2015 23:48	0	1	0	1	0	41.75	54.07	4.112	3.171		4
14400	30/05/2015 23:54	0	1	0	1	0	41.75	54.07	4.104	3.173		4
14401	31/05/2015 00:00	0	1	0	1	0	41.75	54.07	4.095	3.175		4

Figure I31: Optimised Case Simulation

The proposed control scheme shall be implemented using either PLC based controllers or within a SCADA framework. Capital investment required for the control scheme upgrade is estimated to be £20,000 by Tata Steel. Benefits from the scheme are summarised in Table 36.

Economic value of benefits in Table 36 is based on the following cost information:

a. Cost of clarified & filtered HPM water = £ 1 / m^3
b. Cost of Electricity = £ 0.07 / kWh
c. Operating Hours = 8000 hours per year

Based on capital cost estimate of £20,000 and total operating cost benefit of £49,864, the PBP is calculated as 5 months.

15.1.9 CASE STUDY No 9: Efficient usage of spray-on water used at the CC at SSAB in Luleå

Investigations on the CC cooling system were performed in order to understand how installation of new cooling equipment would affect the system, with respect to make up water, total usage of cooling water and discharge temperature from the Laxviken pond system. From the measurement campaign that was carried out, the water flows in the system could be determined. Using water flows and measured temperatures, a mass and energy balance model was developed which represents the cooling circuit. Figure I32 shows a simplified schematic sketch for the CC cooling circuit.

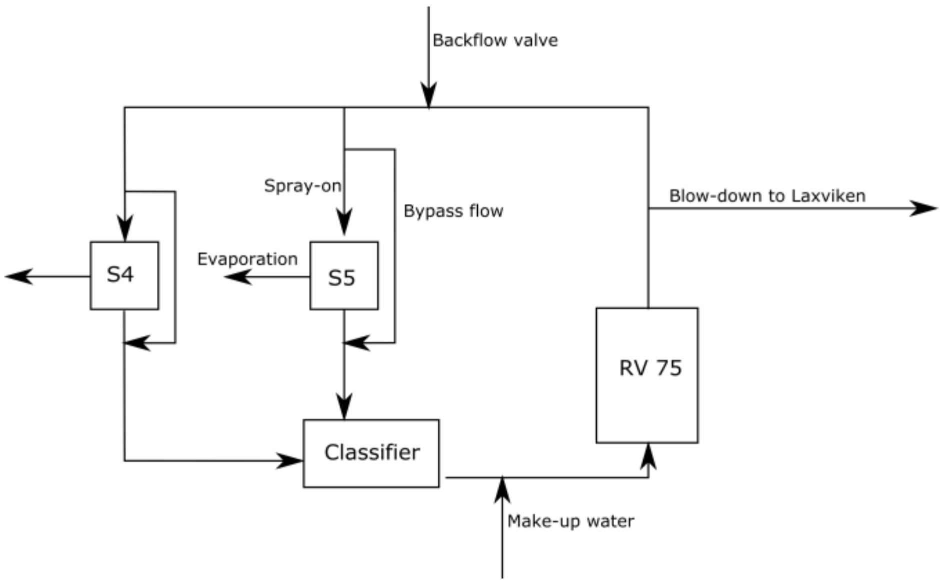


Figure I32: Simplified sketch for the cooling water circuit

The model assumes that the evaporation in the CC machines is equal on both S4 and S5 and that the bypass flow is constant. Using simple energy balances, the cooling capacity of the current cooling tower and the heat added to the cooling circuit from the spray-on water which was not evaporated was calculated.

In the model it is possible to change the production rate and temperatures for target spray on water, ambient air and make up water. For the investigations, the production rate was kept at the same level as during the measurement campaign and ambient and make up water temperatures were set to yearly average of 3 and 7.5°C, respectively.

As reference temperature, the spray on water was set to 30°C and case studies were performed on lowering the temperature to 25 and 20°C, respectively. For reference and case studies the new cooling equipment was dimensioned, with respect to flow of cooling fluid, to have no blow down. The size of the HEX was fixed and the cold water flow was adjusted to achieve no blow down. The old cooling tower was assumed to have the same cooling capacity regardless of temperatures.

As depicted in Figure I32, the water is diluted with make up water before the cooling tower, which is placed in RV 75. This is an inefficient placement of the make up water, since the cooling in both HEX and CT is benefited from high temperature. It also increases the load on the pumps placed inside RV 75. The impact on the system by moving the addition of the make up water to the backflow valve was investigated, as well as the impacts of placing the HEX after the blow down and after the new make up water addition point. The three placements for the HEX are illustrated in Figure I33.

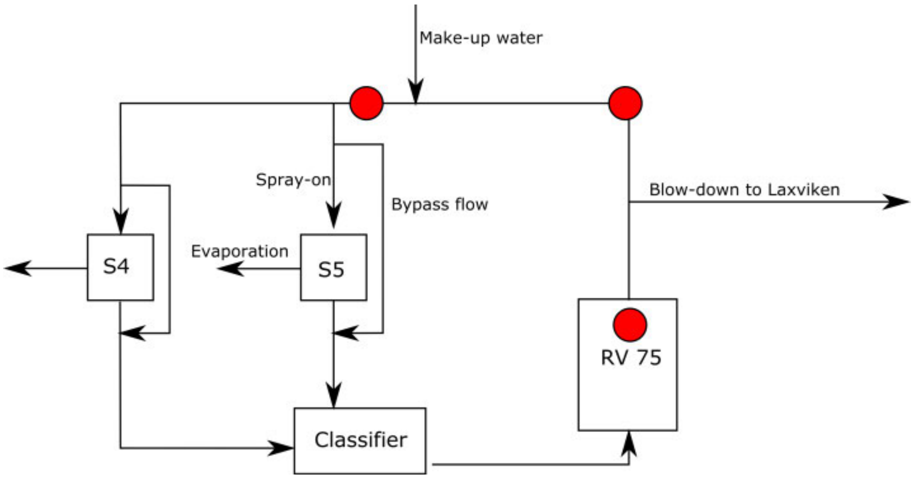


Figure I33: The three placement options for the HEX with new position for the make up water

Using the unit model template developed in the project, the power requirement for the new cooling solutions was estimated. For the power of the pump to the HEX, it was assumed that there would be a 10 m height difference and 400 m of length. The impact on the system for the different temperatures of the spray on water is shown in Table I31.
The pump and fan power shown in Table I31 only includes the power requirement of the newly installed cooling equipment. This does not include the power requirement for pumping the water in the cooling circuit. By moving the position for the makeup water less water is needed to be pumped through RV 75, and thus the entire power usage of the system might be decreased.

		Ref	Ref. MU	HEX, p1	HEX, p1, MU	HEX, p2, MU	HEX, p3, MU	CT	CT, MU
30 C spray-on	T Laxviken [C]	18.9	19.0	19.3	19.4	19.4	19.3	18.2	18.2
	Total cooling water usage [m^3/h]	6027	5938	6217	6161	6174	6273	5733	5733
	Pump & fan P [kW]			58.0	52.0	53.0	65.0	41.9	39.4
	Make up water [m^3/h]	378	289	60	60	60	60	84	84
	Blow down [m^3/h]	313	224						
25 C spray-on	T Laxviken [C]	18.7	19.0	18.7	18.9	18.9	18.6	18.2	18.2
	Total cooling water usage [m^3/h]	6119	5986	6531	6403	6056	6670	5733	5733
	Pump & fan P [kW]			94	80	83	110	42	40
	Make up water [m^3/h]	470	337	60	60	60	60	84	84
	Blow down [m^3/h]	405	272						
20 C spray-on	T Laxviken [C]	19	19	16	17	17	6	18	18
	Total cooling water usage [m^3/h]	6215	6056	8823	7605	7797	11706	5733	5733
	Pump & fan P [kW]			358	218	240	689	42	40
	Make up water [m^3/h]	566	407	60	60	60	60	84	84
	Blow down [m^3/h]	500	341						

MU= new position for make up water,
p1=HEX position at RV 75,
p2= HEX position between blow down and new make up water position,
p3= HEW placed after new make up water position

Table I31: Summary for the different cooling options; temperature of discharge from the Laxviken pond system, total usage of cooling water for the BF, BOF and CC; power required for new cooling equipment; and make up and blow down water to the cooling circuit

For the reference cooling system and 20°C spray on water temperature the limit on the blow down to Laxviken is reached. In this case the lowest possible temperature of the spray on water is 21.7°C for the situation with no blow down. Table I31 also shows the impact on total usage of cooling water from BF, BOF and CC for the different cooling options. From the modelling it seems more beneficial to install a cooling tower since it will have similar performance with respect to spray-on water temperature at a lower power requirement. For the case of 30 and 25°C using CT will also have a lower temperature of the discharge out from the Laxviken pond system. Lowering the spray-on water temperature to 20°C, using HEX will result in lower temperature out from Laxviken, due to the increase in cooling water usage.
Due to the fact that the size of the HEX was fixed for the case studies, there are cases where the cold water flow is very high in order to achieve target spray on water temperature. These flows come with a significantly increased power requirement and it would be more feasible to increase the size of the HEX rather than to increase the cold water flow rate. In addition, due to the very high flows there is a decrease in the temperature of the discharge at the outlet from Laxviken.
However, it might be impossible to operate the cooling circuit with no blow down due to accumulation of chlorides or fluorides in the system. Additionally, the performance of the cooling solution should be evaluated for the summer temperatures to see how the spray-on water temperature would be affected.

15.1.10 CASE STUDY No 10: BF gas treatment system at SSAB in Luleå

The BF gas treatment system at SSAB Luleå plant was studied and modelled in WP 2. The correlations between the recirculation of the gas treatment water and the concentrations of various compound was studied and investigated in more detail in a plant trial (WP 5). The model was further developed based on the results from the plant trials. The model was used in order to investigate the effects of increased recirculation, with and without treatment of the recirculated water. Figure I34 shows a schematic picture of the BF gas treatment system including the different sampling points; ED (after clarifier), EK (after cooling tower), CS (Clarifier sludge) and SB (sedimentation basin).

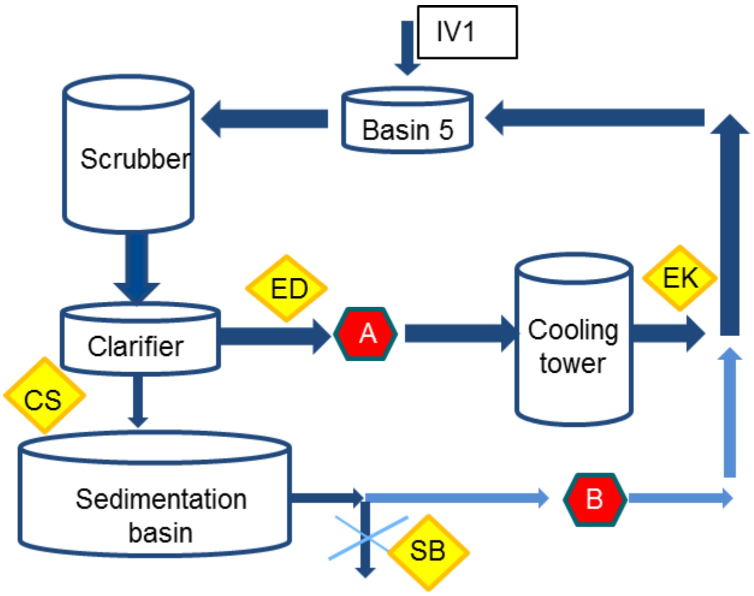


Figure I34 Scheme of the BF gas treatment plant at SSAB Luleå

By increasing the recirculation of BF gas treatment water, the amount of ammonium leaving the system and ending up in the recipient, Inre Hertsöfjärden, would be lower. Chlorides were studied since they are regularly analyzed and can be used to represent other compounds that show similar behavior, such as sodium and fluorides. Previous research (outside the REFFIPLANT project) showed that calcium carbonate causes fouling of nozzles and in the pipelines, which makes it important to include calcium in the simulations. Calcium also represents sulfates since they show the same behavior during the plant trial but only Ca is part of the routine analysis plan.

<u>Increased recirculation in the BF gas treatment system</u>

The case study consisted of simulations of the concentration of ammonium, chlorides and calcium as a function of recirculation for three different scenarios, basically focusing on the best location of a water treatment plant consisting of reverse osmosis:

1. Recirculation of untreated decanted water from Sedimentation basin to basin 5
2. Recirculation of treated decanted water from Sedimentation basin to basin 5, treatment at location B in Figure I34.
3. Recirculation of untreated water from Sedimentation basin to basin 5, treatment of decanted water from clarifier to cooling tower (location A in Figure I34).

The model is based on:

- the unit model library developed in the project as well as
- historical data from SSAB BF and
- correlations between concentrations ED and EK, ED and CS derived from the plant trial in WP 5.

Case 1: Recirculation of untreated water from Sedimentation basin to basin 5.
By iterating the concentration for the current situation, i.e. a bleed-off of 50 m^3/h, steady state is reached for Ca and chlorides (equal amount leaving and entering the system), whereas ammonium (NH_4)is decreasing in the circuit (see Figure I35).

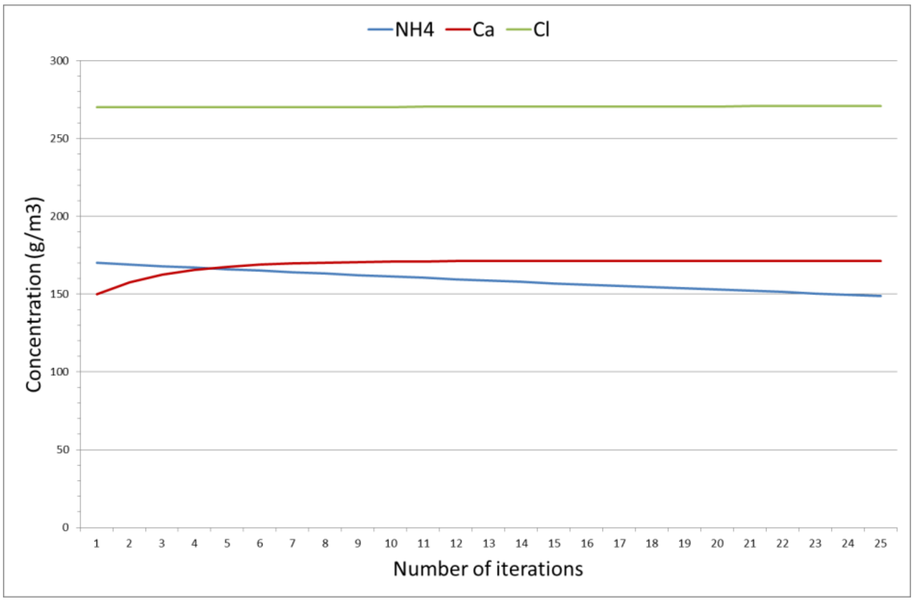


Figure I35: Concentrations of NH_4, Ca and chlorides as a function of numbers of iteration.

However, when the recirculation is increased, there is a build-up of all the investigated compounds including ammonium. Hence, in the case of increased recirculation there will be a need for some kind of treatment of the recirculated water in order to avoid too high concentrations in the system. This is, however, dependent on the concentrations that can be tolerated in the circulating system.

Case 2: RO treatment (location B in Figure I34) of decanted water from sedimentation basin.
The results from the modelling, i.e. the concentration in the circulating system, is shown in Figure I36. Reference concentrations, i.e. concentrations from the period before the plant trial, are indicated as dotted lines in the diagram.

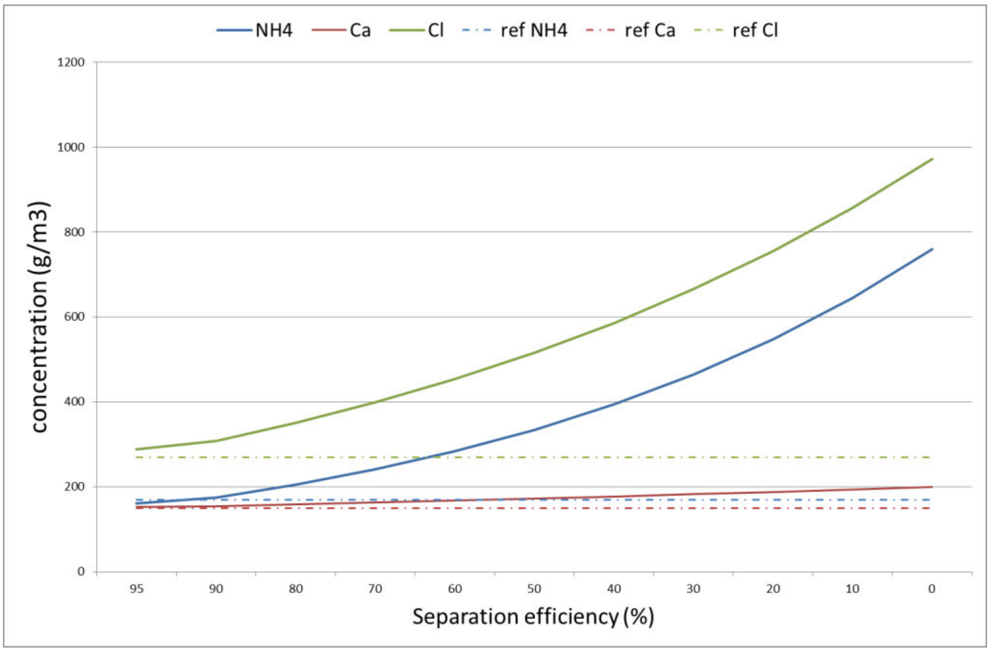


Figure I36: Concentration development in the gas treatment system. The concentration of NH_4, Ca and Cl after clarifier (sampling point ED) Vs. separation efficiency of a RO filter (location B in **Figure I34**).

Case 3: Recirculation of untreated decanted water from sludge basin to basin 5, RO treatment of decanted water from clarifier to cooling tower (location A in Figure I34).
Putting a RO filter treating the overflow from the clarifier, between the clarifier and the cooling tower, would create space to recirculate the untreated decanted sludge water from the BF sludge basin to basin 5. Simulations were made in order to calculate the concentrations of ammonium, chloride and calcium at different points in the system. Figures I37 – I39 show the concentration ED (after clarifier) as a function of separation efficiency for different percentage of the total overflow from the clarifier. The dotted lines represent the reference for each compound i.e. the concentrations from the before period of the plant trial.

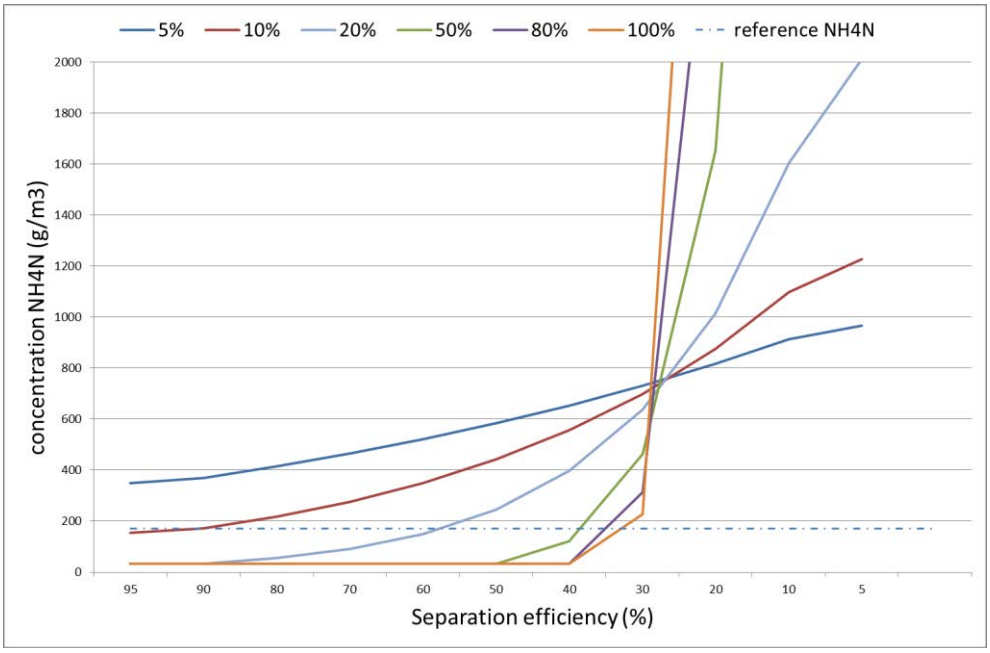


Figure I37: Treatment of different parts of water flow from clarifier. Concentration of NH_4 at ED vs. separation efficiency of the RO filter.

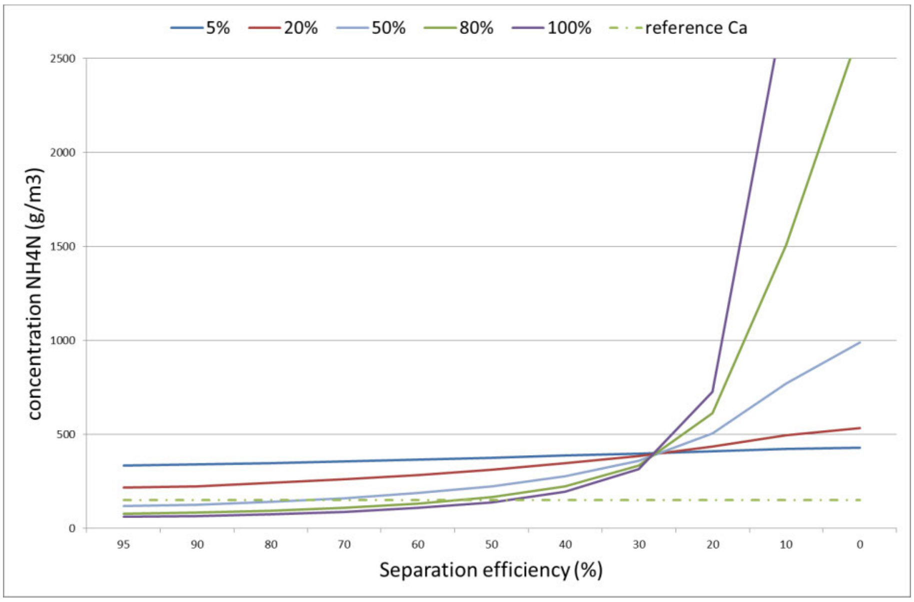


Figure I38: Treatment of different parts of water flow from clarifier. Concentration of Ca at ED vs. separation efficiency of the RO filter.

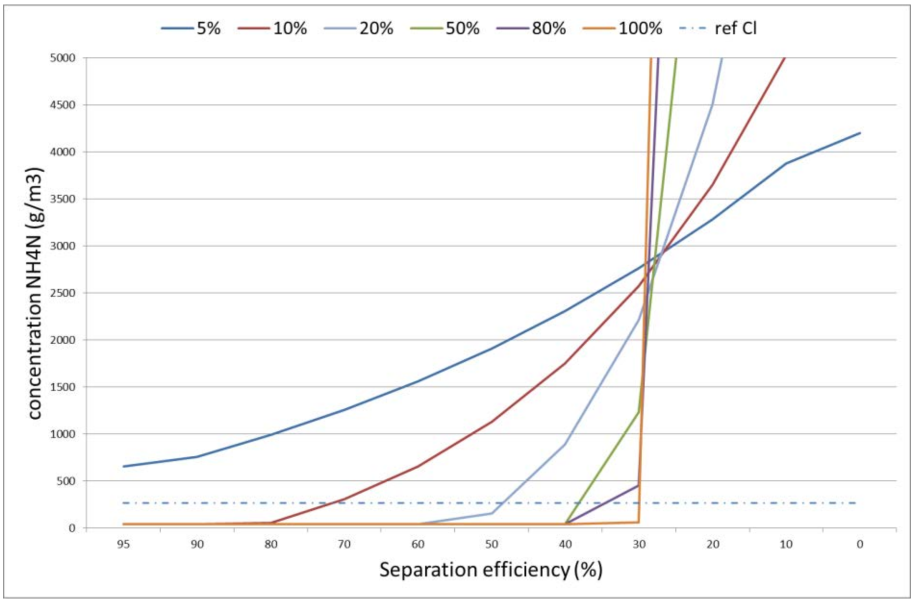


Figure I39: Treatment of different parts of water flow from clarifier. Concentration of Cl at ED vs. separation efficiency of the RO filter.

15.2 PI-based solutions – by products and wastes

A case study for ILVA plant related to waste reuse of BOF slag internally as raw material for pellet production or externally as fertilizing raw material has been simulated by SSSA. Furthermore, a conclusive optimization study has been carried out in order to assess the best way to manage some by-products and wastes minimizing costs and disposal. Details are shown in the next Subsections 19.2.1 and 19.2.2.
MEFOS analysed two cases study related to SSAB Lulea Plant related to the reuse of sludge in briquette production and to the different options for material recirculation. Details are shown in the next Subsections 19.2.3 and 19.2.4.

CASE STUDY No1: improving reuse of BOF slag
The possibility of maximizing the reuse of BOF slag was evaluated by SSSA through the use of Excel-based holistic models. According to the preliminary results of the ongoing RFCS project entitled " Removal of Phosphorus from BOF-slag" (Ref. PSP-BOF), BOF slag has a composition, which makes them potentially suitable for internal or external reuse and recycle. In particular, a phosphorus and calcium rich fraction can be used as a fertiliser raw material (or as soil improver) and an iron rich fraction can be used to make pellets to be used in sinter plant.
SSSA exploited the developed Excel-based holistic models to simulate a BOF slag treatment process and to give a preliminary proof of BOF slag reuse. Each holistic model was previously validated comparing results of simulation and of preliminary tests conducted for the PSP-BOF project. The models were firstly used in their preliminary form, then they were refined (e.g. refining of the grinding and of the magnetic separation of each components according to further experimental and literature data), their accuracy was improved and they were exploited in their final version. The results of the refined model are shown below for a quality of tested BOF slag (BOF slag quality 1).
The treatment process proposed by ILVA partner is composed of three main steps: a cooling stage, grinding and sieving stage and a magnetic separation of the coarse fraction. Magnetic fraction is mixed with fine fraction and its use as sinter plant feed is evaluated. On the other hand, the use of the non-magnetic fraction as fertiliser is valued. A simplified flowsheet of BOF slag recovery treatment is shown in Figure I40.

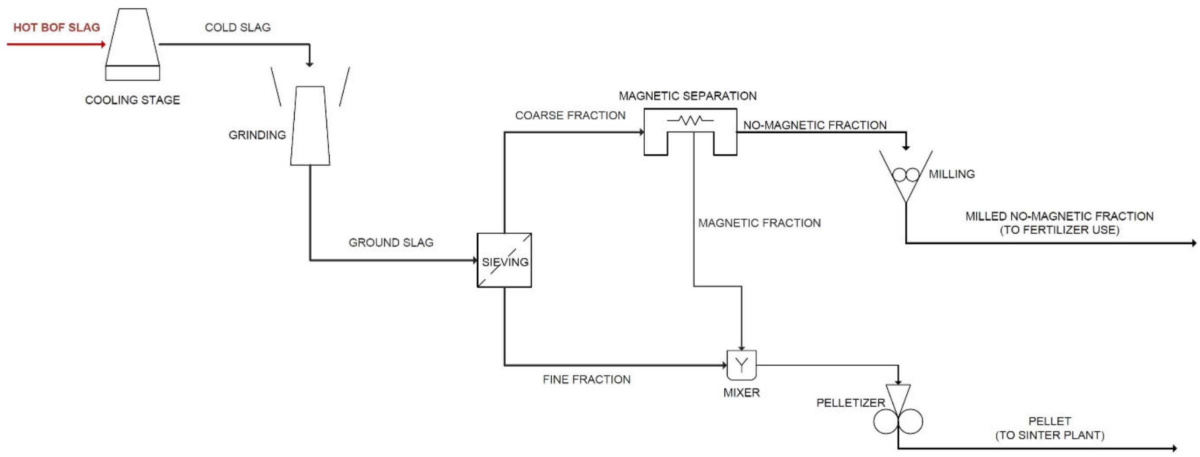


Figure I40: BOF slag treatment flowsheet.

The model global input are:

- mass of the slag to be treated: 2000 t;
- initial slag temperature: 1600°C;
- initial slag PSD (Table I32)
- slag composition in % w/w before and after normalization (Figure I41).

For each step of the whole process, other input data were inserted, such as cooling time, grinding efficiency, magnetic separation efficiency.

mm	mm		
<	**0,063**	% w/w	0,00
0,063	**0,106**	% w/w	0,00
0,106	**0,125**	% w/w	0,00
0,125	**0,15**	% w/w	0,00
0,15	**0,212**	% w/w	0,00
0,212	**0,25**	% w/w	0,00
0,25	**0,5**	% w/w	0,00
0,5	**1**	% w/w	0,00
1	**1,4**	% w/w	0,10
1,4	**2**	% w/w	0,10
2	**2,36**	% w/w	0,10
2,36	**2,8**	% w/w	0,20
2,8	**3,35**	% w/w	0,10
3,35	**4**	% w/w	0,30
4	**4,75**	% w/w	0,10
4,75	**6,3**	% w/w	1,00
6,3	**8**	% w/w	2,00
8	**9,5**	% w/w	20,20
9,5	**10**	% w/w	11,60
10	**16**	% w/w	39,40
>	**16**	% w/w	24,80

Table I32*:* BOF slag initial PSD.

The cooling model gives a BOF temperature of 920°C in the core of the slag after 24 hours of cooling at atmospheric temperature and pressure, while the external layer temperature is 25°C. The model estimates heat losses of about 488 GJ.
The BOF slag PSD after grinding and sieving is listed in Table I33 and the composition in % w/w of each fraction is shown in Figure I42. The fractions with a particle size <0.25 mm are richer in calcium compounds (e.g. larnite) and poorer in ferrous compounds (e.g. magnetite) than the other fractions, which are instead richer in phosphorus. The model predicts a mill energy consumption of about 17,5 MWh.

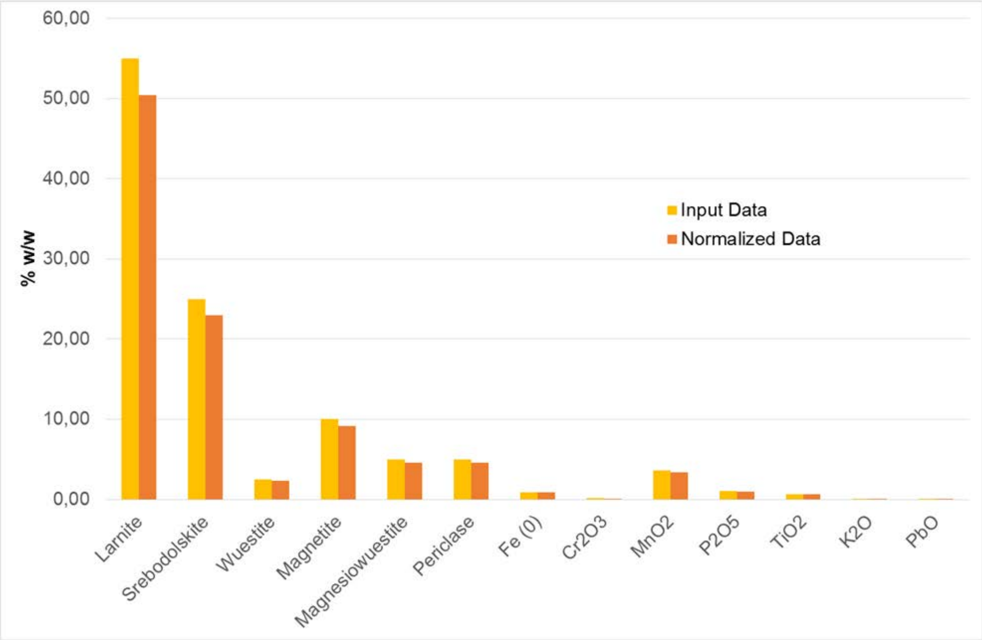


Figure I41: BOF slag initial composition (in % w/w).

mm	mm		
<	**0,045**	% w/w	6,38
0,045	**0,063**	% w/w	7,20
0,063	**0,09**	% w/w	7,04
0,09	**0,125**	% w/w	8,92
0,125	**0,25**	% w/w	11,78
0,25	**0,5**	% w/w	13,40
0,5	**0,8**	% w/w	13,52
0,8	**1**	% w/w	6,97
>	**1**	% w/w	24,79

Table I33*:* BOF slag PSD after grinding and sieving.

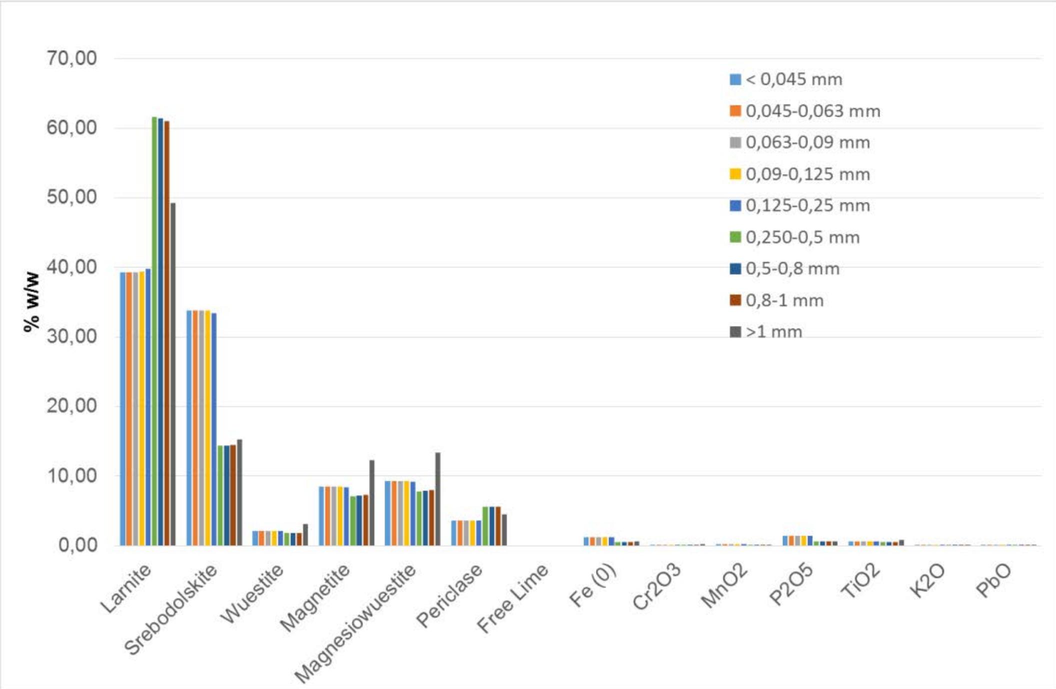


Figure I42: Composition (in % w/w) of each particle size fraction after grinding and sieving of BOF slag.

After the magnetic separation of the coarse fraction, the magnetic and non-magnetic fractions are distributed as follows:

- magnetic fraction: 11.9 % w/w of the coarse slag;
- non-magnetic fraction: 88.1 % w/w of the coarse slag.

The composition in % w/w of each fractions is highlighted in Figure I43.

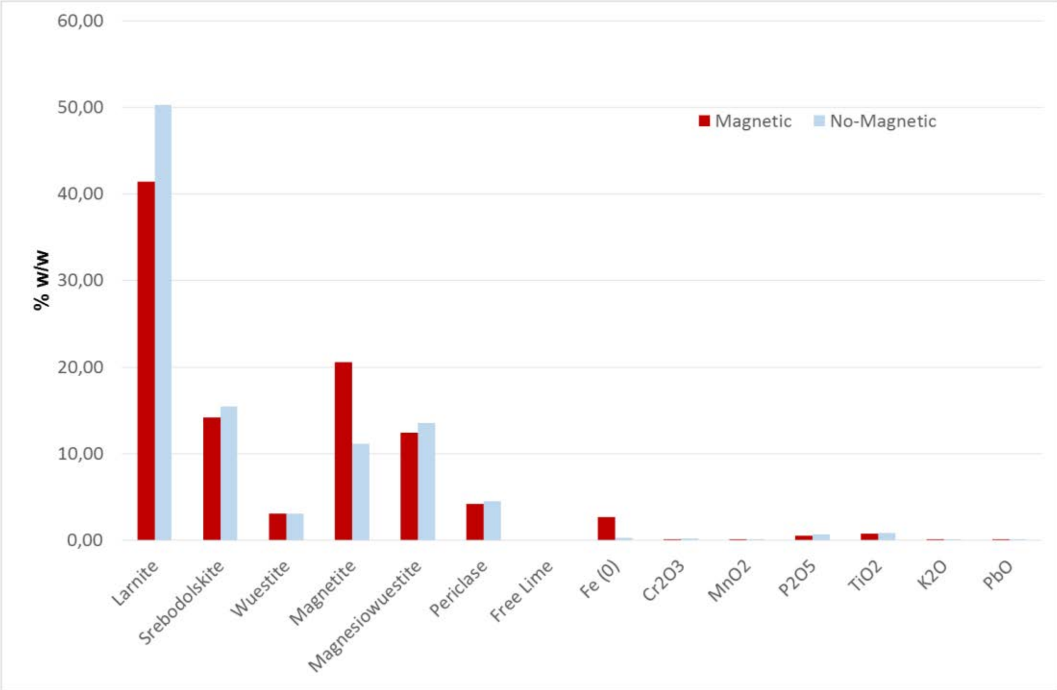


Figure I43: Composition (in % w/w) of magnetic and non-magnetic coarse fraction.

The non-magnetic fraction appears richer in Ca and slightly more concentrated in P compounds than the other ones. Although the P content is still low in this non-magnetic fraction, the model gives a preliminary proof that a well-designed separation process could allow to obtain a BOF slag fraction suitable for exertal use, for instance as fertilizer (more concentrated in P compounds and less concentrated in Fe compounds and metallic iron). On the other hand, the magnetic coarse fraction appears suitable to the use in sinter plant, due to its high content in Fe compounds, such as magnetite, wuestite and metallic iron. It is finally mixed with the fine fraction according to the proposed process scheme obtaining an amount of material of about 80% of pre-treated BOF slag. The model gives the composition in % w/w of this slag fraction as in Figure I44.
The content in larnite (calcium mineral) in the fraction of slag that could be used as pellet raw material is still high, only some of the Fe compounds and metallic iron are more concentrated in the final mix than in the slag before the treatment. This suggests that another magnetic separation can be carried out (e.g. an additional magnetic separation including slag finer fraction) to increase the amount of slag suitable for external reuse (the major fraction) and to obtain a minor fraction with a high Fe content suitable to be internally reused.

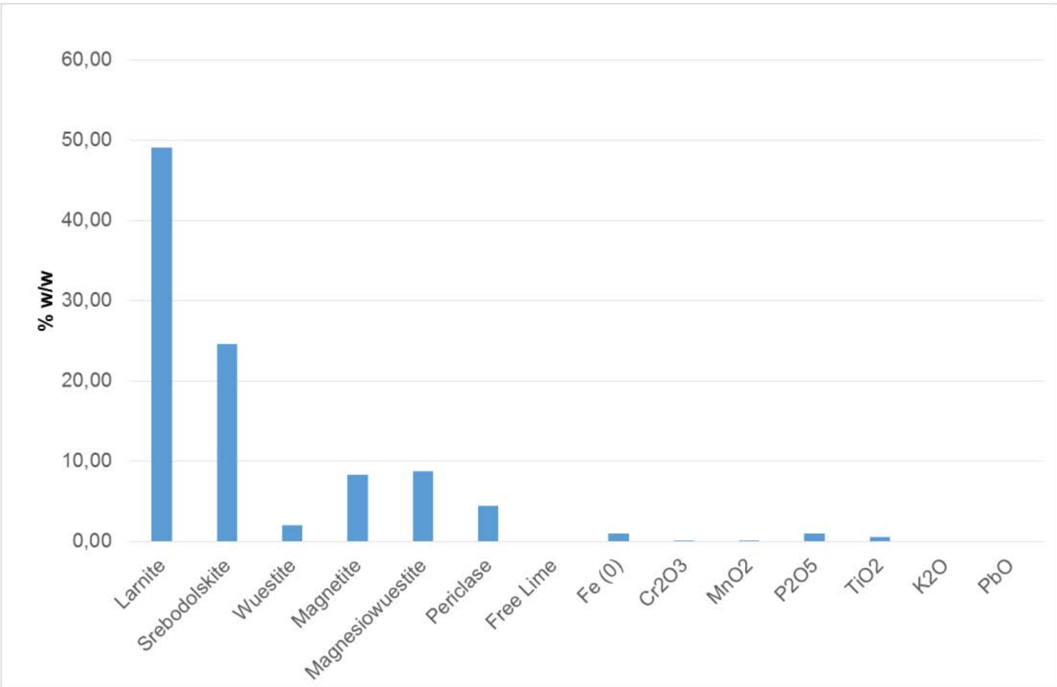


Figure I44: Composition (in % w/w) of slag fraction to pelletize.

An improved BOF slag recovey treatment is thus proposed and simulated (see Figure I45).

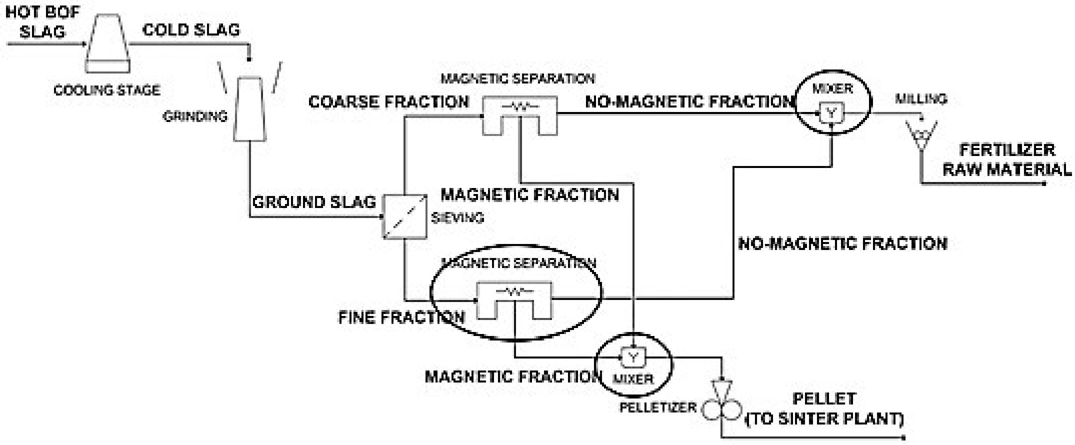


Figure I45: BOF slag improved treatment flowsheet.

The modified treatment includes two different magnetic separations one for the coarse fraction and the other for the fine fraction of the slag. In this way, particles with big differences in size can't hamper the separation of magnetic matter. Finally, the separated magnetic (and non-magnetic) coarse and fine fractions are mixed together. The following BOF slag fractions are obtained through the simulation and their compositions are shown in Figure I46:

- magnetic fraction (coarse+fine): ≈25 %;
- non-magnetic fraction (coarse+fine): ≈75%.

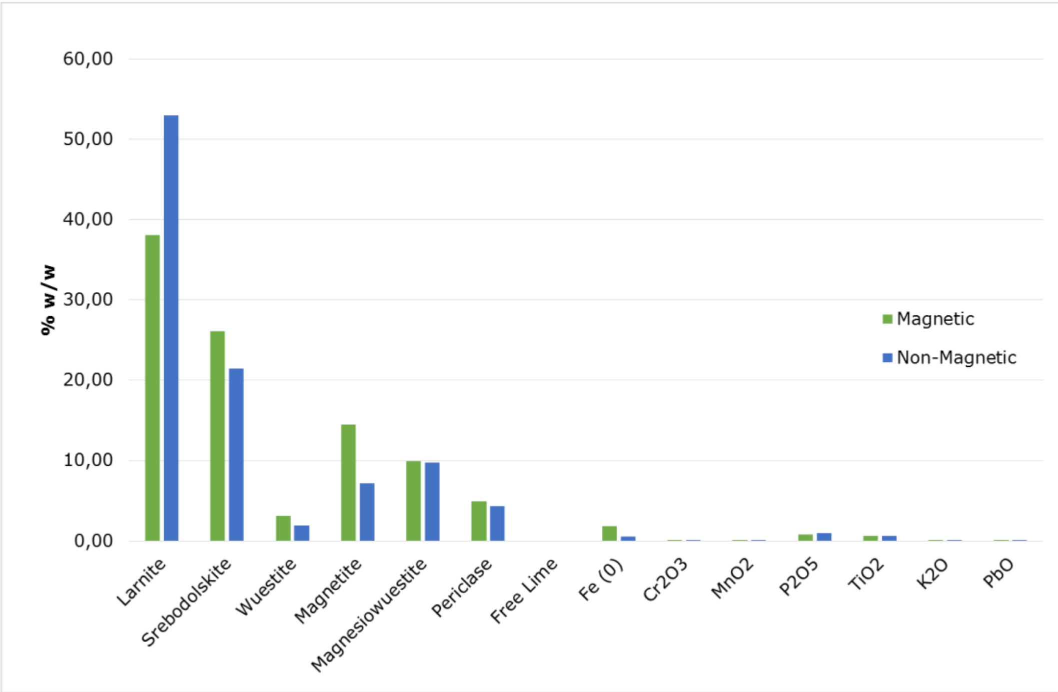


Figure I46: Composition (in % w/w) of two final obtained slag fractions (BOF slag quality 1).

Similar results have been obtained starting from two different quality of BOF slags related to different produced steel grades, as depicted in Figures I47 and I48.
The addition of a further magnetic separation step in the improved BOF slag treatment appears suitable to obtain two different secondary raw materials more concentrated in their key components with respect to the pre-treated BOF slags:

- non-magnetic fraction with a higher concentration of calcium and phosphorous to be used for example in agriculture;
- magnetic fraction richer in ferrous compounds and metallic iron to be internally reused.

It is also clear that field reproductions of simulation results are possible and improvable only with suitable and efficient magnetic separation techniques. For this reason, further experimental studies are needed to find the best way to enhance the efficiency of magnetic separation.
In conclusion, simulation confirms that a full recovery of BOF slags is possible for a potential reuse partially extenally and partially in the form of raw material for pellet production by following the improved recovery treatment. Furthermore, the proposed modified process appears suitable to treat different kind of BOF slags.

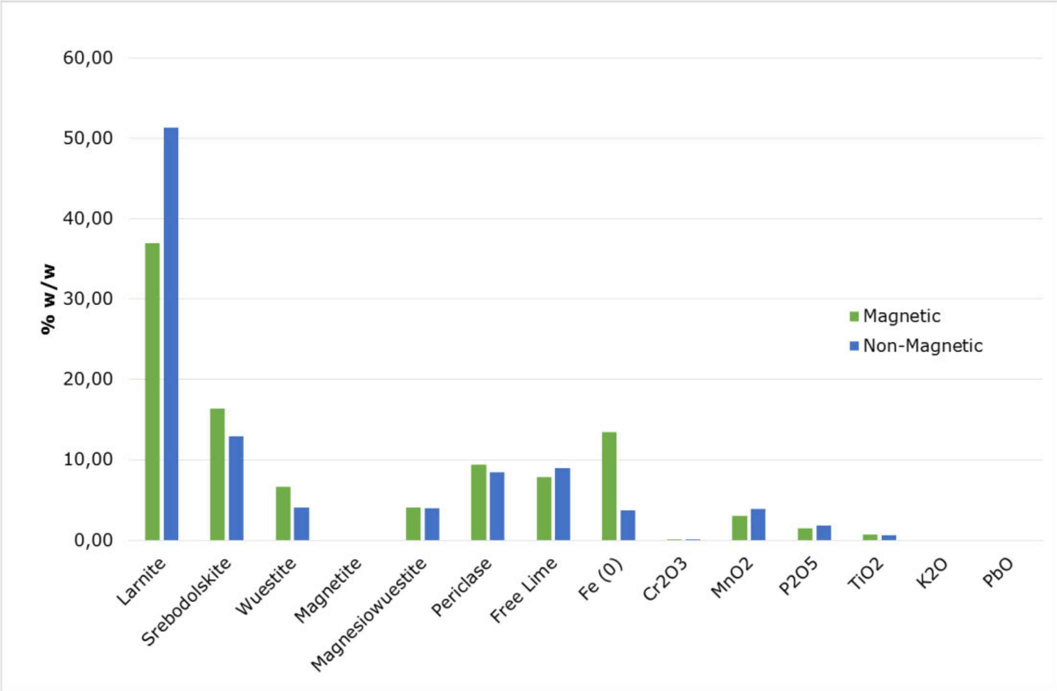


Figure I47: Composition (in % w/w) of two final obtained slag fractions (BOF slag quality 2).

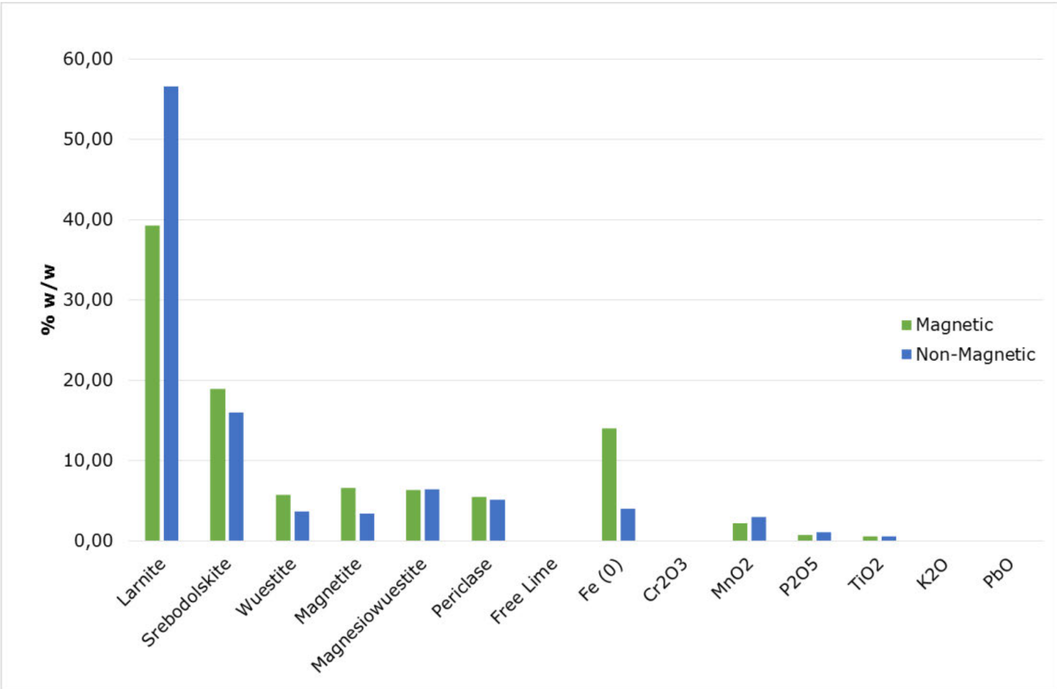


Figure I48: Composition (in % w/w) of two final obtained slag fractions (BOF slag quality 3).

15.2.1 CASE STUDY No2: Optimization of the reuse of by-products or wastes

A conclusive optimization study has been carried out exploiting the results and the indications obtained through the previous case studies and simulations.

These data have been implemented in the reMIND superstructure developed by SSSA (Task 4.3) and depicted in Figure I49.

In particular, according to ILVA main aims, only the following by-products and wastes were considered: BOF slag and sludge, mill scale and oily mill scales. ILVA currently does not recycle BOF slag and possibility of their total reuse are under evaluation (e.g. pellet or fertilizer raw material). Treatment No 1 and 2 for BOF slags refer to the two treatment possibilities analysed in the case study No1 (the original one and the improved one). Washing process and distillation & pyrolysis refer to the two considered treatments for reducing the oil content in oily mill scale. Direct agglomeration and pelletization nodes represent possible internal uses, fertilizer and sale blocks refer to external uses.

The model is based on mass balance starting from the amount of each by-products/waste produced per ton of produced steel and exploits some indicators to allow the optimization.

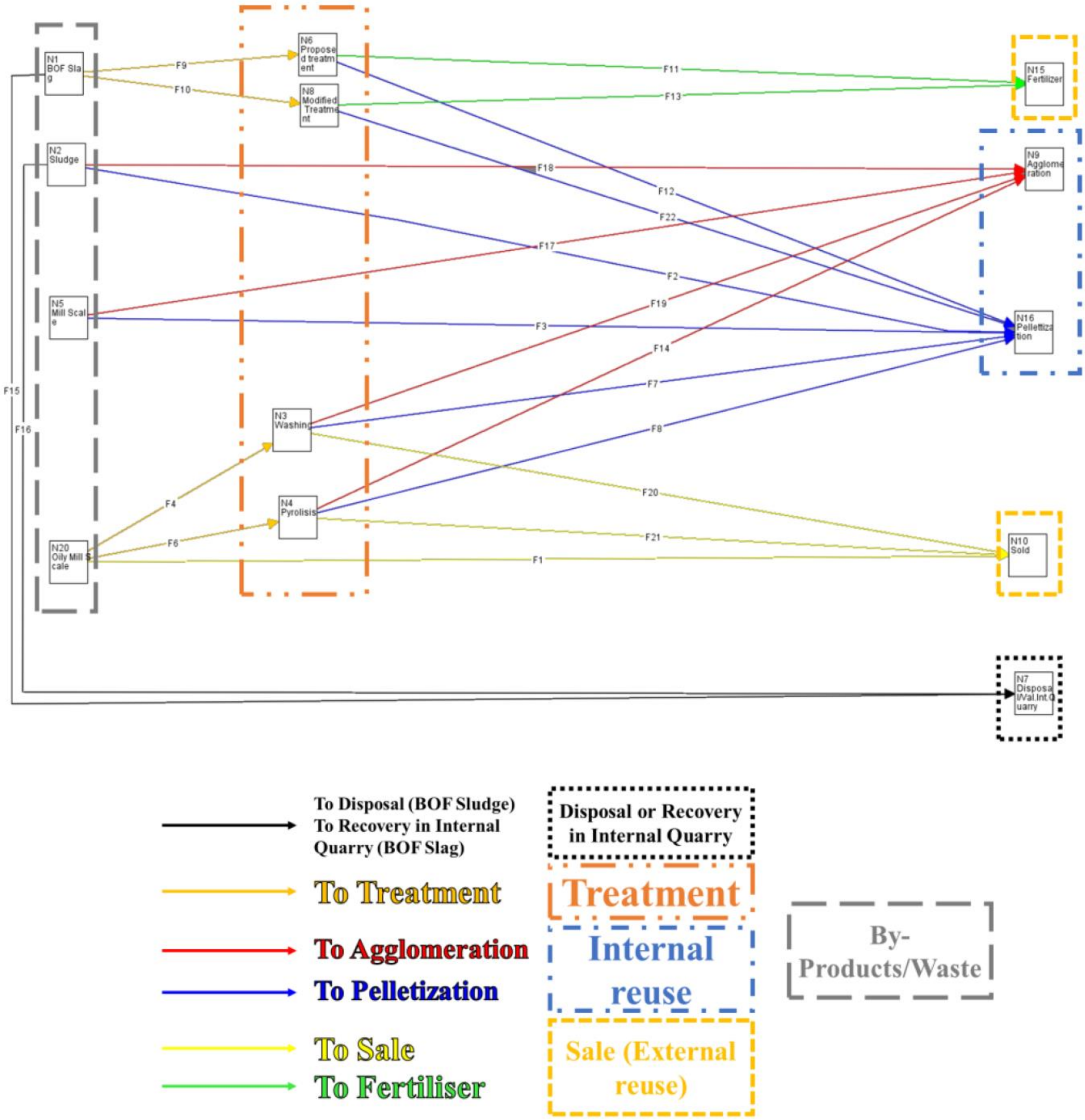


Figure I49: reMIND superstructure to optimize reuse of by-products and wastes.

The following indicators were considered for each stream or treatment: cost, environmental impact, quality of the output products (e.g. pellet quality depends from the raw material particle size distribution or composition, for example from the P content). The indicators values (and some assumptions) have been set considering the following information:

- economical (e.g. pyrolysis is more expensive than washing)
- empirical information (e.g. the use of pellets as agglomeration feed gives better performances in terms of environmental impact than direct by-products feed because the management of fine grain size by-products is avoided at agglomeration storage)

- indications obtained from previous preliminary lab trial carried out by ILVA (e.g. ILVA verified that mill scales are not suitable to give good quality pellets).

After setting the model, two main optimization case studies have been carried out:

1. Minimizing costs and environmental impact (OPT1);
2. Minimizing costs and environmental impact and maximizing quality of output products (OPT2).

Table I24 depicts the results in the form of by-products/waste distribution.

	Direct Agglomeration		Pelletization		Fertilizer		Sale		Disposal	
	OPT1	OPT2	OPT1	OPT2	OPT1	OPT2	OPT1	OPT2	OPT1	OPT2
BOF Slag	N.a.	N.a.	34%	50%	66%	50%	N.a.	N.a.	0 %	0 %
BOF Sludge	0 %	0 %	100%	100%	N.a.	N.a.	N.a.	N.a.	0 %	0 %
Mill Scale	0 %	100 %	100%	0%	N.a.	N.a.	N.a.	N.a.	N.a.	N.a.
Oily Mill Scale	99.15 % (de-oiled scale)	99.15 % (de-oiled scale)	0%	0%	N.a.	N.a.	0,85 % (separated oil)	0,85 % (separated oil)	N.a.	N.a.

Table I34*:* Results of optimization studies related to by-products and wastes reuse.

In both cases, the optimization avoids the disposal and find different way to reuse or sell completely the by-products and wastes. Treatment configuration 1 and 2 for BOF slags are both exploited (Treatment 2 is preferred to Treatment 1) while distillation and pyrolysis treatment for oily mill scale is avoided. The "pellet recipe" obtained in the two cases is shown in Figure I50. Figure I50 highlights that if the quality of the pellets is not considered in the optimization, mill scale is included in the recipe, while a different result is obtained in the second case.

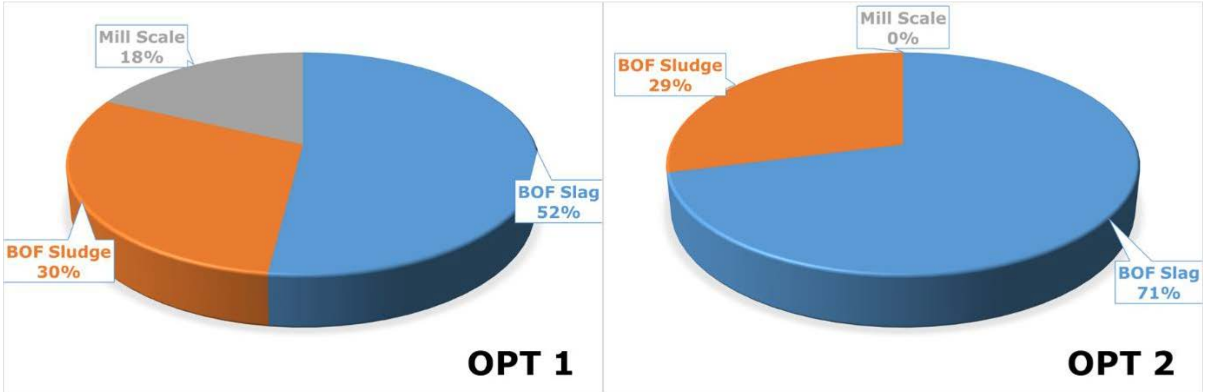


Figure I50: Obtained pellet recipes for the two optimization studies

The fate of main contaminants in the final products, such as Zn and Pb that can be derived by BOF sludge or Cr and V that can be introduced by BOF slag, is neglected due to the very low content in the considered initial by-products. In particular, Vanadium in the BOF slag after tapping and before the magnetic separation is usually about 400-1000 mg/kg while total Chromium is between 1000 and 1800 mg/kg. A typical analysis of trace compounds in BOF slag is presented in Table I35.

Species	**Value** *[mg/kg]*
Sb	<1.4
As	<1.4
Be	<1.4
Cd	<1.4
Cr tot	1700
Cr (VI)	78
Hg	<0.14
Mo	<1.4
Ni	<1.4
Pb	3.8
Se	<1.4
Tl	17
Te	<1.4
V	970
Zn	<1.4
PAHs	<0.5
TOC	<5000*
Aromatic organic solvent	<0.10
Phenols	<0.5
Total Hydrocarbon	162.5
pH = 11.8	

*percentage by weight of dry matter

Table I35*:* Typical analysis of trace chemical species in BOF slag.

On the other hand, Zinc and Lead into the BOF sludge are very low and an internal ILVA research work gives the mean values of these contaminants during the last three production years that are reported in Table I36.

Species	Value per year *[mg/kg]*		
	2013	2014	2015
Pb	3.7	<1.4	80
Zn*	17.10	7	700

*The Zinc content may show unexpected and uncommon fluctuations due to the probable erroneous addition of galvanized scrap

Table I36*:* Lead and Zinc content in BOF sludge in the last three production years

15.2.2 CASE STUDY No3: reuse of sludge in briquette production

SSAB developed a model and MEFOS pre-tested the possibility of taking advantages from sludge reuse.

In June 2014 briquettes with alternative composition was manufactured. BOF fine grained sludge, a material that ordinarily goes to landfill, was dried and blended into the briquette mix. 12% of the mix was BOF fined grained sludge. The amount of the fine grained BOF sludge is based on the annual production of sludge and briquettes. The briquettes (around 8000 ton) were charged to the BF during two weeks in July 2014.

A system analysis case study was made based on data collected from full-scale tests performed at SSAB during summer 2014. The modelling was made simulating two different briquette mixes (B1 and B2) to BF, presented in Table I35. 15% of the briquette content, approximately 13.5 kg/t_{HM}, was BOF fine fraction sludge by reduced content, kg by kg, of BF dust in briquette B1 and reduced content of desulphurisation (deS) scrap in briquette B2. Simultaneous tests with injection to BF of some 6.4 kg BF dust/ t_{HM} were performed in case B1 and B2. The B2 concept corresponds to the full scale trials while the briquette B1 in the case B1.1. Figure I51 shows potential future scenarios.

Material	CaO	MgO	SiO2	Al2O3	TiO2	Mn	P	V	S	Zn	C	Fe
Ref. Briquette	21.11	2.06	6.53	1.82	0.71	0.64	0.04	0.38	0.84	0.07	9.01	43.08
B1	22.55	2.45	5.84	1.54	0.67	0.72	0.04	0.34	0.77	0.04	2.71	47.02
B2	21.48	2.47	6.14	1.61	0.52	0.66	0.04	0.39	0.66	0.09	8.48	41.82
Ladle slag	41.41	5.93	7.05	28.07	1.20	4.86	0.39	0.50	0.08	0.01	0.2	7.48
BF dust	9.87	1.30	6.21	2.16	0.36	0.29	0.02	0.13	0.54	0.40	44.56	21.65

Table I35: Chemical composition of the reference briquette, briquettes B1 and B2, ladle slag and BF dust used in the model (%).

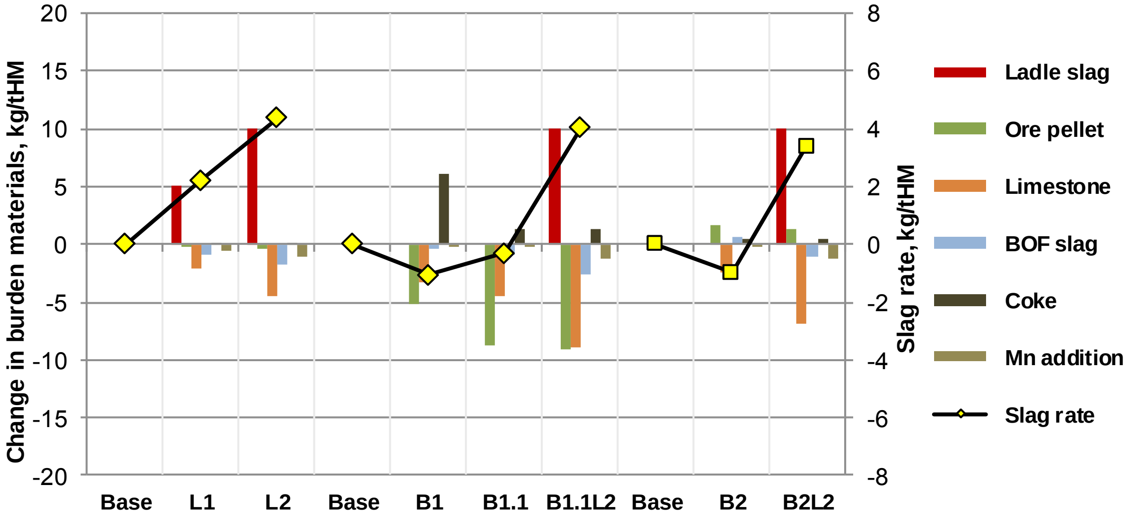


Figure I51: Results of recycling simulations (kg/tonne HM):

Base – Reference scenario with 6.4 kg BF dust injection/tonne HM,

L1 – recycling of 50% of generated ladle slag, injection of 6.4 kg BF dust/tonne HM and recycling of reference briquette,

L2 – recycling of 100% of generated ladle slag, injection of 6.4 kg BF dust/tonne HM and recycling of reference briquette,

B1 – recycling of briquette with BOF fine sludge by reduced BF dust (B1) and injection of 6.4 kg BF dust/tonne HM,

B1.1 – recycling of briquette B1 and injection of 18.1 kg BF dust/tonne HM,

B1.1L2 – recycling of B1, injection of 18.1 kg BF dust/tonne HM and recycling of 100% of generated ladle slag,

B2 – recycling of briquette with BOF fine sludge by reduced deS scrap (B2), and injection of 6.4 kg BF dust/tonne HM,

B2L2 – recycling of B2, injection of 6.4 kg BF dust/tonne HM and recycling of 100% of generated ladle slag.

Some of the general specific and governing conditions and limitations set for the case study modelling were:

- Annual hot metal production calculated to circa 2 Mt.
- BF ore pellet mix 100 % MPBO (Olivine-fluxed pellet).
- Basicity BR in the BF slag 1.40 [BR (Bell's ratio) = $(CaO+0.7\times MgO)/(0.94\times SiO_2+0.18\times Al_2O_3)$].
- Amount of injected coal in BF 136 kg/ t_{HM}.
- Steel scrap recycling 9.3 kg/ t_{HM}.
- Maximum P content in hot metal from the BF 0.037%.
- Mn content in hot metal from the BF 0.33%.
- Charged amount of BF briquettes 89.7 kg/t_{HM}.
- BOF fine fraction sludge content in briquettes B1 and B2 13.5 kg/t_{HM}.
- Generated amount of ladle slag 10 kg/t_{HM}.
- Generated amount of BF dust 18.1 kg/t_{HM}.
- Available BOF slag amount for recycling (fractions > 5mm) about 48 kg/t_{HM}.
- Total Zn amount charged to the BF roughly 114 g/t_{HM}.

Using the developed system integration simulation model TOTMOD (BF, HM desulphurisation and BOF) a total of seven different material recycling scenarios were simulated. The case study scenarios includes recycling of BOF fine fraction sludge via briquettes to the BF, injection of BF dust and recycling of ladle slag to BF. Figure I51 shows results from the different case study scenarios regarding changes in burden materials and BF slag rate. The 0 line represent the reference case (Base).
The results from the case study indicate possible gains in reduced need for iron ore pellet and limestone in scenarios simulating BOF fine fraction sludge recycling via briquettes B1 and injection of BF dust (such as depicted in Figure I52).

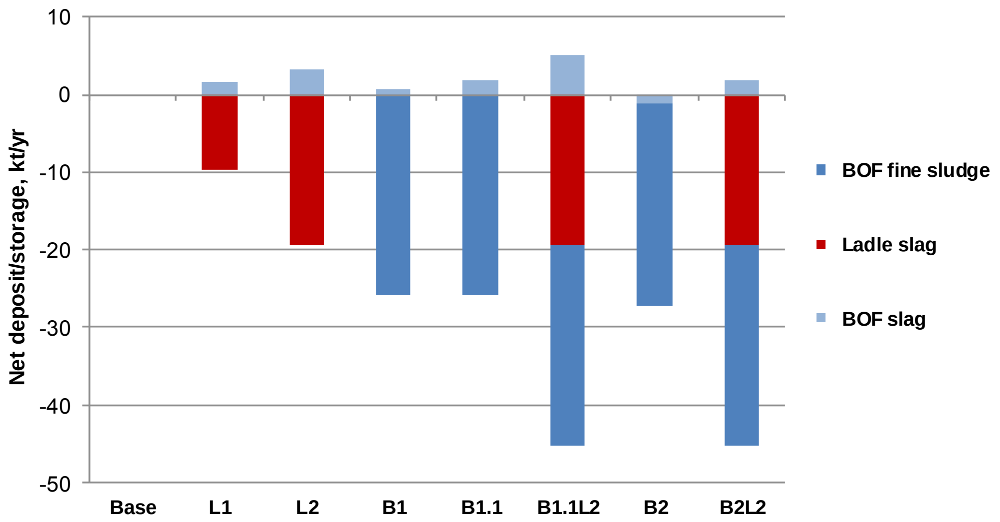


Figure I52: Effect on landfill/storage volumes of BOF fine sludge and ladle slag recycling to BF (kt/year).

The BF slag rate is decreased in scenarios where BOF fine fraction sludge and BF dust is recycled without adding the ladle slag recycling (scenarios B1, B1.1 and B2). Increased BF dust recycling, utilising the BF dust high carbon content, significantly decreases the coke rate (illustrated in scenarios B1 and B1.1). Scenarios analysing effects of charging briquette B2, in which addition of BOF fine sludge was made by reduced deS scrap, simultaneously with injection of BF dust show decreased use of limestone and a minor increase in iron ore use due to the decreased Fe content in the briquettes B2 compared to the reference. In scenario B2 a minor increase in BOF slag recycling is also noticed. Results from steel ladle slag recycling shows only slight positive effects on iron ore pellet savings due to lower Fe content compared to BOF fine fraction sludge. Using 100% of the generated ladle slag decreases the limestone use with roughly 4.5 kg/t_{HM}. The oxidic content (mainly SiO_2, MgO and Al_2O_3) in ladle slag increases the BF slag rate by about 4 kg/tonne HM in scenarios with 100% recycling. However, the manganese oxide in ladle slag slightly decreases the Mn addition and the aluminium content may have a positive influence on the use of BF slag in external applications. Both BOF fine sludge and steel ladle slag recycling to BF show potential to decrease the yearly amount of material to landfill. However, the potential is larger for BOF fine sludge, such as depicted in Figure I52.
The Zn input to BF increases from around 114 g/t_{HM} in the reference scenario (Base) to maximum 130 g/t_{HM} in scenarios with both BOF fine sludge recycling and recycling of all generated BF dust. The Zn content in BF dust increases from 0.34% in the reference to maximum 0.40%. In the BF sludge, the content of Zn is increased from 0.48% to at the most 0.56%. All the results of this analysis are reported in Table I36.

Zn balance		Base	L1	L2	B1	B1.1	B1.1L2	B2	B2L2
Totalt Zn input	g/t_{HM}	113.59	114.08	114.58	90.59	129.10	130.09	129.12	130.11
Zn from iron ore	g/t_{HM}	19.93	19.92	19.92	19.85	19.80	19.79	19.95	19.95
Zn via briquette	g/t_{HM}	62.76	62.76	62.76	39.85	39.85	39.85	78.23	78.23
Zn via BF inject	g/t_{HM}	21.12	21.12	21.12	21.12	59.79	59.79	21.12	21.12
Zn in BF dust	%	0.341	0.342	0.343	0.259	0.397	0.399	0.397	0.399
Zn in BF sludge	%	0.481	0.482	0.484	0.365	0.559	0.562	0.559	0.563

Table I36: Zn input to BF (g/t_{HM}) and Zn in BF dust and BF sludge (%) in the analysed scenarios.

The conclusions drawn from the case study – potential cost savings are:

- Reduced use of iron ore pellet (maximum decrease about 9 kg/t_{HM} in scenarios B1.1 and B1.1L2). However, slightly increased iron ore pellet use in scenarios charging briquette B2 due to its lower iron content.
- Reduced use of limestone (maximum decrease about 9 kg/t_{HM} in scenario B1.1L2).
- Decreased BF slag rate in scenarios B1, B1.1 and B2. Ladle slag recycling increases BF slag rate by about 4 kg/t_{HM} in scenarios with 100% recycling due to its content of oxidic material (SiO_2, MgO and Al_2O_3).
- Somewhat reduced Mn addition in scenarios with ladle slag recycling.
- Landfill reduction potential approximately 26 000 tonne/year from BOF fine sludge recycling and about 19 000 t/year from ladle slag recycling.

Other effects from the analysed case study scenarios are:

- Minor increase in coke rate (with the exception of scenario B1 in which the use of BF dust was significantly reduced).
- Minor changes in BOF slag recycling compared to the reference scenario (Base).
- Somewhat less S and V contents in HM in scenarios B2 and B2.L2.
- Slightly increased Al_2O_3 and decreased S content in BF slag in scenarios with ladle slag recycling.
- Total Zn input to BF increases from approximately 114 g/t_{HM} to a maximum of 130 g/t_{HM}.

15.2.3 CASE STUDY No4: material recirculation at SSAB Luleå

Results from the cases for material recirculation investigated at the SSAB Luleå plant was implemented in the superstructure of the reMIND software. Each case was implemented in the BF-node and optimised scenarios using linear solver cplex was performed. The implemented cases are shown in Table I37, In the first scenarios the optimisation was performed by minimising deposits and energy. Constraints on deposits have been implemented.

Kg/t HM	Ref.	50%-BOF-sludge	100%-BOF sludge	50% SM-slag	100% SM-slag	BOF-sludge, SM-slag	BOF-sludge, SM-slag Incr. LD-slag	Dust-inj
HM-prod	Float	Float	Float	Float	Float	Float	Float	Float
Pellets	1302	1303	1295	1310	1308	1293	1288	1311
Coke,	323	322	322	323	323	322	322	322
PCI	131	131	131	131	131	131	131	131
LD-sludge	0	11	22	0	0	22	22	0
SM-slag	0	0	0	5	10	10	10	
BF-dust inj.	0	0	0	0	0	0	0	11
Lime stone	18	14	10	16	14	6	0	18
BOF-slag	47	47	47	47	48	48	58	47

Table I37: Cases simulated in Excel Totmod and implemented in reMIND software

Case 1 to 8 was implemented in the BF node in the reMIND model. The optimisation was made to minimise energy with fixed constraints on maximum allowed deposits from the steel plant. The model allows all cases and a mix of cases for each maximum deposit. Figure I53 shows how the most energy efficient mixture of cases when allowing a certain amount of deposits. It can be seen that when allowing less and less deposits case 3 will be the most energy efficient case.

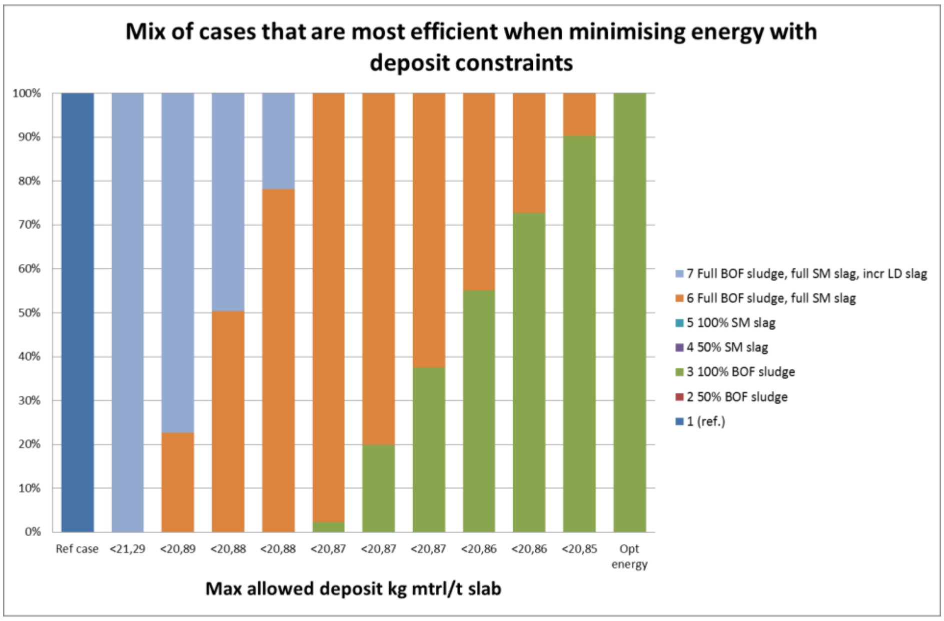


Figure I53. Energy efficient mixture of cases when allowing a predefined amount of deposits

In Figure I54 a sequence scenario is seen for with total energy consumption for each case. Case 3 is the most energy efficient case and uses 60 MJ/t HM or 0.33% less energy than the reference case. Case 3 also recycles about 22 kg/ t steel more material than the reference case which adds up to about 46 kton less deposit material per year.

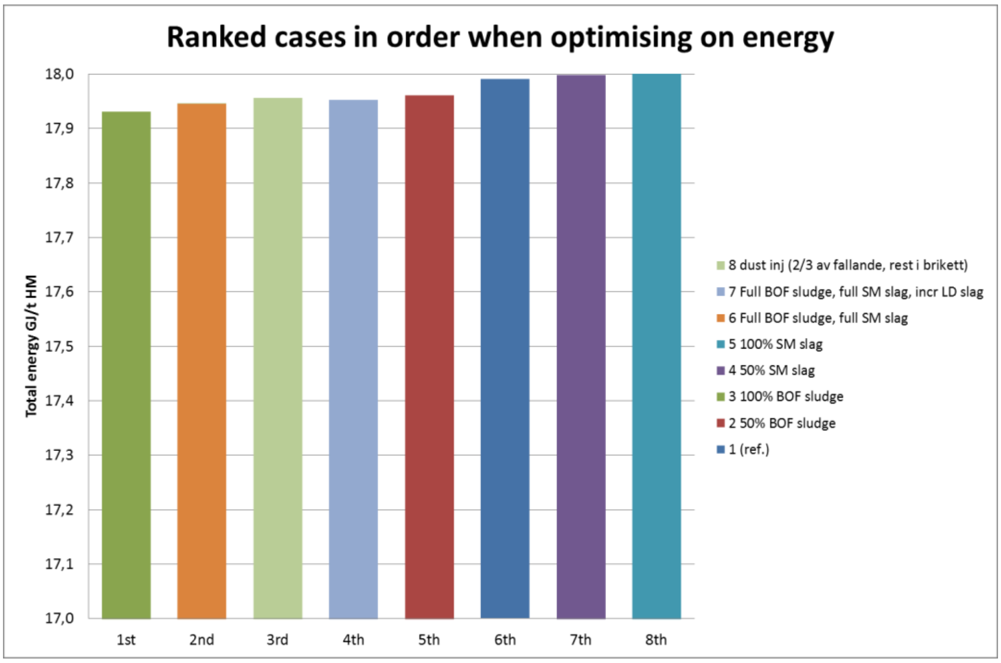


Figure I54: Total energy consumption for each analysed case

Figure I55 shows the Pareto analysis of the influence of increased deposits on the energy consumption. It can be seen that while decreasing the deposit there is a small penalty in energy consumption in the system. This can be explained by the fact that recycled material with high iron content replaces iron ore pellets with a higher iron ore content. More slag needs to be melted and more energy has to be used. Also controlling the slag with lime stone will in some cases increase the energy consumption in the BF.

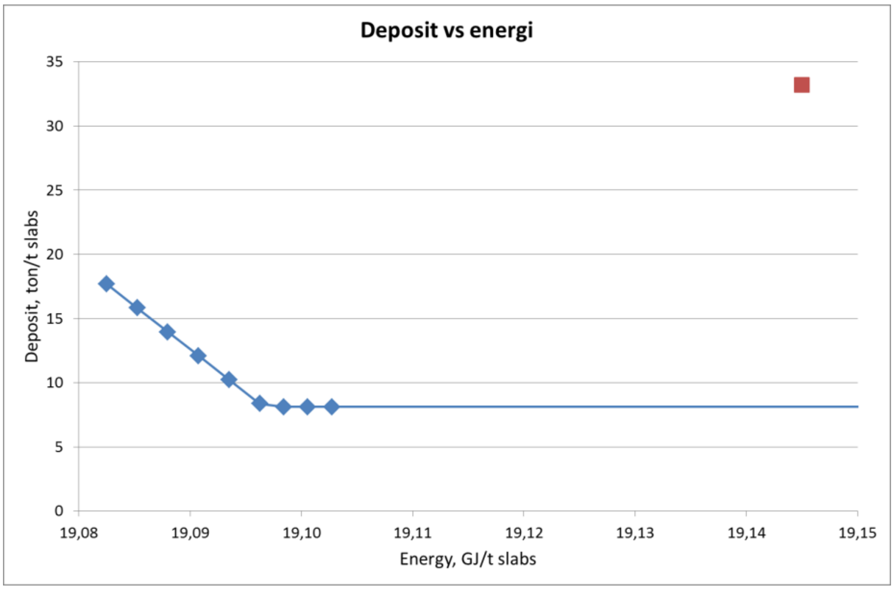


Figure 155: Pareto analysis with multi-criteria objectives to minimise both energy usage and deposits.

16 APPENDIX L - Divulgation material and guidelines for analysing, developing and testing process integration solutions for the steel industry (D4.4)

PIL shared details of its case studies by the following three mediums:

a. Papers published in the REFFIPLANT Workshop within the WCST-2015 conference (see Deliverable D5.4)
b. A synthetic guideline document, which is be helpful to engineers from other steel plants who wish to reproduce similar case studies in their respective plants. The document is reported in this appendix and is also available on the REFFIPLANT web site

Guideline document to cases studies development

Introduction

The overall aim of the Reffiplant project is to improve efficiency of resources (materials, water, energy) in integrated steelmaking plants both by minimising them at source and by finding integrated solutions for recycling, reuse, and treatment of waste water. In this regard, PIL (Process Integration Limited) studied water systems at Tata Steel plant and identified several process integration (PI) based solutions which can be replicated by other steel plants.

Details of these PI based solutions can be found in the Reffiplant final report. However, the idea behind this document is to reflect upon our experience and develop guidelines illustrating the correct way to formulate such problems, and the subsequent steps to be followed and the analysis to be made in order to reach the optimal solution. It took 3 years of investigation and research work to apply PI methodology on steel plants and it is aimed that by means of this document, tools developed and other divulgation materials from this project, engineers from other steel plants will be able to replicate such case studies in their respective steel plants.

This document starts with generic work process and generic guidelines which can be applied for the development of any case study in steel plant water systems. This is followed by case study specific guidelines on applicability and nature of solutions that can be achieved from such case studies.

General Work Process Followed by PIL

As far as the analysis of the case studies related to the Tata Steel water network is concerned, PIL followed a three step work process in order to identify the improvement opportunities and carry out further optimisation work. The details of the work process are illustrated in Figure 1.

The work process highlights the importance of engaging with operators and technical staff directly involved in day-to-day operations of the plant. One of the difficulty faced while conducting water studies is the lack of available data. In general water systems are scarcely monitored and it takes several weeks to get reliable spot measurements. Thus asking for large amount of data without engaging operators on what kind of potential benefits can be achieved can be problematic.

In general, it is better to develop details of the case study in three steps with increasing levels of details in each subsequent step. This not only helps to garner support from operators and management team but also enables engineers to carry on their investigations in parallel to data collection efforts. Instead of waiting for all the data to be collected before starting the analysis, it is a good idea to start filling missing information based on best guesses from operators or based on typical values available from other steel plants or based on estimates from engineering calculations. This enables to initiate investigation and provides sense of which parameters/assumptions are critical for the study thereby helping in prioritising the data collection list.

Figure L1 summarises the major steps involved in this work process:

Optimisation Stage 1 – Data Collection and Preliminary Investigations

1. Define project scope based on benchmarking studies and management priorities
2. Collect plant data and process information
3. Generate heat and mass balance in the form of a simulation spreadsheet
4. Perform first phase of optimisation studies using results from the following analyses: composite curve analysis, sensitivity analysis, comparison of best practices from other steel plants, reuse/regen-reuse analysis
5. Generate an exhaustive list of potential solutions

Optimisation Stage 2 – Verification of Preliminary Results

6. Discuss proposed solution with Tata Steel water chemistry/treatment experts and plant engineers to find out any possible problems including pH, conductivity, spatial feasibility, capital cost etc.
7. Work closely with Tata Steel engineers in order to find ways to overcome some of these constraints. Refine and rework the details for such solutions.
8. Discard the remaining infeasible solutions

Optimisation Stage 3 – Modelling and Cost Estimation

9. Provide data requirements list for further modelling and optimisation work. Work out measurement plan for missing data.

10. Develop & validate spreadsheet based on non-linear models (Note that these models were used to better estimate the results for the proposed re-piping suggestions.)
11. Perform second phase of optimisation studies to workout appropriate retrofit details in collaboration with Tata Steel
12. Quantify benefits e.g. water savings, quality improvements etc. and to provide preliminary cost estimates.
13. Check feasibility of proposed solutions and discard infeasible solutions.

(Note that many of these solutions were still retained if deemed feasible for future operating scenarios such as increased production capacity and stricter environmental legislations.)

14. Perform final stage optimisation (phase 3) on promising case studies and provide more detailed cost-benefit analysis

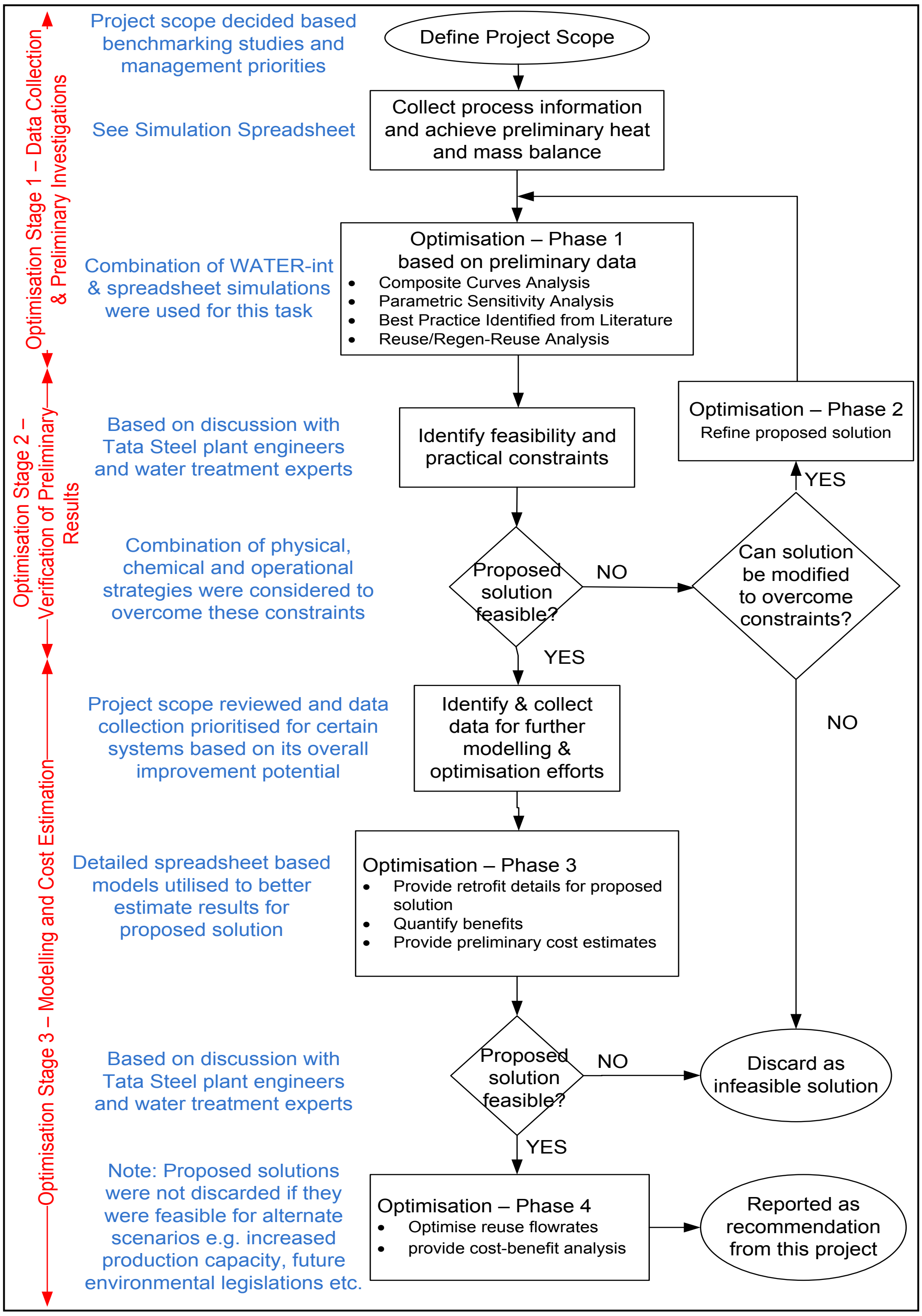


Figure L1: Three step iterative work process followed by PIL

General Guidelines for Case Study Development

Besides the work process discussed above, the following guidelines shall be useful to develop any case study related to water systems in integrated steel plants.

a. Data Collection

The following data sources are commonly available in steel plants and shall be reviewed to extract relevant information:

1. Legionella database

It is mandatory by regulation to monitor the water quality of a cooling tower reservoir in order to ascertain the risk of legionella disease. A cooling tower is a common element of most water circuits in steel plants including blast furnace gas washing. Thus the following useful information can be extracted from such database: Flowscheme of water circuit, typical contaminants and their concentrations, operating guidelines for cycles of concentration, maximum contaminant levels permitted etc.

2. Documentation regarding fresh water abstraction and subsequent treatment units

Fresh water abstraction records indicate the total fresh water used on site which in turn can help in estimating fresh water demand of any particular water circuit. The treatment unit design document can help in modelling and estimation of fresh water quality in terms of contaminant concentrations.

3. Discharge water analysis

Discharge water flowrate and lab analysis of contaminant concentrations is mandatory by government regulation. Thus the following useful information can be extracted from such database: permitted contaminant concentrations in waste water discharge (limits), discharge water flow variations (can be correlated with rain water harvesting), critical contaminants which are operating close to their permitted limits.

4. Pump information

Since the number of flow meters are limited on site, pumps design information and their electricity consumption logs can help determine flow rates of corresponding streams.
Besides check if any pressure, level, temperature or flow measuring instruments are in place and look for their corresponding logs.
After assessment of available information, measurement campaigns can be arranged in order to collect missing data. However it should be noted that large inventories of water are involved in steel plant water circuits and also connection between unit operations (e.g. between clarifiers and HCs) can involve cyclic transfers instead of smooth continuous transfer. Thus there are considerable transient effects that need to be nullified before achieving a valid heat and mass balance around any given system. In this regard, spot measurements need to be repeated at least three times and a flowmeter needs to be kept in place for at least one week’s time.

b. Base case simulation & validation

A number of simulation tools (e.g. Water-int, Aspen Water or other tools offered by water treatment companies) can be used for setting up and validation of the base case describing the current performance and constraints of the system. In general, the following strategy is advised for the development of simulation models in this regard:

1. Stage 1 – Data collection & Reconciliation

Excel spreadsheets are best served for this purpose. It is useful to collect data for a slightly wider scope and also to collect data from multiple sources including design and operational records in order to cross-check that numbers available are within expected ranges. Such data collection also helps in data reconciliation, validation and in setting limits for various variables.
Besides excel spreadsheets can be used collect data regarding performance of certain equipment, thereby enabling the semi-empirical modelling of such equipment.

2. Stage 2 – Simplified simulation model

Water-int is best suited for generating simplified simulation models which can be used for optimisation purposes at a later stage. Based on reconciled data, process loads and separation factors can be back-calculated and a preliminary mass & energy balance can be quickly achieved using drag-and-drop functionality of Water-Int™ interface. A number of parameters might have been guessed at this point and thus sensitivity analysis can be carried out to ascertain which parameters are more critical and thereafter prioritising data collection list.
Besides, Water-int also generates composite curves which can be used for understanding system bottlenecks, setting reuse targets and identifying key contaminants.

3. Stage 3 – Rigorous simulation model

Aspen Water or other simulation tools offered by water treatment companies are best suited for this purpose. Such models need extensive data collection, however if done properly they provide predictive capability which can be used for improve accuracy of simulation results.
Such detailed model can also be used for rating mode calculation and can be utilised to benchmark equipment performance and find opportunities for machine specific operational optimisation.

Note that stage 3 i.e. development of rigorous simulation model can be skipped for feasibility studies and would be employed later while making final investment decision. If the engineering team do not have the capability to develop such rigorous models, tasks of accurately verifying the effect of the proposed solution can be delegated to water treatment companies.

c. Formulation of optimisation problem

Formulation of optimisation problem involves deciding the objective function(s), describing the system in terms of modelling equations and specifying the constraints in terms of lower and upper bound on each variable. Such formulation tasks are usually achieved by developing mathematical equations for objective function, models and constraints from scratch and coding them in commercial optimisation softwares such as MATLAB, GAMS or gPROMS.
Water-int^{TM} has simplified such tasks for MILP (Mixed Integer Linear Programming) formulation of water systems. It has a user-friendly interface to specify context specific values and the resulting mathematical formulation gets generated automatically in the back-end. These formulations can then be solved using linear and non-linear solvers within Water-int or it can be linked to GAMS solvers.
The following features are available within Water-int^{TM}:

1. Objective functions: Both flow based (minimise freshwater demand, wastewater discharge or treatment unit flow rate) and cost based (minimise operating cost, minimise annualised total cost) objective functions can be selected. These cost functions can be further modified by selectively specifying the cost coefficients.
2. Models: Both equipment models and cost parameters can be specified.
3. Constraints: Lower and upper bound can be specified for each variable considered in the formulation.

d. Translation of optimisation solutions into implementation plans

As discussed earlier, models need to be simplified in order to make them suitable for linear optimisation problems. Thus the final optimisation solution needs to be verified using rigorous simulation models. Further sensitivity analysis can be studied to fine-tune the final result for optimum results and in line with system constraints and ease of implementation. Thereafter final techno-economic evaluation can be completed to justify the implementation of the solution.

Case Study Specific Guidelines

CASE STUDY No 5: Lagoon 1 Water Reuse in BF Gas Wash Systems,
The lagoon water becomes an important source of reuse water if it accumulates a significant amount of rainwater. In that case, discharge water contaminant concentrations will be much lower than the limits through this dilution effect, and the reuse of such water source involves zero to low cost treatment. However the extent of reuse will vary depending upon the amount of rainfall in that region and how far the gas washing section is operated from its limits. In general the lagoon water can be reused in any gas washing section (including BF and BOS) and such strategy can result in a significant reduction in water footprint of the site.

CASE STUDY No 6: Pond A Water Reuse in BF Gas Wash Systems
The Blast furnace gas washing (BF GW) circuit is a major contributor of ammonia. Hence containment of blowdown from the BF GW circuit will help in achieving a significant reduction in ammonia levels in the final discharge water. Thus blowdown reuse should be maximised at every recycle opportunity i.e. first in the HC section and then in the settlement lagoon (Pond A). In general, the following sources are good candidates for BF GW water utilisation: slag granulation unit, sinter plant and bowsering stations.
In general, low cost ammonia reduction strategies can be uncovered through such studies.

CASE STUDY No 7: Recycling of the BF GW HC overflow water with suitable treatment
The gas washing section of the blast furnace collects significant amounts of iron (866 kg/h iron for 3 Mt/y of steel production capacity). However this iron cannot be reused if not collected selectively by separating the Zn and Pb from it. Around 70-80% of this iron can be recovered by using HCs. Thus they should be the first equipment that is considered for iron recovery. Second step would be to add a magnetic filter which can recover the remaining 20-30% of the iron in the BFGW blowdown stream.
In general, these case studies involve low-to-medium capital investment and the payback period can be extremely attractive if good quality iron can be recovered from them. Thus the design of the HC and magnetic filter are critical for the success of such case studies. Also such solutions improve water quality in both gas washing section and waste water discharge.

CASE STUDY No 8: HPM-Ancholme System Water Recovery & Control
This case study highlights the importance of communication between multiple pumps operating within the same system. Improper settings of level control and lack of communication between pumps can lead to pressure fluctuations, loss of pressure in water mains, wastage of pumping

electricity, and lost opportunity of water recovery from reuse sources. Time based dynamic simulation of such systems and fine-tuning of level settings & control strategies can prevent the above mentioned issues. Such simulations are not complicated and can be replicated in excel spreadsheets for analysis purposes. The resulting control strategy can then be implemented using PLC based automated control system which is a relatively low cost solution.

SSSA developed generic guidelines to the modelling and simulation approach developed within REFFIPLANT, which are codified in the following document

Improving resource efficiency through a general-purpose methodological approach combining standard techniques, modelling and simulation

Introduction

A better management of resources reducing waste materials and minimizing raw material intake is the aim of the REFFIPLANT project and according to the "Zero Waste" European directive this is a common objective of several steelmaking industries.

To this aim, SSSA developed the present document in order to give guidelines and advices to the staff of steelworks outside the REFFIPLANT consortium related to the overall methodological approach elaborated, formalised and pursued within the REFFIPLANT project.

The documents is organized as follow: Section 2 introduces the overall methodology, while Section 3 deepens each phase it is composed of. Furthermore, deep information about main used simulation software are given in the description of the Modelling & Simulation step.

Overall methodological approach for improving efficiency in resource management

Several can be the issues to address when process modifications or plant revamping have to be done in order to improve the efficiency of the resource management. The combination of simulation and on-site investigations can simplify the problem and can reduce man-hours spent to find the best solution. In addition, a strict collaboration between researches and plant managers and engineers is fundamental because know-how can be shared and different skills and expertise can be combined.

Based on these presuppositions, the methodological approach can be represented in the onion diagram depicted in the Figure 1**.**

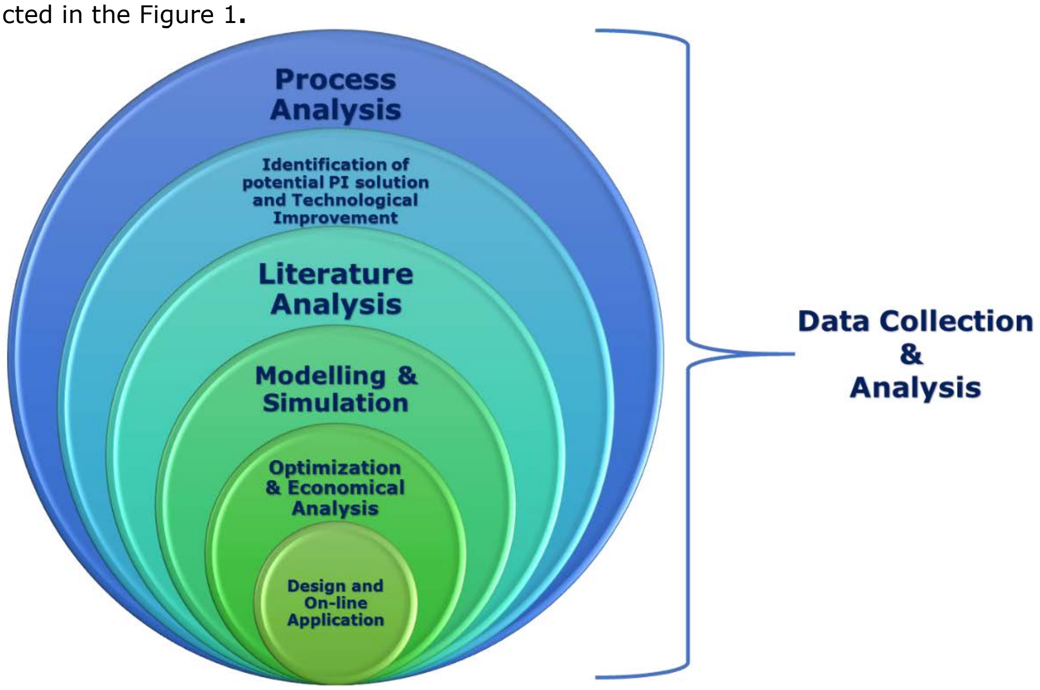


Figure1 Methodological approach diagram.

The methodology is composed by a series of steps which forego the goal of the on-line application but only in this way is possible to acquire a deep knowledge of the process to analyse and to avoid costly investigations related to non viable or non convenient solutions. The diagram highlights that data collection and analyses is a fundamental step to be carried out in the whole investigation study, as only a deep data collection allow avoiding the neglecting of important process parameters.

Steps of the methodological approach

Process Analysis

The first and main step is the process analysis. The process know how has to be acquired and the collaboration between researcher and steelworkers is of utmost importance. The process analysis have to be carried out through a deep examination of process route, Piping and Instrumentation Diagrams (P&IDs) related to main production process and to auxiliary treatments and equipment datasheet. In this way, a deep knowledge of the current industrial practices can be acquired.

Identification of potential PI solution and Technological Improvement

A detailed process analysis allows identifying possible improvement margins or bottlenecks. In this phase, common and well-established techniques can be used in order to obtain a list of potential PI alternatives or plant improvement.

In the case of water system, water pinch analysis is a systematic technique, usually carried out by plant managers: the starting point is the identification of similarity of water properties, contamination and process constraints in order to identify potential water sources and water sinks. Clearly data collection is fundamental in order to acquire the following information for the pinch analysis: streams flowrates, chemical compositions, equipment and pipes sizes and capabilities, treatments and process efficiencies, plant layout for water sources and sinks allocations, process constraints (e.g. in terms of contaminant amount). The development of source and sink composite curves or the water cascade analysis is the following phase. The first approach is widely adopted: it considers each water-using operation focusing on the mass transfer of one or more contaminants from the process to the water streams and the limiting composite water profile is the results of the pinch analysis. However, in the case of a single contaminant this kind of investigation has a high accuracy. On the other hand, when multiple contaminants must be considered, some simplifications are required and deeper assessment have to be done in order to avoid neglecting important parameters that lead to unfeasible solutions. Furthermore, water pinch analyses does not consider the interactions between contaminants, the contaminants variation and the possibilities that ad-hoc treatments can be required to obtain suitable water to be reused.

In the case of by-product and waste management, preliminary experimental investigations are needed. Indeed, deep analyses of by-products and waste features through conventional techniques (e.g. XRF, XRD, SEM analyses, leaching test, etc.) are fundamental to identify potential possibility of internal or external recovery after or without treatments. It is possible that a by-product in the current situation is contaminated (e.g. mill scale from oil) or need to be separated in its main fractions (e.g. magnetic and non-magnetic); for this reason the possibility to develop a new treatment or to apply well know technologies can be identified in this step.

In conclusion, this step is of primary importance to outline the scope of the subsequent deep analyses.

Literature Analysis

This step aims at the following objectives:

- Achieving a deep theoretical insight of the considered problem
- Searching if similar problems were addressed
- making a benchmarking of existing technologies suitable to treat for example a kind of by-products or water coming from a production area
- filling eventual missing data.

Modelling & Simulation

In order to make complete analyses of the identified potential PI solutions or technological improvements, Modelling and Simulation (M&S) can be exploited. Indeed, M&S allow obtaining information about the behaviour of a process, a treatment or a phenomenon in a wide range of conditions, also uncommon or that cannot be tested easily or safely.

Modelling is the first sub-step and consists in the conceptualization of the considered system and have the aim of representing industrial processes (existing or not) composed of some unit operations and linked by material and energy streams. Each phase of the real process have to be adequately represented and it is possible that a single operation have to be represented through different sub-units to consider each phenomena or that multiple real operations have to be aggregated in a single one because they characterise a single phenomenon. Simplifications can be necessary but it is important that the parameters fundamental for the final aim of the study are not neglected during the modelling. From this considerations, it is clear that the model have to be developed as similar as possible to the real system (if it is exists also in a pilot scale) and its results have to be similar to the real case. For this reason, data collection is fundamental: if data are not available, an ad-hoc experimental campaign is needed. In the case of new processes, parallel experimental studies (e.g. laboratory tests) are fundamental in order to represent each involved phenomenon in a way that is the as close as possible to experimental results, literature and experience information.

The model developed and tuned in this way represents a sort of virtual plant that can be used to make scenarios and sensitivity analyses changing operating conditions or configurations (e.g. the addition of a new water stream or the analyses of different physical treatment arrangement). Indeed, the model can be used in the simulation phase. In this phase the model is run in order to assess complex or unexplored scenarios filling the approximations made in the preliminary phase of the proposed methodology and giving useful indications for the next final steps: simulation answer to the "what if" question.

In this phase, a selection of the correct simulation software is essential. A software can be chosen according to the level of detail and the complexity required. The choice can be also guided by licencing costs.

This aspect is well depicted by the REFFIPLANT project, in which four different software were used:

- Microsoft Excel®
- Water-Int™
- reMIND
- Aspen Plus®

Microsoft Excel®
Microsoft Excel® can be used to develop theoretical, holistic or empirical models of a unit operations, resource users or process treatments. The model have to be based on algorithm in which only main parameters are considered. The simplified developed models can be used stand-alone or linked together for preliminary and less accurate investigations or can be included as a part of more complex models developed with commercial simulation software. Microsoft Excel was used within REFFIPLANT to develop holistic/heuristic models of water and by-products treatments. Some of them were included in the Water-int™ software. Other ones were used in the evaluation of the best arrangement of treatment units to separate BOF slag in its main fractions in order to allow the complete reuse or to generate scenarios data to be used in reMIND software.
Water-Int
This software was developed by Process Integration Ltd (PIL); some holistic models of water treatments developed during the REFFIPLANT project were included in Water-int™. It is based on linear optimisation framework and does not consider complex ionic interactions between different chemical species. It works on the basis of fixed or linearly varying separation factors based on theoretical laws and it can be used for preliminary studies of simulation and optimization of the structure of an industrial water network minimizing for example economic and environmental impacts. More information about its use are given by PIL in the Water-Int User Guide.

reMIND®
reMIND is a Java-based software based on the Method for analysis of INDustrial energy system which is based on Mixed Integer Linear Programming. The software allows the development of a complex superstructure of nodes and branches in which several aspect of a process are considered. The user can insert the data obtained by Excel models, other simulations or real situations and the software is able to create a list of equations that can be used by optimization software to pursue a multi-objective optimization of the developed system according also to the defined constraints. In the REFFIPLANT project, reMIND proved to be a powerful tool to analyse and optimize solutions for management of solid streams of by-products and wastes.
Aspen Plus®
Aspen Plus® is a commercial simulation software part of the AspenONE® Engineering suite, focused on process engineering and optimization. It allows the development of rigorous models with a high accuracy and the monitoring of almost all the features that in a real plant are normally monitored.
It has been intensively used within REFFIPLANT in complex scenario and sensitivity analyses, as it is a very flexible software that allow the modelling and the analyses of very different chemical species and processes (e.g. electrolytes, water and solids systems, etc.) considering the interactions between the considered species. This is possible thanks to a significant number of databanks of chemical compounds and libraries of several kind of unit operations, which are included in the software, as well as to the possibility to include customized blocks.
The translation of a process into an Aspen Plus model follows five main steps:

- Specify the chemical components in the process (they can be defined if not presents in databanks)
- Specify thermodynamic models to represent the physical properties of the components and mixtures in the process
- Define the process flowsheet (unit operations, streams to and from the unit operations, …)
- Specify the component flow rates and the thermodynamic conditions (temperature, pressure, etc.) of feed stream
- Specify the operating conditions for the unit operation models

Before the modelling in Aspen Plus very important is the full understanding of the process to be modelled and of the issue to be focused. In this way is possible to choose the best property method that is fundamental for the property calculation and so for the calculation of results: for example a water network in which electrolytes are presents need the "ELECNRTL" property method. Some indications are given in Figure 2.

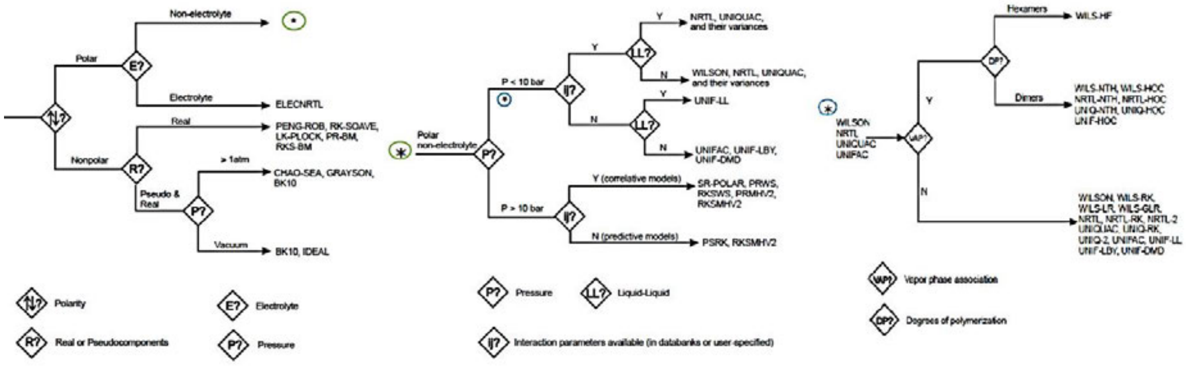


Figure 2 Indications to choose the best property method in Aspen Plus®

Furthermore, the understanding of the problem to model allows focusing only on the most relevant aspects, by neglecting those issues and aspects that do not affect the considered phenomena. In this way, a global process is divided into its main conceptual aspects, which have to be represented in the simplest possible way in order to save valuable time and developed a fast model implying low computational costs.
As previously mentioned, Aspen Plus® can be customized: for instance, it is possible to create new compounds or complex mixtures, new unit operations as well as to customize calculator blocks in order to compute some parameters. Within REFFIPLANT, this feature has been widely adopted and some examples of customization are here listed: oil in oily mill scale has been modelled as a mixture of pseudo-components created by Aspen Plus® starting from some oil parameters, electrical conductivity in water solution has been calculated through an ad-hoc written FORTRAN-based calculator block. The software allows also the integration of previously developed Excel models. It is clear that the user has many degrees of freedom in such customization.
Depending to the aim of the investigations, the simulations can be carried in steady state or in dynamic environment: steady state simulations were suitable to the aims of REFFIPLANT.
Finally Aspen Plus® allows a simplified management of complex model with Aspen Simulation Workbook that connects the model with Excel spreadsheet and allow controlling it from a more familiar software.

Optimization and Economical Analyses

Simulations can provide useful indications on the behaviour of an existing plant changing the operating conditions or the current configurations in the analyses of different solutions related to the resource management. Moreover, indications on the efficiency of a treatment to provide potentially reusable material can also be obtained by simulations. However, it is possible that the best solution identified analysing the simulation results is not the best in terms of economic and environmental impact. To this aim, a parallel economic analysis (costs and barriers) and multi-objective optimization studies to minimize the costs and the environmental impact are fundamental in order to find the best solution to the analysed problem between the most promising simulation solutions.
Furthermore, the optimization of some process parameters can be carried out through on-site trials and experiments exploiting pilot plants.

Design and On-line Application

The deep analyses carried out in the previously described steps allow identifying and designing the best solution to improve resource management without risks in terms of safety, environmental impact and costs. The application of unfeasible solutions are avoided.

17 APPENDIX M – Other deliverables from WP4

17.1 D4.3 Tools for total site analysis for testing process integration solutions

Water-int™ software is primarily designed for targeting and conceptual design of water minimisation and distributed effluent treatment network problems. This software was used during the initial phases of the project in order to identify potential list of process integration solutions. Further enhancements were made during the project in order to improve its usability for water systems of integrated steel-making sites. Details of the software and associated enhancements achieved during the Reffiplant project can be found in the 'Water-intTM User Guide' document (see also Section 21.2 – Deliverable 4.5).

17.2 D4.5 Training course on the tools for total site analysis devoted to engineers and process operators with guidelines for customization

As discussed earlier in Section 5.3.4 WP4 – Task 4.5, PIL developed a user guide document for WATER-intTM software. This user guide starts with a discussion of the underlying principles behind water pinch analysis and superstructure based optimisation techniques. Then it introduces the WATER-intTM interface & functionalities and how to setup/utilise them correctly for different class of problems. This discussion is further reinforced by demonstration of sample case studies. This user guide document can also be found on the REFFIPLANT website.

SSSA developed a training course for high-level plant technical staff on the general purpose modelling and simulation approach developed within REFFIPLANT as well as the simulation tools that were exploited in the project. A particular attention has been devoted to Aspen Plus® simulations, as Water-Int sumulations are already covered by the documents developed by PIL, while Excel and reMIND are simulation tool whose usage is already well consolidated in the steel field.

18 APPENDIX N - Results of assessment of the on-site tests of the new solutions (D5.1)

18.1 Tests on water systems

ILVA carried out tests on the possibilities of improve the quality of coke-making area wastewater in order to maximize its reuse. To this aim, a pilot plant having UF and RO units in series was used. The main characteristics of the pilot plant are
Figure N1 shows a simplified flowsheet of the pilot plant, in which chemical additions are not shown.

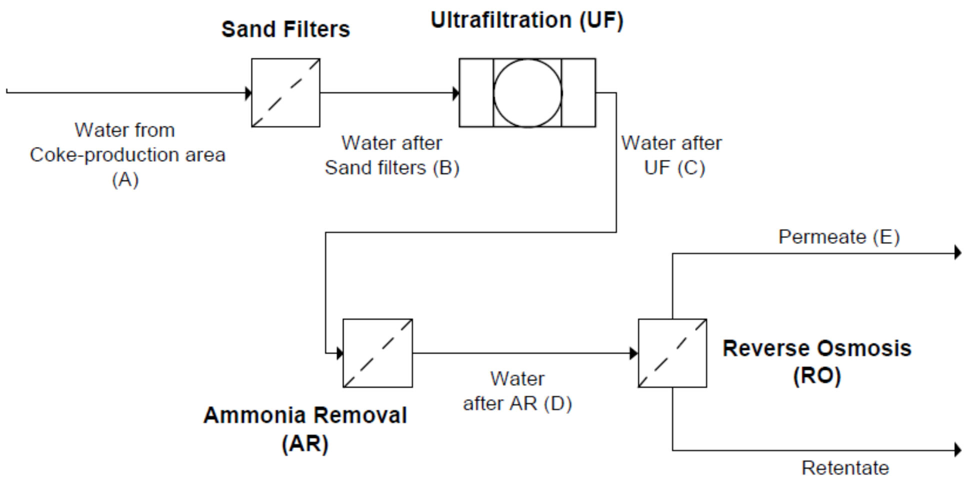


Figure N1: Simplified flowsheet of pilot plant.

Table N1 summarizes the main features of the UF experimental plant, while Table N2 reports the main features of the RO experimental plant.

UF plant characteristics	Unit	Value
Membrane type	---	DOW SFP 2860
Nominal pore diameter	µm	0.03
Membrane diameter	Mm	225
Membrane area	m²	51
Number of membrane	---	1
Total filtration area	m²	51
Flow configuration	---	Dead end Flow
Filtrate flow , T = 25 °C	l/(h*m²)	40 ÷ 120
Flow range	m^3/h	2 ÷ 6.1
Max inlet module pressure, T = 20 °C	Bar	6.25
Max transmembrane pressure	Bar	2,1
Max temperature	°C	40
Backwash frequency	Min	20 ÷ 60
Max TSS	mg/l	100
Expected filtrate SDI	---	≤ 2.5

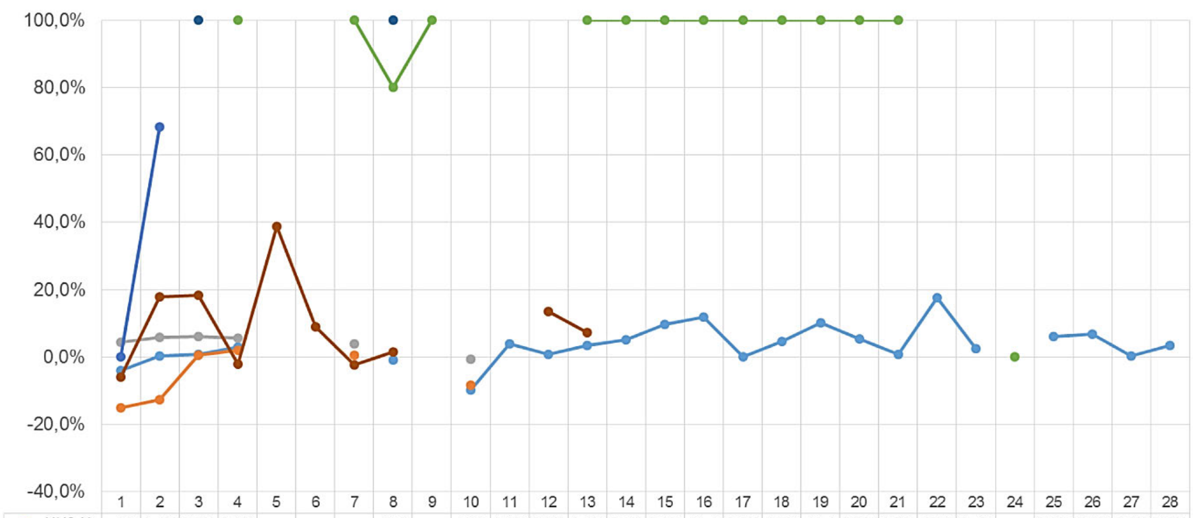
Table N1: Characteristics of the UF experimental plant

RO plant Characteristic	Unit	Value
Membrane type	---	DOW BW 30 – 4040
Membrane diameter	Inch	4
Membrane area	m²	7.2
Max operating temperature	° C	45
Max operating pressure	Bar	41
Max feed flow rate membrane	m^3/h	3.6
Max feed flow rate membrane	l/(h*m²)	500
Max pressure drop	Bar	1
Max feed SDI	---	5
Permeate flow rate (*)	l/h	379
Stabilized salt rejection (*)	%	99.5
Configuration plant	---	One stage
Number of membrane 1° stage	---	4
Number of membrane 2° stage	---	2
Total filtration area 1° stage	m²	28.8
Total filtration area 2° stage	m²	14.4

Table N2: Characteristics of the RO experimental plant. (*) Permeate flow and salt rejection based on the following test conditions: 2,000 ppm NaCl, inlet pressure 10.3 bar , 15 % recovery.

The the recovery rate of the UF stage is 89.5%, while the recovery rate of the whole RO stage is 60%.

The tests were carried out with or without RO treatment in order to assess if this expensive treatment is necessary. The results of the trials without RO are reported in Figure N2, where removal efficiencies in stream C with respect to comtaminants amount in stream B are shown.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
NH3-N	-4,0	0,4%	0,7%	2,9%				-0,8		-9,9	4,0%	0,8%	3,4%	5,0%	9,6%	11,9	0,0%	4,5%	10,1	5,3%	0,7%	17,6	2,4%		6,2%	6,9%	0,2%	3,5%
NO2-N	-15,	-12,	0,7%	2,1%			0,6%			-8,4																		
NO3-N	4,5%	5,8%	6,2%	5,5%			3,9%			-0,6																		
CN free	0,0%	68,4																										
Fe				100,			100,	80,0	100,				100,	100,	100,	100,	100,	100,	100,	100,	100,			0,0%				
Mn			100,					100,																				
COD	-5,9	17,8	18,3	-2,0	38,8	8,8%	-2,2	1,4%				13,5	7,3%															

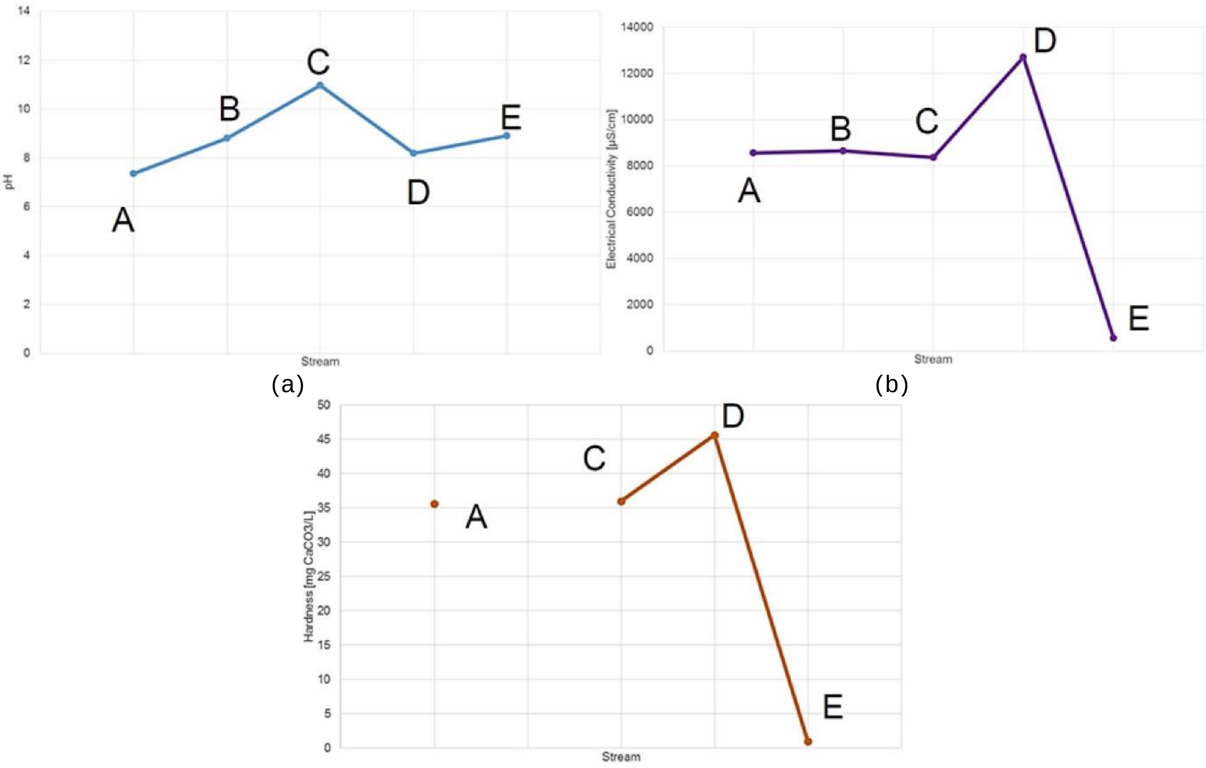
Trials

Figure N2: Removal efficiencies of main contaminants after UF in treatment process withouth RO (stream C)

The main average results are:

- Removal efficiencies
    - NH_3-N 3,5 %
    - NO_2-N -5,4 %
    - NO_3-N 4,2 %
    - CN Free 34,2 %
    - Fe 91,4 %
    - Mn 100 %
    - COD 9,6 %
- Hardness
    - IN (stream B) 294,1 mg $CaCO_3$/L
    - OUT (stream C) 241,5 mg $CaCO_3$/L
- Electrical conductivity
    - IN (stream B) 9168,6 µS/cm
    - OUT (stream C) 8947,1 µS/cm
- pH
    - IN (stream B) 8,6
    - OUT (stream C) 9,6

The results prove that UF partially remove the contaminants but is not sufficient to obtain high quality water. For this reason, other trials were carried out with RO treatment in series to the UF.
The obtained average ph, EC and hardness trends during the global treatment (with RO) are reported in Figure N3. Their trends is affected by the addition of some chemicals (e.g. lime, $FeCl_3$, polyelectrolyte, etc.) and by the removal of contaminants during the treatment. RO drastically reduced the salts content in the permeate and this is reflected by a drastic reduction of electric conductivity to an average value of about 563 µS/cm and of hardness to 1 mg $CaCO_3$/L.



(a) (b) (c)

Figure N3: Average values of the main water parameters during the treatment process with RO: (a) pH, (b) Electrical Conductivity, (c) Hardness.

In addition, the removal efficiency of ammonia after the related process is shown in Figure N4 and an average removal efficiency of about 80% is obtained. Furthermore, the removal efficiencies of the main contaminants after UF and after RO are compared in Figure N5 and N6. It is clear that RO allows obtaining an almost complete removal of the contaminants. UF is capable to remove almost completely Fe and Mn but it is not capable to remove salts and N species. For this reason, the RO treatment appears fundamental in order to obtain high quality water to be reused.

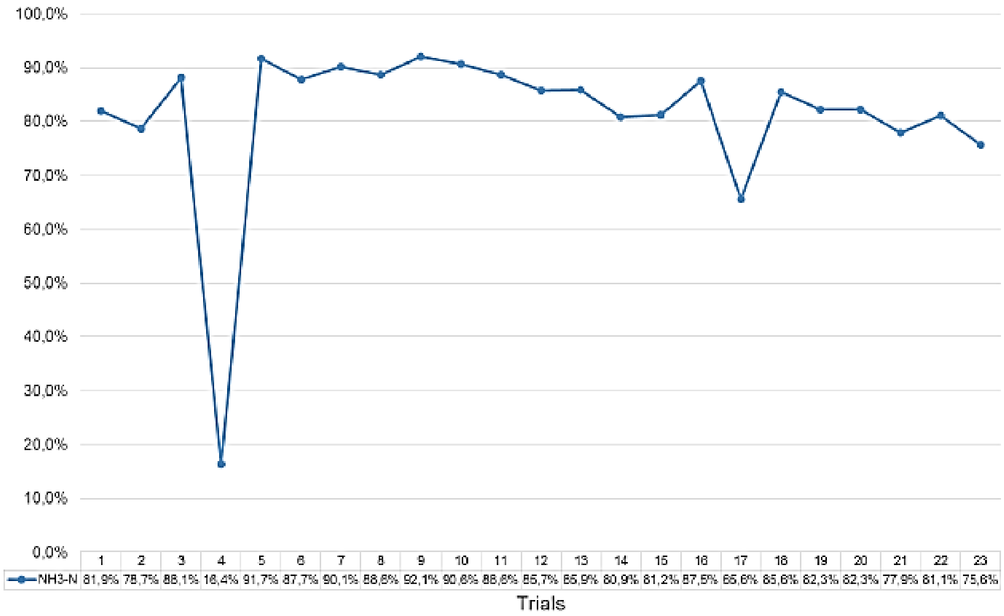


Figure N4: Ammonia removal efficiency (stream D)

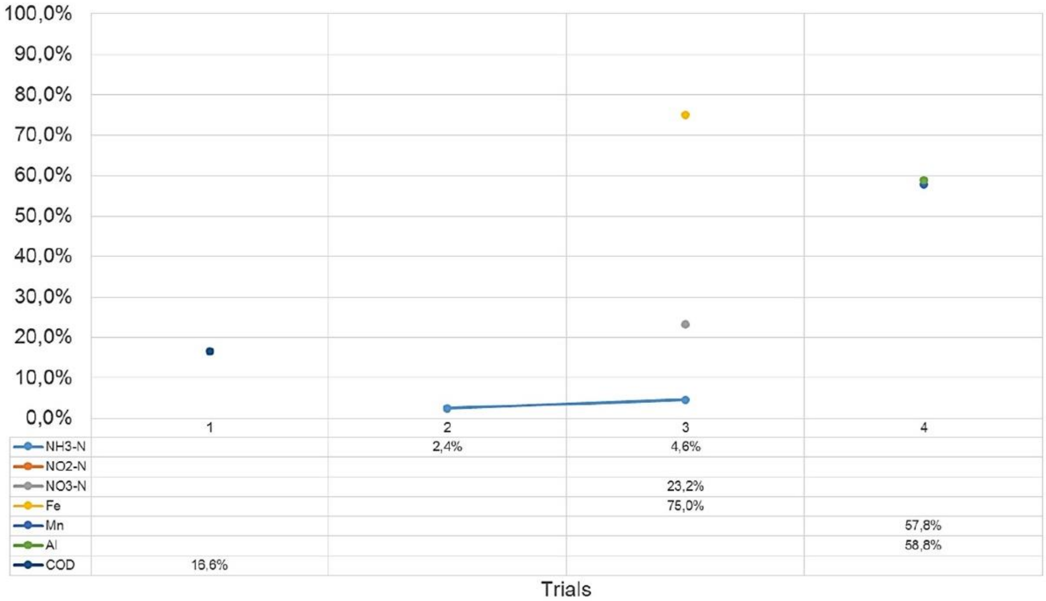


Figure N5: Removal efficiency of relevant compounds after UF (stream C)

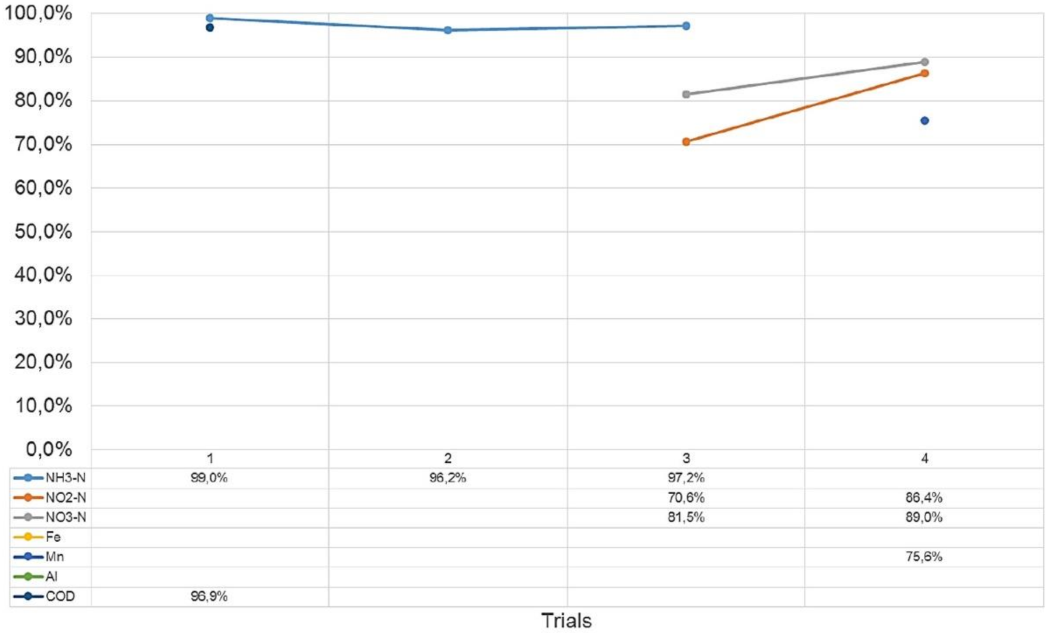


Figure N6: Removal efficiency of relevant compounds after RO (stream E)

Tata Steel carried out MF trials at the BF GW area. Within these trials the recycling of the BF GW HC overflow water was investigated coupled with suitable treatment. Filtration of suspended solids in the recycled HC overflow is a first step. Additional treatment of the water for reducing Ammonia and Chlorides is also necessary - a 10% side-stream of the cooling tower water may be sufficient. A commercial magnetic separation unit was assessed for the filtration of suspended solids in the HC overflow (see Figures 40 and 41).

The results of the analysis of the water sampling at the inlet and outlet of the magnetic separator are shown in Figures N7 and N8. The results show that higher flow rates have a major effect on reducing the efficiency of solids removal, which may be stripping the captured solids off the magnets. Removal efficiency (Reduction %) of solids increases with increase in inlet solids concentration,

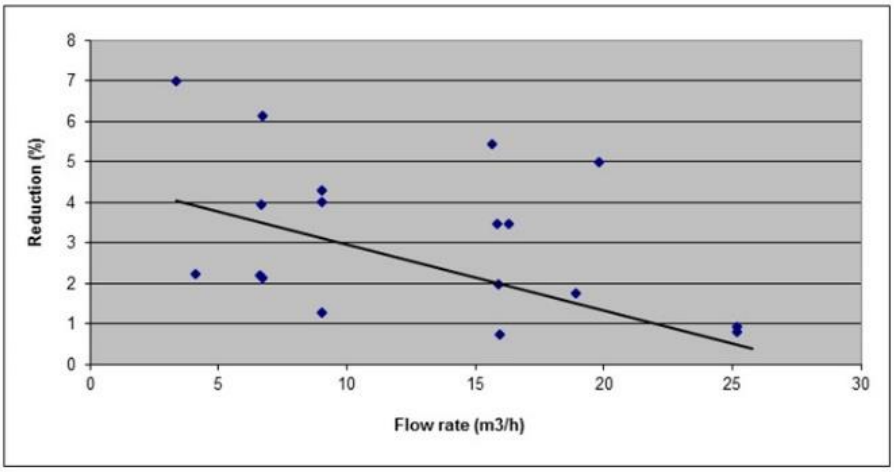


Figure N7: Analysis of the magnetic separator performance wrt flowrate

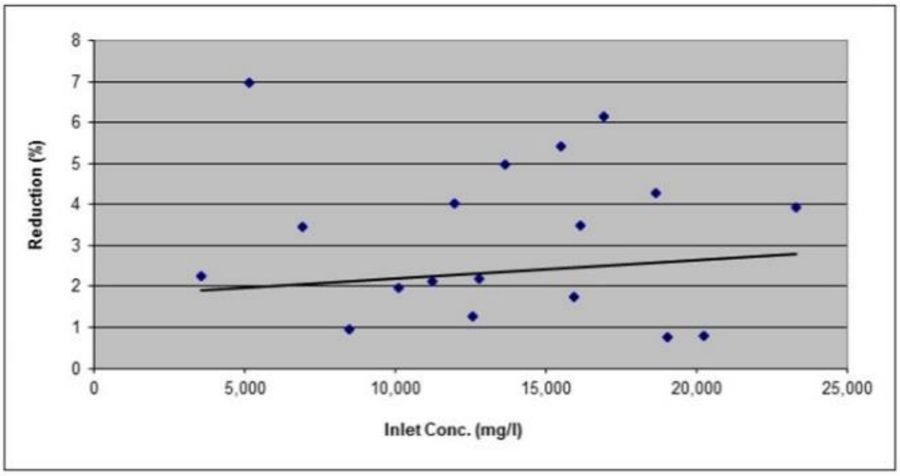


Figure N8: Analysis of the magnetic separator performance wrt inlet concentrations

Results of the analysis on the dry solids using a XRF technique to find the percentages by weight are shown in Table N3. There is a reduction in Zn, which means that the sludge produced from this filtration technique will have a high content of Zn that makes it unsuitable for reuse in the blast furnace via the sinter plant.

	TSS (g/l)	Fe (wt%)	Zn (wt%)	Pb (wt%)	S (wt%)	Ca (wt%)
Inlet	12.7	37.61	13.22	1.69	2.63	3.47
Outlet	12.3	35.61	12.89	1.69	3.33	3.4

Table N3: Analysis of inlet and outlet water of the magnetic separator (<5% efficiency)

More than 99% of the solids are >0.8 um and are made of less than 38% Fe. The rest of the particle is made of non-magnetic material (i.e. the suspended solids in the BF GW water are weakly magnetic). This may be the reason for the low removal efficiency (<5%). However, the trial showed that magnetic separation is a feasible means of filtration for the BF GW HC overflow water. However a new design is needed to achieve high efficiencies (>90%). To achieve high removal efficiencies (>90% efficiency), a new magnetic separation system needs to be designed. Based on the high costs of sending/treating the water to lagoon 1 plus the cost of cooling tower maintenance and performance, it may be possible to install suitable water treatment to achieve a payback in a reasonable time.

SSAB pursued a trial campaign on the recirculation of the water coming from the BF gas cleaning system. The trials are divided into 3 phases; "before", "trial" and "follow-up". Three samples were taken as reference before the actual trials started (before). During the trials, samples were taken more often in order to follow the assumed increase in concentrations. The trials were followed by three follow-up samples taken over the following week. For each sampling occasion, water samples were taken at ED, EK and at CS (see Figure I35 in Appendix I). At CS analyses were performed on both the water phase and the sludge phase. The samples schedule is reported in Table N4.
The water samples were analyzed with regard to: temperature, pH, suspended solids (SS), conductivity, hardness, p-alkalinity, m-alkalinity, TOC, Ca, Na, Fe, Cl, NO_2, NO_3, CN, Phenol, Zn, Zn filtered, SO_4, F, Al and Si.
The sludge phase was analyzed with regard to: TS, Fe, CaO, SiO_2, MnO, P_2O_5, Al_2O_3, MgO, Na_2O, K_2O, V_2O_5, TiO_2, Cr_2O_3, Volatile Solids (VS), C and S.

Period	Date	Time	Sample points water	Sample point sludge
Before	2015-04-13	8:20	ED, EK, CS	CS
Before	2015-04-14	8:10	ED, EK, CS	CS
Before	2015-04-16	8:00	ED, EK, CS	CS
Trial	2015-04-20	07:35	ED, EK, CS, SB	CS
Trial	2015-04-20	10:00	ED, EK,	CS
Trial	2015-04-20	13:00	ED, EK, CS	CS
Trial	2015-04-20	15:00	ED, EK, CS	CS
Trial	2015-04-21	08:00	ED, EK, CS	CS
Trial	2015-04-21	13:00	ED, EK, CS	CS
Trial	2015-04-22	08:00	ED, EK, CS, SB	CS
Trial	2015-04-22	12:00	ED, EK, CS	CS
Follow-up	2015-04-23	08:00	ED, EK, CS, SB	CS
Follow-up	2015-04-24	9:20	ED, EK, CS	CS
Follow-up	2015-04-27	8:30	ED, EK, CS	CS

Table N4: sampling schedule for the trial

The data were evaluated by a time scale study, where the samples were plotted versus time. Furthermore, the concentrations were evaluated versus the sludge flow from the clarifier (degree of recirculation) for the compounds that appeared to have a correlation with the sludge flow. This procedure was performed both including and excluding the follow-up samples. Finally, for compounds where historical data existed, the trial data and the historical data were compared in order to establish or reject correlations.
For evaluation of the campaign, the compounds were divided into four groups. For the compounds belonging the first group, the concentrations are not affected by the degree of recirculation; for the ones in the second group, the concentration of the compound is increased as a function of increased recirculation; for the compounds in the third one, the concentration is decreased, while the compounds in fourth one were not detected or with few detected samples (see Table N5).

Increased concentrations	Decreased concentration	Not affected	Not detected
conductivity, Na, m-alkalinity, Ca, Cl, ammonium, sulfates, F, Si	Fe	pH, TOC, TS, Al, Zn,	p-alkalinity, CN, phenols, hardness

Table N5: Classification of the different compounds based on how they were affected by increased recirculation

The sludge composition during the trial was compared to sludge composition for January to May 2015 in order to determine if the samples were within normal variations. This was also performed for the Fe concentration in sampling point ED and EK, since data was equivocal.
In order to fully understand the behavior of ammonia nitrogen in the studied system, the NOx in the off gas from BF-gas combustion at the carbon injection was evaluated. If the ammonium was increased in the recirculated gas wash water, it could affect the BF gas wash capacity for ammonia. It is however not possible from available data to determine if there is such a correlation. The NOx analysis is only performed intermittently, and varies a lot depending on BF process operation.
Since the sampling normally is less than during the trial, correlations between the concentrations ED and EK and water from CS respectively were derived from trial data. The correlations were used for case studies of various methods for treating and increasing the recirculation of the sludge water (WP4). The correlations were developed for ammonium, chlorides and calcium.
Figure N9 shows a summary of the concentration of the compounds with an increased concentration for the entire trial period (from before to follow up) for sample point ED.

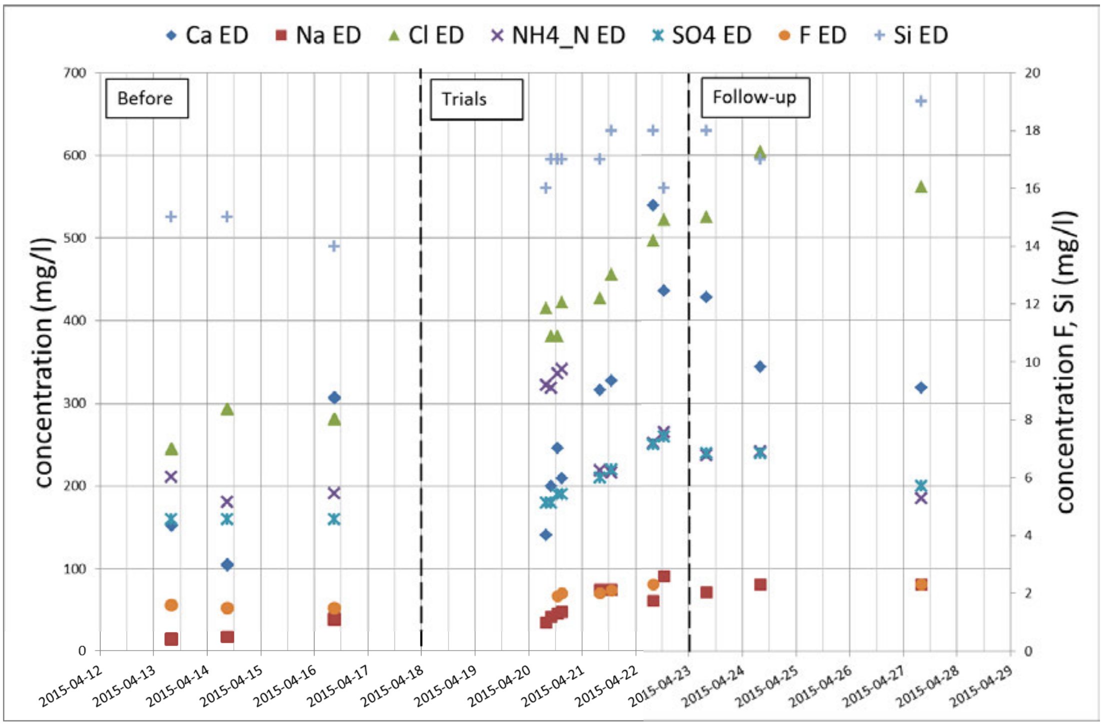


Figure N9: summary of the compounds that were affected by the increased recirculation (Ca, Na, Cl, NH_4N, SO_4, F, and Si) in sampling point ED.

All compounds in Figure N9 show a tendency to an increased concentration in the water samples as the recirculation is increased (sludge flow leaving the system is cut in half), but the absolute increase and the behavior as the degree of recirculation is reset varies. The concentrations of chlorides, sodium, fluorides and silica stay on approximately the same level as during the trial, while the concentrations of calcium, ammonium and sulfates decrease.
A detailed study of all above mentioned compounds was performed. As an example, Figure N10 shows conductivity vs time for all sampling points. The empty dot indicates the first sample of the trial campaign, and is taken just before the sludge flow is decreased. The conductivity increases rapidly when the sludge flow was decreased. When the flow was restored on the 24th of April, the conductivity reached its peak and started to slowly return to the same level as before the pilot trial. The conductivity does not reach the initial levels during the follow-up period, but it appears to be decreasing.

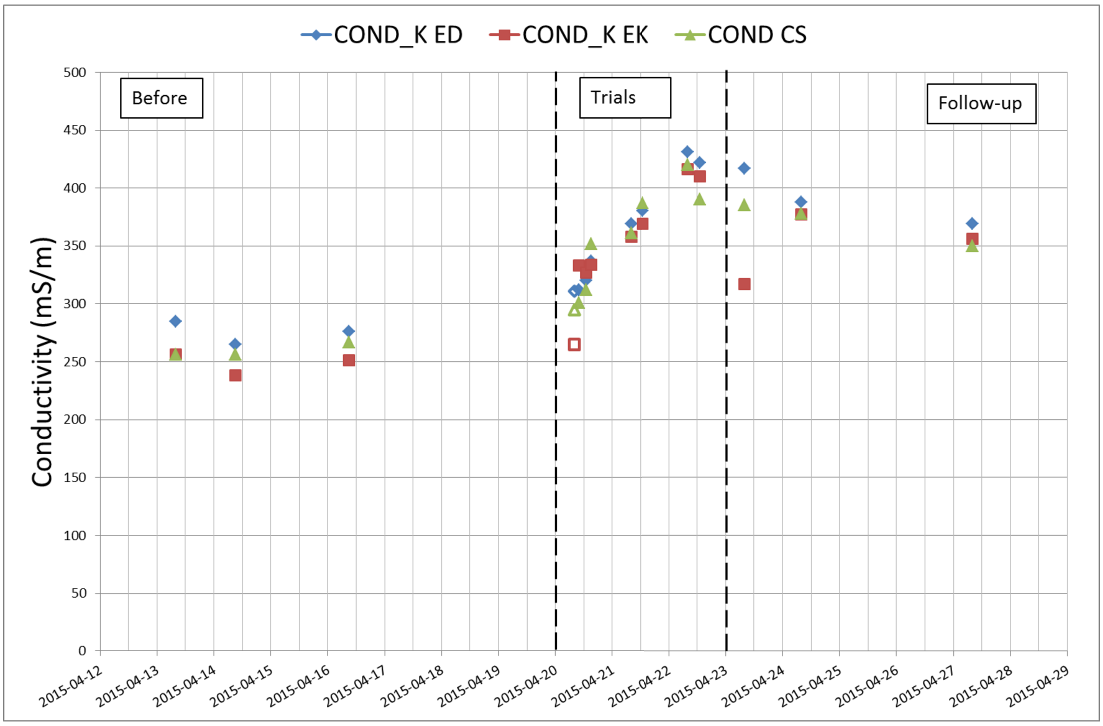


Figure N10: Conductivity vs. time

Figure N9 shows the conductivity vs sludge flow for all the samples from the campaign. Figure N10 shows the corresponding correlation excluding the follow-up samples. As can be seen from Figures N11 and N12, the correlation is stronger when the follow-up samples are excluded. Corresponding studies were performed for chlorides, sodium, sulfates and fluorides, ammonium, calcium and silica as well with the same outcome. Hence, there are correlations between the concentrations and the increased recirculation. The adaption to a lower recirculation ratio will take longer or shorter time for different compounds, possible because of solubility products and the possibility of formation of metal complex. pH, TOC, Al, Zn and suspended solids were not affected by the sludge flow. Figure N13 shows suspended solids as an example.

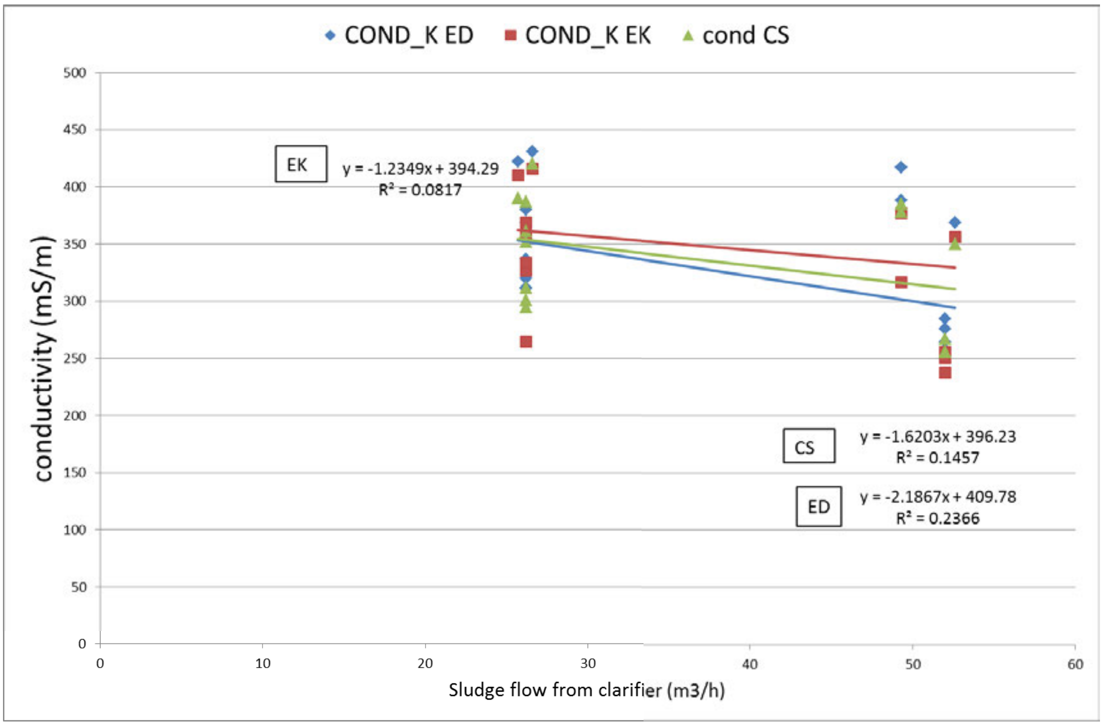


Figure N11: Conductivity vs. sludge flow from clarifier

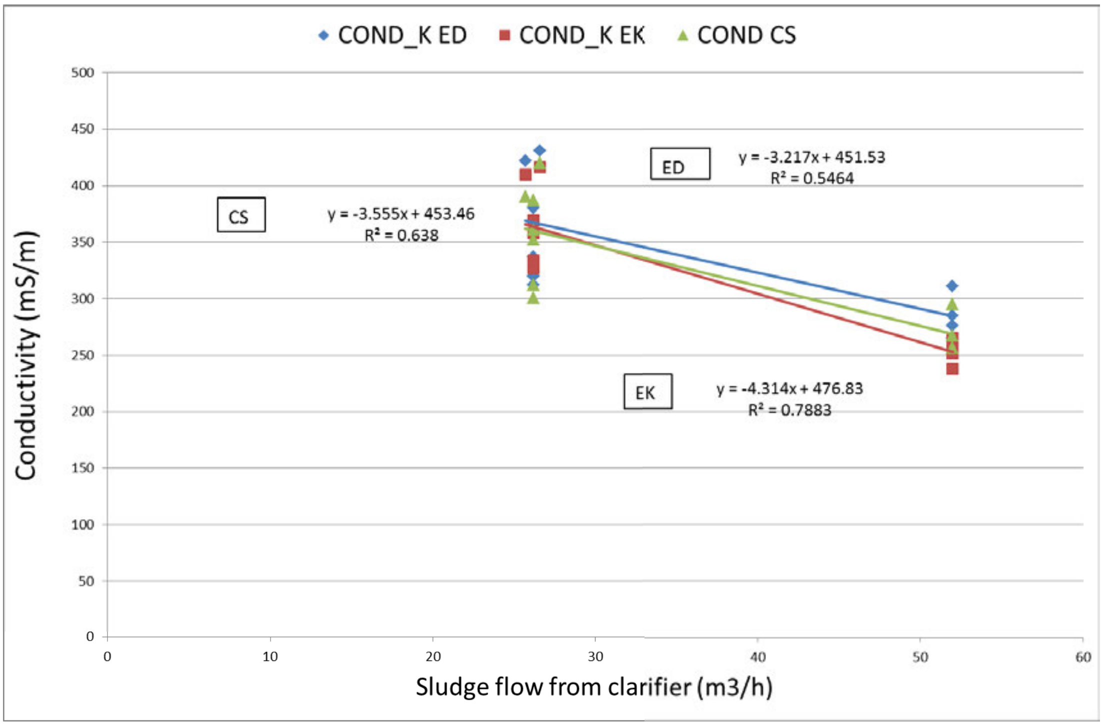


Figure N12: Conductivity vs. sludge flow from clarifier excluding follow-up samples

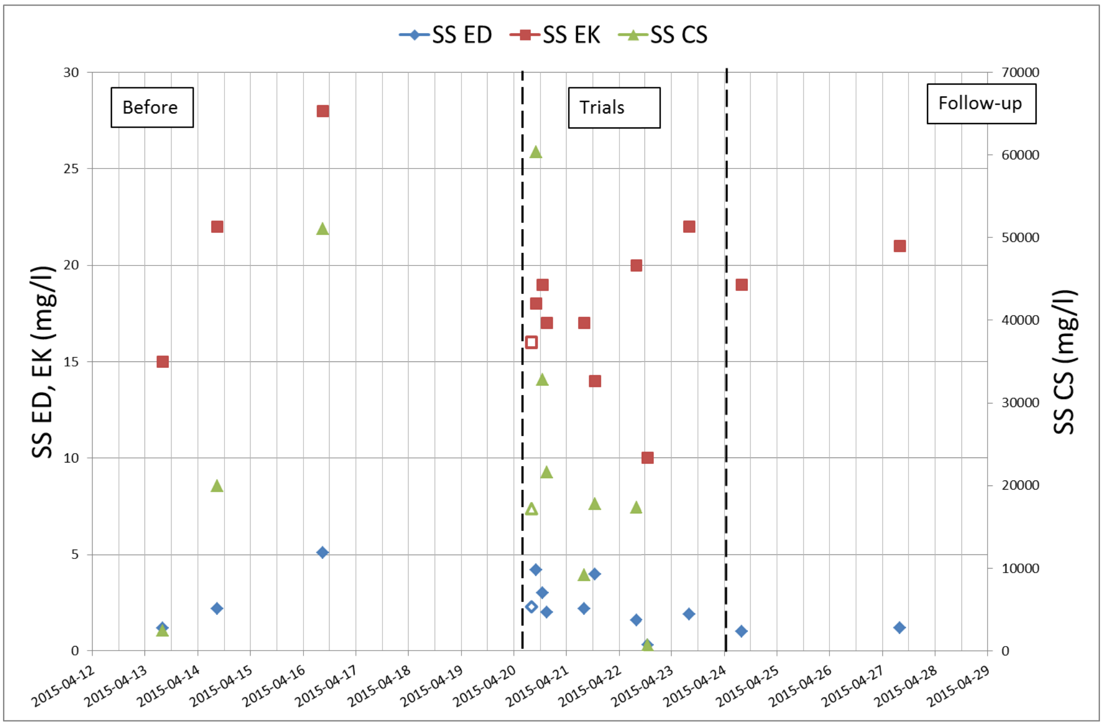


Figure N13: Suspended solids vs. time.

Phenols were only detected in a few samples, seemingly independent from the pilot trials. CN was not detectable at all during the sampling campaign. Hardness was analyzed, but reported as >20 mg/l for all samples.

It is not possible to determine from available data if the total solids (TS) in the sludge flow changes or not. The chemical composition of the BF-sludge was unchanged during the pilot trials. Historical data show no correlation between any concentrations in the BF sludge and the degree of recirculation, and all samples from the pilot campaign are within normal variations.

When comparing historical data and trial data, almost the same correlations were found for ammonium, chlorides, suspended solids, pH and Zn. Ammonium and chlorides are affected by the changed sludge flow, while suspended solids, pH and Zn are not. However, the results for Ca and Fe give mixed readings. Historical data show no correlation between Fe and sludge flow, but the trial data shows a lower concentration of Fe as a function of increased recirculation. Comparing trial data with data from January to May 2015, it is unclear why the samples from the "before" period are that high. The trial and follow-up samples appear to be within normal variations. There is most likely no correlation between the Fe content and the increased recirculation. Historical data showed no apparent correlation between the increased recirculation and the Ca concentration, while the trial campaign indicated that there was a correlation.

Figure N14 shows historical data, trial data and model results for the ammonium concentration ED as a function of the sludge flow from clarifier (increased recirculation) The results are quite consistent even though the spread in the historical data is somewhat larger for the lower sludge flow from clarifier. The empty dots represent the follow-up samples from the trial and are a little off set, as explained above.

Figure N15 shows historical data, trial data and model results for the Ca concentration ED as a function of the sludge flow from the clarifier (recirculation ratio) Analysis of historical data for Ca showed no correlation whereas the trial data clearly indicated a correlation. It appears as if there is a larger spread of the Ca concentration in the historical data which could explain the missing correlation. There are many other parameters in the BF operating practice that affects the Ca concentration, but considering the trial campaign, the sludge flow will affect the concentration. However, the model results show only a small effect of the Ca concentration by increasing the recirculation.

Figure N16 shows the corresponding plot for chlorides. The model results is consistent with both historical data and trial data (if excluding the empty dots which represent the follow-up samples from the trial campaign discussed above)

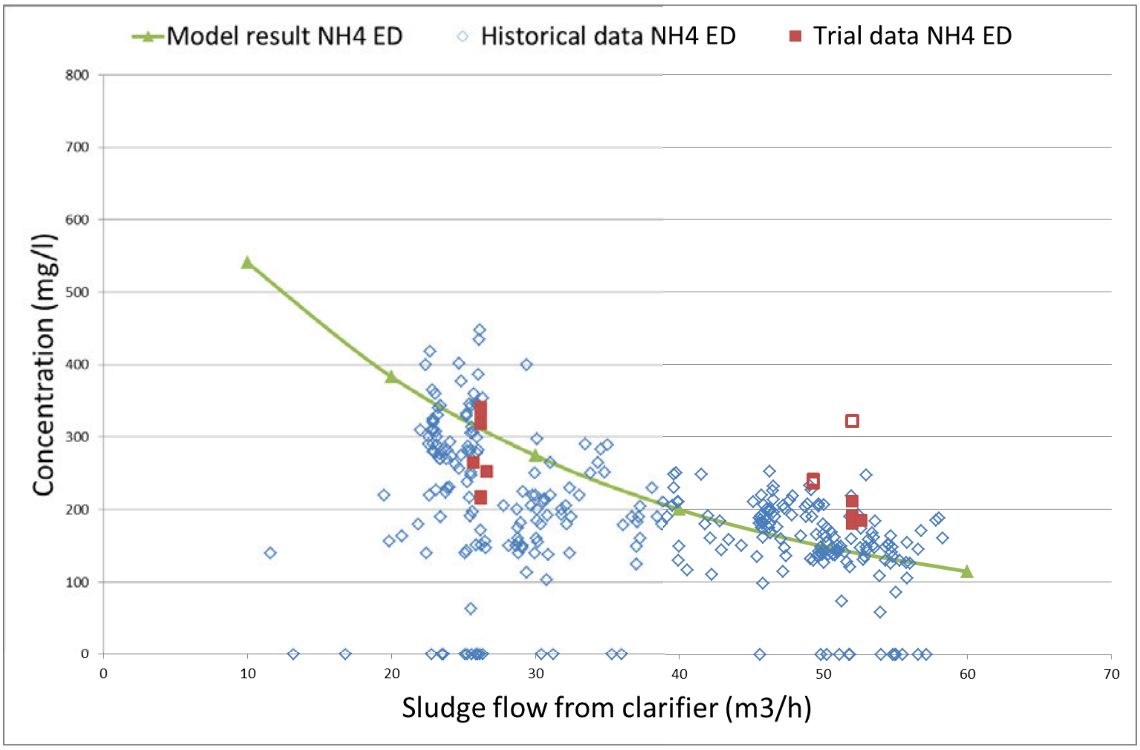


Figure N14: Comparison of model results, historical data and plant data for ammonium concentration ED vs sludge flow from clarifier (degree of recirculation)

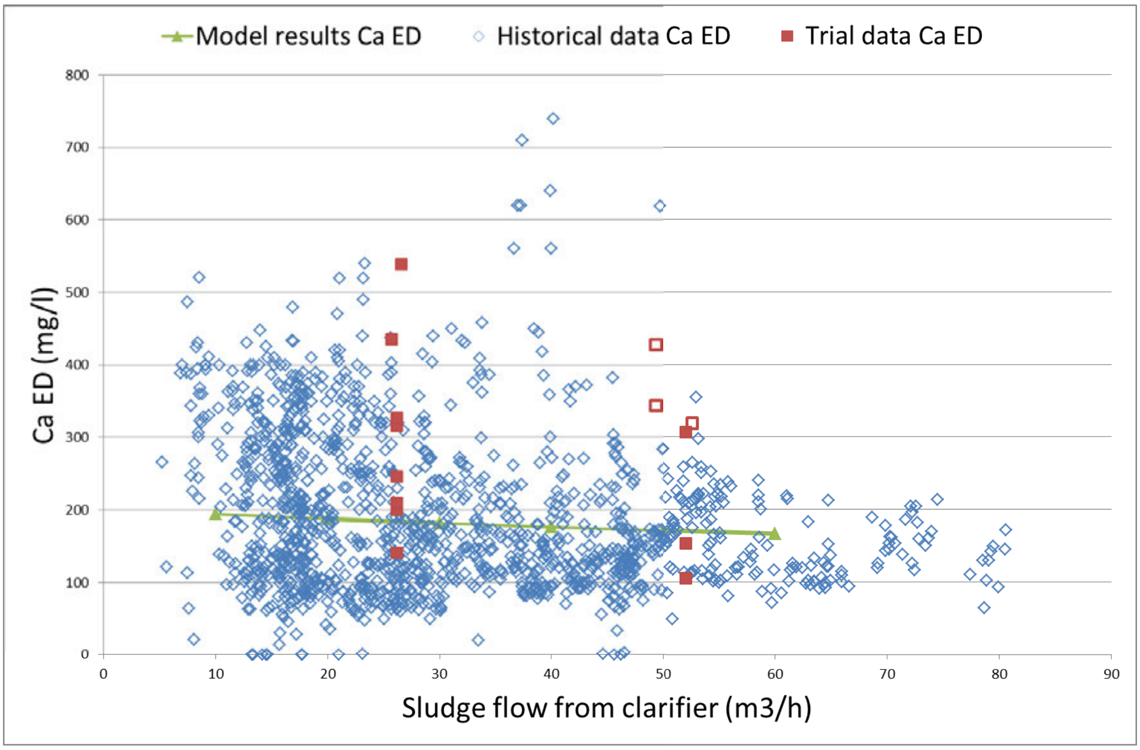


Figure N15: Comparison of model result, historical data and plant data for calcium concentration ED vs sludge flow from clarifier (degree of recirculation)

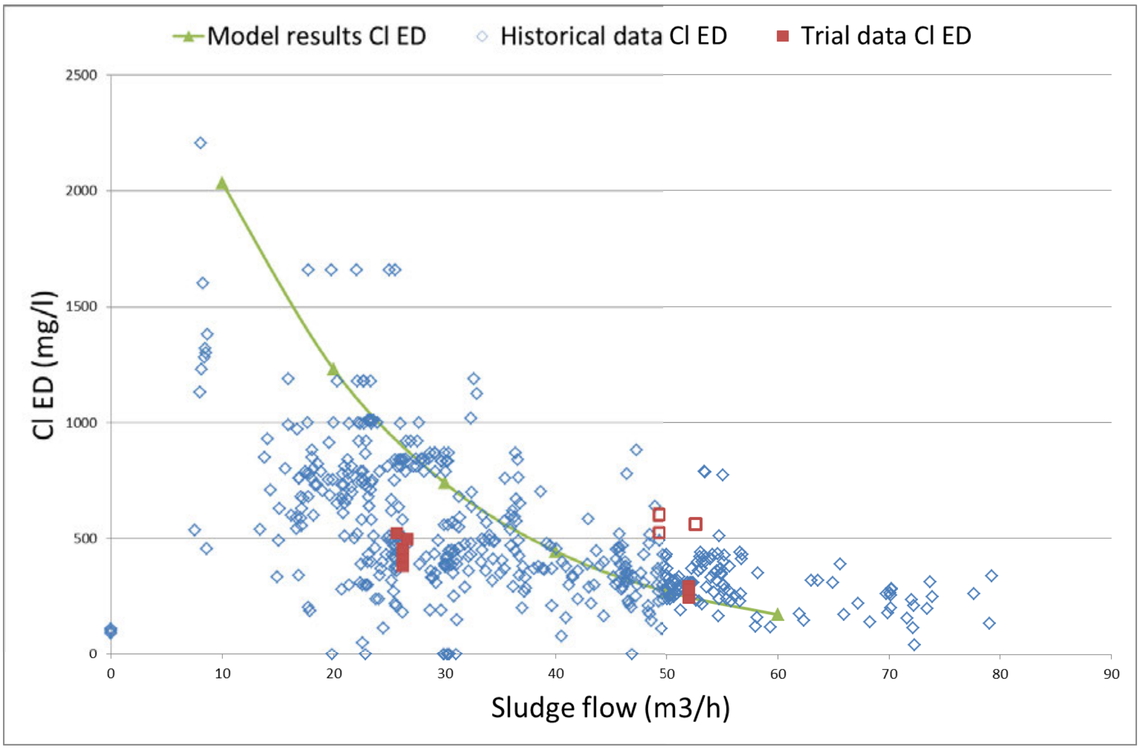


Figure N16: Comparison of model result, historical data and plant data for chloride concentration ED vs sludge flow from clarifier (degree of recirculation)

18.2 Tests on materials recycling

ILVA carried out on-site trials in order to maximize the recycling, reuse of by-products in particular BOF slag, and reduce their disposal in the internal quarry. To this aim, an investigation was developed to find a good mixture of by-products in terms of type, feature and percentage in order to obtain pellet suitable to be fed in sinter plant.
Firstly, ILVA carried out some preliminary tests in order to find the best pre-treatment for BOF slag that allows achieving the best fraction of this by-product to be used in pelletization, exploiting also the indication obtained from the assessment reported in Section 19.2 of Appendix I. The preliminary result obtained by these tests was that the best small-size procedure is to grind the BOF slag, to separate them into different particles size fractions and to select the fraction with a grain size < 2mm because of the lowest P content (0.36-0.37 %wt). Moreover, manual magnetic separation with neodymium magnet is avoided in this case, as Fe enrichment and P depletion are negligible.
Afterwards ILVA carried out some preliminary pelletization tests (as reported in the PSP-BOF project) with only partial satisfactory results but such tests gave useful information for further experimentation: in particular a good practice is to moist and homogenize for 24 hr the selected fraction of BOF slag (grain size <2mm) in order to obtain a BOF slag moisture of about 14% before the pelletization procedure.
After these preliminary tests, ILVA followed the indications obtained by SSSA through the simulations carried out through reMIND software on possible by-products mixtures to be used in pellet production, as depicted in Table N6.

	BOF slag	BOF sludge	Mill scales
Pellet "frit" 1	52 %	30 %	18 %
Pellet "frit" 2	71 %	29 %	0 %

Table N6: Obtained pellet mixtures from SSSA simulation by reMIND.

Starting from these results, ILVA laboratory prepared the by-products amounts according to the suggested percentages and to the previous obtained pre-treatment indications. Then it blended them exploiting an Eirich mixer in order to obtain an amount of 50 kg of good homogeneous mixtures per trials. Then, spring water was added to the mixtures together with biders such as lime and cement in order to help the pelletization process that has been carried out through a pelletizer disc, after the division of the obtained mixture in several batches of about 10 kg. Some quality tests have been finally carried out such as the size assessment (size of pellet is important for the sinter process) and compression tests: a compression strength of almost 2 KgF is needed to use pellets in the sinter plant. Pellet frit 1 showed a compression strength lower than such limit, while Pellet frit 2 showed an average value of 1.95 KgF computed over 5 compression tests, which is acceptable although slightly lower than the above discussed theoretical limit.
The pellets obtained following the "Pellet frit 1" simulated composition resulted in a low quality product in terms of amounts and quality, as depicted in Figure N11. On the other hand, the second mixture ("Pellet frit 2) allowed obtaining very good pellets: a great amount of high quality pellets in terms of size and of compression test value have been produced. These results highlights that mil scale is note suitable as pellet raw material. Furthermore, these outcomes were expected because the first "frit" composition was obtained withouth considering the quality of final product (e.g. pellet) in the optimization study but only minimazing costs and environmental impact.
After these first results, ILVA refined the mixture composition optimizing the content in binders: the obtained best final mixture is 70% Fe-rich fraction of BOF slag, 20% BOF sludge, 9% Cement and 1% Lime. The obtained pellets are shown in Figure N12 and the composition of obtained mixture is reported in Table N7. The pellet production yield is about 90%.

Component	FeO	Fe(0)	Fe_2O_3	SiO_2	Al_2O_3	CaO	C	MgO	MnO_2	P_2O_5	Other
%wt	1.7	13.9	26.3	8.5	2.5	29.5	2.1	4.6	4.1	0.6	6.2

Table N7: Composition of the obtained good quality pellets.

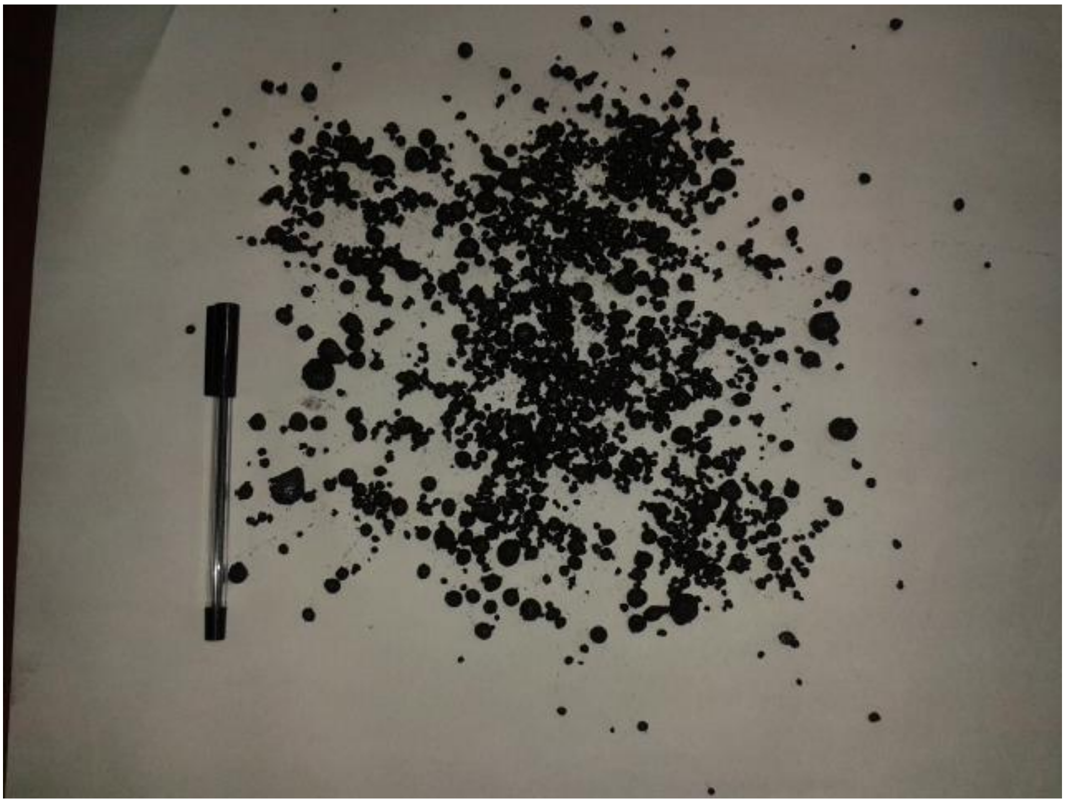


Figure N11: Low quality pellets produced with the mixture compositon n°1.

Figure N12: High quality pellets produced following the "winning formula".

The "winning pellet formula" is very similar to the simulation result obtained by reMIND optimizing the reuse of considered by-products through the minimization of costs and environmental impacts and the maximization of pellets quality. This proves that the software through the developed superstructure model for by-product/waste management can be a useful tool for steelmaking staff in terms of time saving to find the best way to better manage their resources.

Indeed the developed on-site trials did not include tests where the produced good quality pellets are fed to the sinter plant. Therefore, conclusions on the technical effects on the sinter quality and potential savings of virgin raw material cannot be drawn. Such work is included in the research work of the ongoing RFCS project entitled *"Removal of phosphorus from BOF-slag"* (PSP-BOF).

On the other hand, The possibility to produce good quality pellets has a positive impact on both the environmental ad the economic side. According to the Italian regulation, the BOF slag is a non-dangerous waste, which is recovered at no costs for the companies in the internal quarries, but the pellets production contributes to reduce the amount of material which is internally disposed. At the standard production capacity of Taranto ILVA steelworks, (8 Mton/y of crude steel), as the average production of BOF slag is 90-100 kg/ton of crude steel, at least 720 Kton/y of BOF slags are produced by the 2 steel shops of ILVA, undergo an iron removal by industrial magnetic separation and finally the inert part is disposed the internal quarry (after leaching tests to evaluate the compliance of the key parameters with Italian regulation limits). The handling of this material inside the facility through giant trucks named *dumpers* implies a relevant cost, as the dumpers cover a steeply sloping road which is 3 km long, with a relevant fuel consumption and related environmental impact. By producing the above described pellets at industrial scale, up to 50% of BOF slags could be reused in a facility located close to the sinter plant, where the pellets are used. The remaining fraction of the BOF slag devoted to external uses could be handled through conveyor belts. A final non negligible environmental benefit could be obtained by avoinding to manage the fine grain size by-products at the agglomeration storage. Moreover, the potential for reduction of costs of material transportation and handling is estimated at about 66% of current costs.

SSAB_carried our on-site trials regarding the recycling of several materials into the BF.
The first on-site trials concerned the use of fine grained BOF sludge to prepare briquettes to be fed to the BF. Such trials involve a complex preparation stage, which includes drying, piling and mixing of the BOF sludge, before they are mixed together with other recycling material in the briquettes. The BOF sludge contains around 36 % moisture. During the summertime fresh BOF sludge was dried in prepared areas.
The sludge was evened out to a 0.5 m high layer and a tractor with a harrow was used to prepare the wet BOF sludge for drying. The moister content after 2-3 weeks of drying was decreased to 18% which was considered appropriate for briquetting. The production of about 80.000 tons of briquettes, with 12% of BOF sludge started in October and continued until the end of January. Other materials that are briquetted are annual produced amounts of fine grained steel scrap, coarse BOF sludge, briquette fines, filter dusts, some amount of BF dust and small amounts of mill scale and different sludges. Compared to the ordinary briquette recipe it was primarily deS scrap that was reduced during the briquetting trials. During 4 months in the winter of 2014-2015 the briquettes containing BOF sludge were charged to the BF at an approximately rate of 100 kg per ton hot metal (kg/tHM). The cold strength of the briquettes is checked by a tumbling test. The tumbling strength (TTH).is the most important quality aspect for the briquettes charged to the BF. Figure N13 shows briquettes in the briquetting plant. The production of briquettes with 12% of BOF sludge went well and no effect could be seen on the TTH of the briquettes. In effect, the TTH of briquettes with BOF sludge are in line with TTH of ordinary briquettes, as depicted in Figure N14.

Figure N13: Briquettes (photo Stig-Göran Nilsson, Jernkontoret)

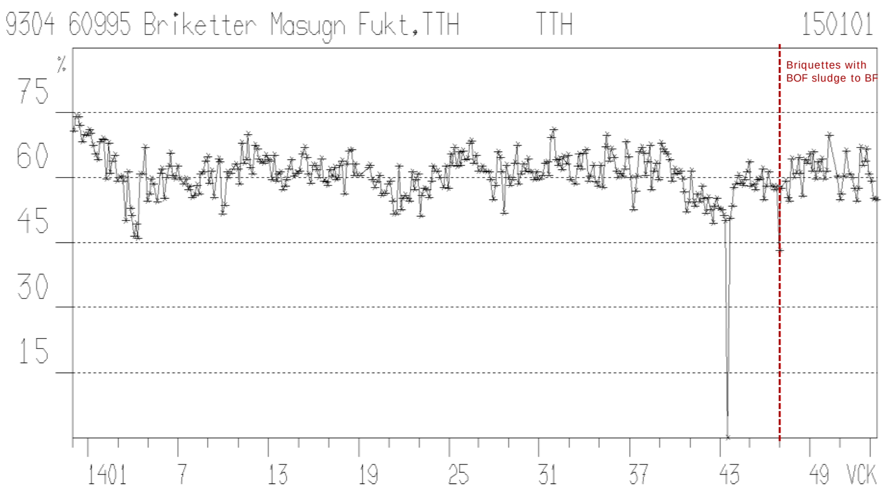


Figure N14: Tumbling strength (TTH) for briquettes charged to the BF.

Shortly after the production the moister content in the test briquettes was slightly higher than in ordinary briquettes. When the test briquettes were charged to the BF, 4 weeks later the moister content was the same as in ordinary briquettes. No clear effect could be seen regarding the Zn content in the BF dust or BF sludge but there was a minor trend of increased Zn content in the briquettes in the later part of the trials. Analyzes of briquettes before, during, after and the year before the briquette trial, indicates that the Fe content is somewhat lower during the tests than the year before, (see Figure N15). Still the Fe content in briquettes just before the trial is in the same level as during the trials.

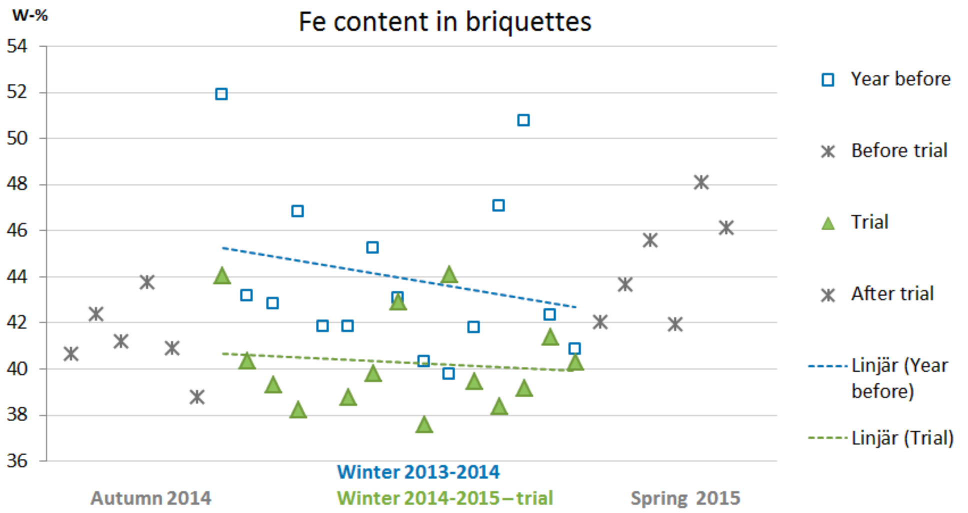


Figure N15: Fe content in briquettes the year before, months before during and after production of briquettes with BOF dust

Looking at the consumption of iron carriers charged to the BF depicted in Figure N16, it can be seen that with an increased recirculation of briquettes the pellets and scrap usage is clearly reduced. The charged amount of iron bearing material is higher during the test period compared to the year before probably due to the lower Fe content in the briquettes. No effects on the production or hot metal quality could be seen during the trial.

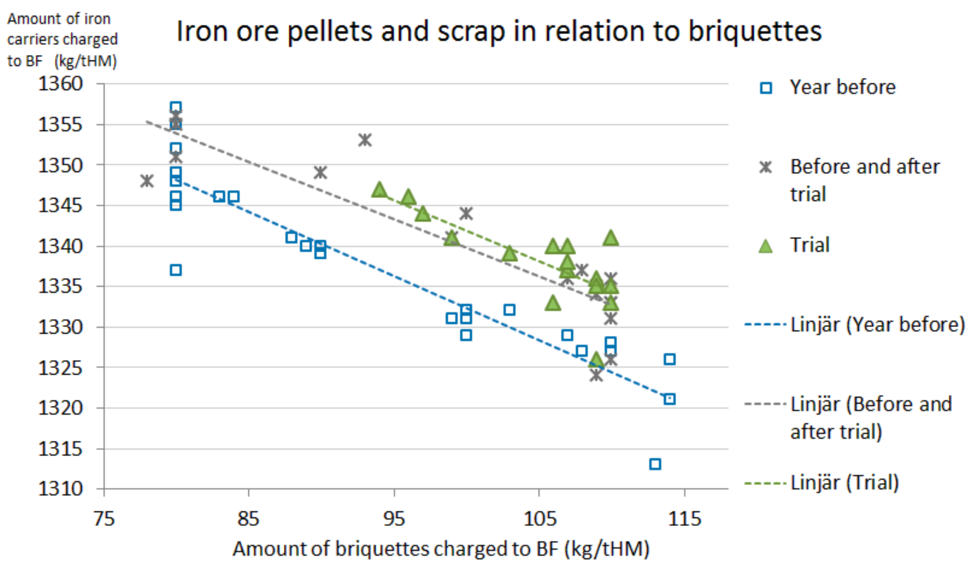


Figure N16: Charged amount of other iron carriers to BF in relation to charged amount of briquettes

Moreover, on site tests were developed on the use of LS as supplementary slag former in BF (to partially replace limestone and BOF slag) during three periods.
An amount of 10 to 25 kg/t_{HM} was charged to the BF, totally 6800 tons. All of the handling and the charging of the LS to the BF went smoothly during the trials but the investigation was hampered due to the alternation of pellets types and some process disturbances, which were not caused by the LS. Data from the process data handling system for the BF at SSAB Luleå, was used in the evaluation. The slag rates during the test periods was expected to be increased but an investigation considering the data of the whole year was pursued and the conclusion was achieved

that the variations in the slag rate were in the range of normal fluctuations. The only obvious effect of LS as slag former in the BF was an increased Al_2O_3 content in BF slag (see Figure N17). This is due to the fact that LS contains 20 - >30% Al_2O_3 while BOF slag and limestone contain a percentage of alumina lower than 2%.. An amount of 10 kg LS/t_{HM} increased the Al_2O_3 content in BF slag with around 1%. This result is in accordance with modelling case with increased LS.

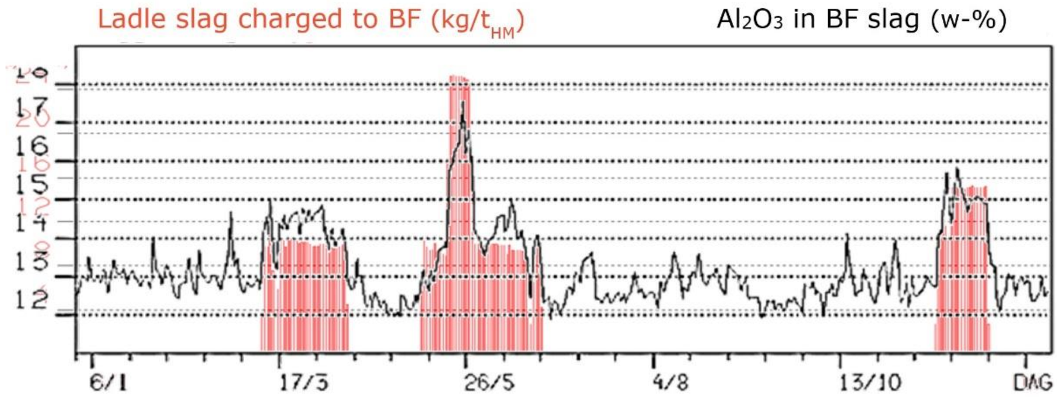


Figure N17: effects of LS charged to the BF (red staples), alumina content in BF slag (black curve)

19 APPENDIX O - Results of investigations of achievable improvements in resource efficiency through full-scale implementation of the selected technologies (D5.2)

19.1 Solutions for water efficiency

The selected PI-based solutions for water efficiency that were investigated through the on-site trials in the involved steelworks were evaluated in terms of contaminants in the related water streams, investment and operating costs and savings (or eventual cost) of fresh water, according to the preliminary analysis that was pursued in Task 1.1 of WP1 (see also Table 1).

At ILVA the joint application of UF and RO was assessed in order to maximize the reuse of wastewater in the cokemaking area by producing a stream of high quality water. The joint application of UF and RO allowed an almost complete removal of the contaminants and a recovery of 67% of the inlet stream, but implies a considerable investment. The disposal of the retentate does not represent a cost, as the amount of contaminants allows in any case its discharge.
The CAPEX is estimated around 1.2 M€ for a plant treating about 100 m^3/h of wastewater with a permeate yield around 60% (which is obviously higher than the one of the pilot unit, being an industrial installation), i.e. capable of producing up to 60 m^3/h of high quality water. Also the operating costs, mainly related to energy, maintenance and chemicals, are not negligible. Therefore the economic viability highly depends on the boundary conditions, i.e. the availability and cost of freshwater (which also represents the value of the recovered high quality water) as well as on the cost of chemicals and energy required for running the treatment process. As the operative life of the plant whithout substantial revamping is estimated to be 20 years, the economic viability has been evaluated in terms of parametric evaluation PBP. Figure O1 depicts how the DPBP of the considered option depends on the prices of permeate and retentate streams.

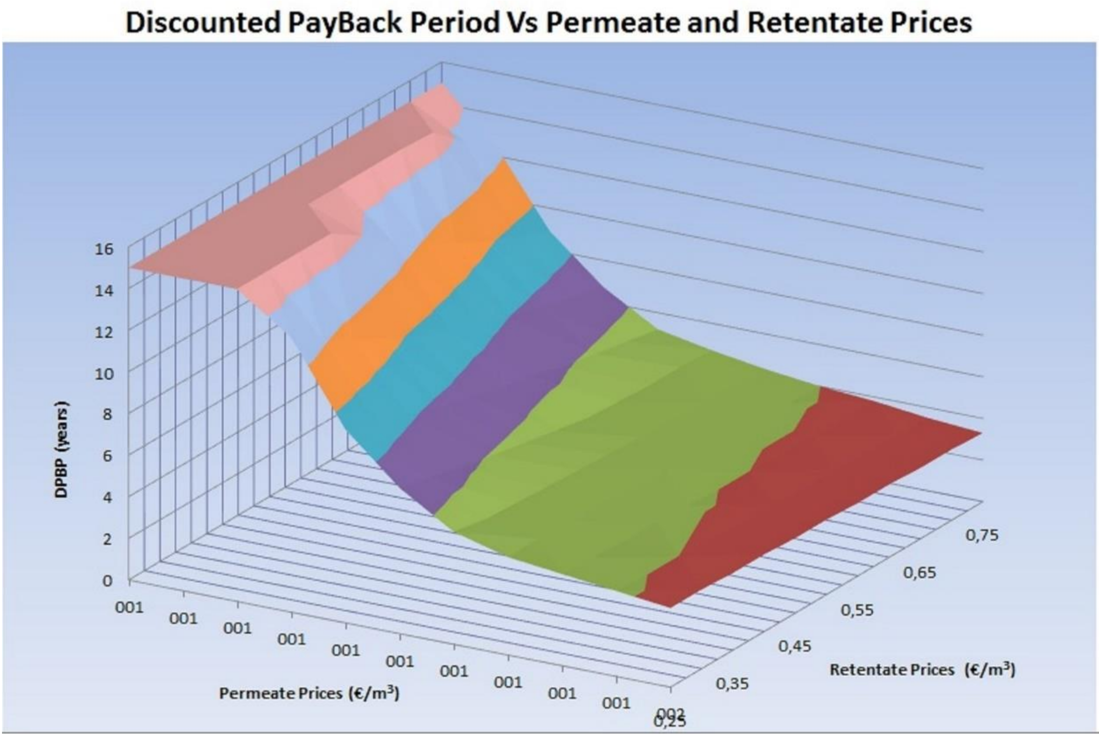


Figure O1: Discounted PBP Vs prices of the permeate and concentrate streams

All the new solutions developed for the Tata Steel UK site were of direct relevance and great interest to the site management. Despite of the fact that full implementations of the analyzed solutions were not possible due to the economic conditions of the company in 2015, an assessment of the potential improvements based on simulation results were pursued.

CASE STUDY No 5: Lagoon 1 Water Reuse in BF Gas Wash Systems

As illustrated in Appendix I Section 19.1.5, the final solution proposed for this case study involves the installation of a RO treatment unit (flow = 50 m^3/h), pump (flow = 71 m^3/h) and pipeline (4" Sch 40; Length = 2 km) (see Figure O2). Capital investment required is around 1 million £.

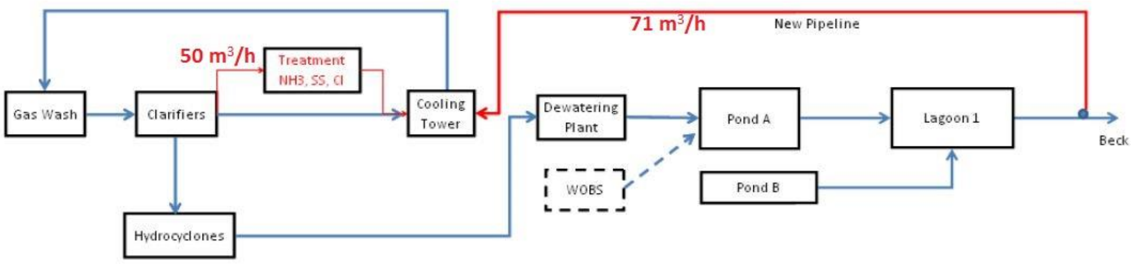


Figure O2: Schematics of final solution for Lagoon 1 water reuse case study

However, there are substantial benefits in terms of the following aspects:

- Improvement of the discharge water quality to Beck
- Improvement of the inlet water quality to the BF GW cooling tower
- Water conservation (freshwater demand (= waste water discharge) is reduced by 71 m^3/h)
- Lower cost of maintenance

Table O1 summarises the PBP calculation for this case study. As shown, the proposed case study has an attractive PBP of 1.5 year in this case. Table O2 illustrates the water quality improvements in the BF GW cooling tower inlet and Lagoon 1 discharge.

CAPEX	1 Million £
OPEX	0.516 Million £/yr
Savings	1.168 Million £/yr
PBP	1.5 years

Table O1: PBP for Lagoon 1 water reuse case study

	TSS mg/L	NH3 mg/L	Cl mg/L	TDS mg/L	Reuse from Lagoon 1 m^3/h	Discharge to Beck m^3/h
Lagoon 1 discharge water quality						

Before	18.6	5.4	326	1830	0	435
After	18.6	4.72 (-13%)	325	1835	71	364(-16%)
BF GW Cooling Tower Inlet Water Quality						
Before	31.8	54.8	496	2143	0	435
After	30.2 (-5%)	40.2 (-22%)	465 (-6%)	2089 (-3%)	71	364(-16%)

Table O2: BF GW & Lagoon 1 water quality comparison for proposed RO unit solution

CASE STUDY No 6: Pond A Water Reuse in BF Gas Wash Systems

As illustrated in Figure O3, the final solution proposed for this case study involves the installation of pump (Flow = 75 m^3/h) and pipeline (5" Sch 40; Length = 1 km). Capital investment required is around £21,000. While operating cost of recycling 75 m^3/h of Pond A water is estimated to be around 63,000 £/yr.

In general, there are substantial benefits in terms of improvement of the water quality of the BF GW water and lagoon 1 discharge to river. Table O3 illustrates these improvements. As can be seen from the table, ammonia levels can be reduced up to 85% if suitable source could be identified to use additional blowdown from BF GW circuit in this case. However, it is difficult to quantify benefits from discharge water quality improvements especially in terms of reduction in ammonia levels. In this case, PBP is estimated by back-calculating cost of avoidance ammonia air stripping treatment to achieve similar reduction of ammonia levels in discharge water. A PBP of 1.2 years is estimated in this regard.

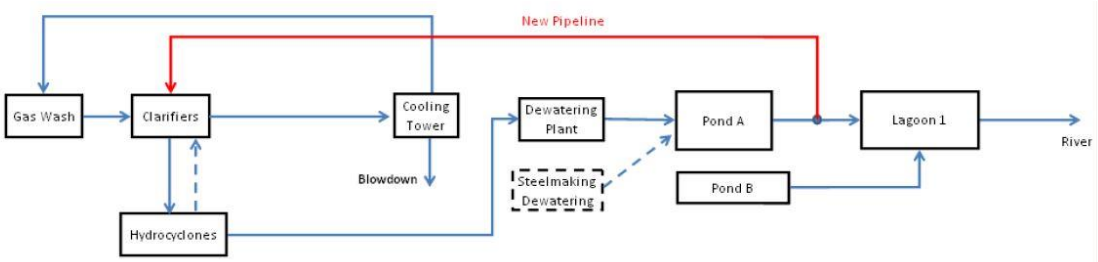


Figure O3: Schematics of final solution for Pond A water reuse case study

Case No.	Pond A Water Reuse	Increase in b/d flow	BF GW Water Quality					Lagoon 1 Water Quality				
			TDS	TSS	Cl	NH_3	pH	TDS	TSS	Cl	NH_3	pH
	m^3/h	m^3/h	mg/L	mg/L	mg/L	mg/L	-	mg/L	mg/L	mg/L	mg/L	-
Base Case	0	0	2089	26.8	482	53.6	7.30	1801	19.8	308	4.11	8.44
1 HC Rec.	75	75	1987	27.7	454	39.6	7.51	1760	17.5	270	0.61	8.38
			% change vs current case					% change vs current case				
1 HC Rec.	75	75	-5%	3%	-6%	-26%	3%	-2%	-12%	-13%	-85%	-1%

Table O3: BF GW & Lagoon 1 water quality improvements in Pond A water reuse case study

CASE STUDY No 7: Recycling of the BF GW HC overflow water with suitable treatment

As illustrated in Figure O4, the final solution proposed for this case study involves the installation of RO treatment unit (flow = 58 m^3/h) and MF (flow = 103.5 m^3/h). Capital investment required is 1.55 million £. If the capital investment is deemed high, the proposed solution can be modified from recycling of all 3 HCs overflows to recycling of 2 HCs overflows which has a capital investment need of 0.83 million £.

The following benefits can be achieved from the proposed solution:

- Improvement in water quality of 1) lagoon 1 discharge and 2) BF GW cooling tower;
- Water and energy savings;
- Lower cost of dewatering (per ton of sludge).
- Recovery of Fe-rich sludge which can be reused in BF GW

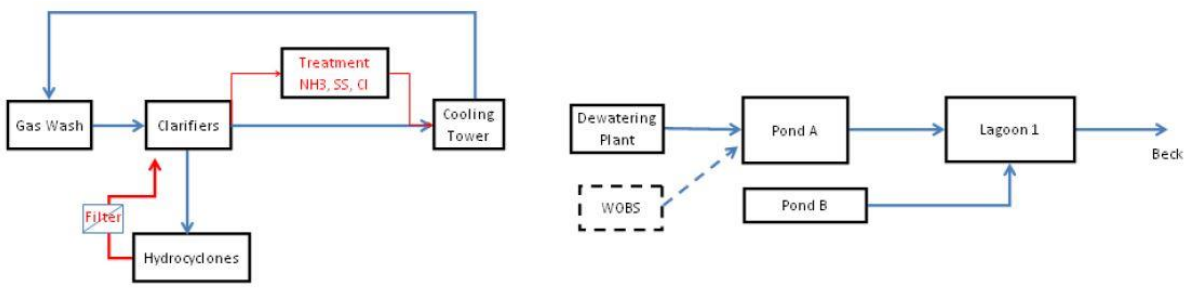


Figure O4: Schematics of final solutions for HC overflow recycling case study

Table O4 summarises the PBP calculation for this case study. As shown, 3 HCs overflow recycle case has a PBP of 1.5 years, while the lower investment option of 2 HCs overflow recycle has a slightly higher PBP of 2.1 years. Table O4 also summarises the benefits in terms of water savings, Fe-rich sludge recovery, suspended solids in BF GW cooling tower inlet and ammonia reduction in the final discharge water.

Case Description	Units	2 HC Recycle **(η = 90%)**	3 HC Recycle **(η = 90%)**
RO Treatment Flow	m^3/h	13	58
Filtration Flow	m^3/h	69	103.5
Capital Investment	Million £	0.83	1.55
Net Operating Cost[a]	Million £/yr	0.35	-0.27[b]
Payback Period	Yr	2.1	1.5
Water Savings	km^3/yr	56	336
Δ Iron Recovery	tons/yr	847	1499
Suspended Solids in Cooling Tower Inlet	mg/L	24.9	24.1
NH_3 Reduction in Lagoon 1 Discharge	%	15%	90%

Table O4: PBP and benefits from HC overflow recycling case study

Note:

a. Assuming that the magnetic filter is well designed to produce reusable sludge.

b. Net operating cost is negative in this case because reduction in pumping cost is more than operating cost of magnetic filter.

c. Under the current BF GW water operation configuration, water (make-up) consumption is 107 m^3/h, cooling tower water TSS is 29.8 mg/L, and lagoon 1 NH_3 is 3.4 mg/L.

CASE STUDY No 8: HPM-Ancholme System Water Recovery & Control

The final solution proposed for this case study involves the installation of the proposed control scheme either PLC based controllers or within a SCADA framework. Capital investment required is estimated to be 20,000 £. The following benefits can be achieved from this case study:

- Maximum water recovery from HPM in the Ancholme water system;
- Energy savings;
- Stable supply pressure (~ 4 bar);

Table O5 summarizes the operational benefits from the case study, while Table O6 indicates that the proposed solution has a PBP of 5 months.

	Current Operation	Optimised Operation	Benefits / Savings	Corresponding Economic Value
HPM Water Recovered in Ancholme, m^3/h	36.3	41.7	5.4	£43,200 / yr
Total Power Consumption, kW	91.5	79.6	11.9	£6,664 / yr
Pressure loss to Fire Hydrants, hr/yr	77	0	77	---

Table O5: Operational benefits from HPM-Ancholme system water recovery and control case study

CAPEX	20,000 £
Savings	49,864 £/yr
PBP	5 months

Table O6: PBP for HPM-Ancholme system water recovery & control case study

At SSAB the optimization of recirculation of quenching water at the CC and the reuse of water in the BF gas cleaning system were assessed through data collection (also through specific measurement) and simulations. Moreover the analysis of alternative treatments of BF sludge water e.g. reuse after treatment was assessed also through a specific on-site trial campaign.

Case study on optimization of recirculation of quenching water at the CC.

The problem was to target a stable temperature for the inlet water to CC cooling system by minimizing the amount of discharged water and inlet water. Currently mixing with fresh water is a method to decrease the temperature of inlet water and obviously the amount of water added depend on the fresh water temperature. Simulations pointed out an inefficient placement of the make up water and the benefit to use a Cooling Tower (CT) rather than a heat exchanger (HEX). The impact on the system by moving the addition of the make up water to the backflow valve was investigated.

By moving the position for the makeup water less water is needed to be pumped and thus the entire power usage of the system decreases. For the case of a spray-on temperature of 30°C, a saving of 294 m^3/h in make-up water can be achieved by also eliminating the blow-down, by paying the price of an increased energy consumption for Pump and fan (that is however lower with respect to the use of an HEX). The saving in make-up water is even more evident when considering lower temperatures for the spray-on water. However, in the practice it is not possible to operate the cooling circuit with no blow down due to accumulation of chlorides or fluorides in the system.

Additionally, the performance of the cooling solution should be evaluated in summer conditions to see how the spray-on water temperature would be affected.

Case study on the reuse of water in the BF gas cleaning system
Both the simulations and the experimental trials put into evidence that an increased concentration of NH_4, Chloride or Ca as the recirculation rate increases is a limiting factor that prevents the mere recirculation to be increased. The solution to this problem consists in the inclusion of a treatment stage in order to treat the overflow of the clarifiers. The available data do not allow a clear estimation of the limit recirculation rate, which is achievable in this way and will be object of future investigations.

19.2 Solutions related to material reuse and recycling

The selected PI-based solutions for resource efficiency through enhanced material recycling, that were investigated through the on-site trials in the involved steelworks, were evaluated in terms of overall amount of wastes and by-products that are recovered ad not landfilled and overall amount of saved primary raw materials, according to the preliminary analysis that was pursued in Task 1.1 of WP1 (see also Table 2).

Case study on pellets production to recycle BOF slag into sinter plant
The improvement related to the investigation of new PI-solutions through the use of simulation techniques (e.g. reMIND simulation) is related mainly to saving time to proceed to the best by products mixture that means less man/hours dedicated to preliminary tests and so less costs for the steelwork management. In addition, the recovery of BOF slag by pelletization, results in an improvement of this by-product recovery and in a reduction of environmental impact.
The recycle of these by products could slightly decrease the use of some virgin raw materials (iron ore and virgin limestone, with related extraction and transportation from mines, e.g. in ILVA study case from South America). However, the developed on-site trials did not include the feeding of the pellets into the sinter plant and of the agglomerated material into the BF. Therefore, conclusions on the potential savings of virgin raw material cannot be drawn. Indeed, the technical evaluation of the use of the produced pellet in sinter plant is under evaluation in the RFCS PSP-BOF project in which the consortium is testing the use of pellet in the sinter plant mixture.
On the other hand, the investigated solution is relevant to achieve the "zero waste" goal of European Directive on waste production and management. In effect, according to the Italian regulation, the BOF slag can be a non-dangerous waste, that currently can be recovered without additional costs for ILVA in the quarries as mentioned in the European Directive 2008/98, but it could be a by-product for other uses. The pellets formation and its management at the agglomeration plant stockyards is a practice with a considerable potential to improve environmental management, as it can lead to a reduction of waste material. Considering a total production at ILVA of 8 Mton/y of crude steel (in standard operating conditions) and an average production of 90-100 kg of BOF slag per ton of crude steel, this means that a minimum amount of 720 Kton/y of BOF slags are produced and sent to the industrial magnetic separator and to the internall quarry. The handling of such material involves a relavant cost in terms of transportation of such material with special giant trucks named dumpers, which have to travel for 3 km on road with high gradient. In the new solution, depending on the results of optimization studies (see Table I34 within Section 19.2 of Appendix I) up to 50% of BOF slags (the Fe-rich and P-poor fraction) could be reused to produce pellets in a location close to the sinter plant, where the pellets are used. The remaining fraction of the BOF slag devoted to external uses could be handled through conveyor belts. This has a benefic environmental impact also in terms of reduction of emissions within the plant coming from the transportation. To sum up, a reduction of 66% of the costs related to transportation and handling of the material can be achieved. Further environmental benefits derive from the fact that the management of fine grain size by-products is avoided at the agglomeration storage.
Investment costs for the implementation of such solution are related to the realization of the industrial pellettization plant.

Case study on recycling of BF flue dust into the BF
Major cost savings are envisaged, as direct injection is a cheaper operation with respect to briquetting, while no reduction in the production of the briquetting plant is foreseen, as the IF injected flue dust can be replaced by a suitable scrap mix. Moreover there is a reduced need for iron ore pellet, coke and limestone. The possibility to recycle BF flue dust by injecting it directly into the BF will mean that 20 kTons less material is put on landfill.

Case study on recycling of BOF sludge in the BF via briquettes
There is a direct cost saving by replacing purchased iron ore pellets with high iron content recycled material. Noticeably In the preliminary modelling and simulation work in the calculation the BOF sludge was assumed to be a complement to other briquetted materials, while in the on-site trials BOF-sludge replaced the deS scrap, which has higher Fe-content and hence the usage of pellets

increased. As there soon will be a lack of suitable material for briquetting the BOF sludge can be a good complement.

The utilization of BOF sludge will mean that 25 kTons less material is put on landfill and 12 ktons of Fe is recovered every year at SSAB in Luleå. The translation of such advantages in economic terms is difficult due to the variations of the raw material prices: with a weakening in iron ore prices as seen during 2014 and the beginning of 2015 the cost benefit will decrease. Costs for landfills and future predictions of increased taxes on landfills would need to be accounted for, as well as changes in operating costs for preparing material for the briquetting plant or sinter plant.

Increased use of limestone due to recycling of some materials also has a penalty on material costs as well as energy carriers.

Capital expenditure is limited, due to the availability of a briquetting plant in the steelworks and of a suitable space to perform natural drying of the BOF sludge to eliminate moisture. However, the estimated operating time in Lulea is limited to the spring-summer period due to the particular climate conditions, which however do not apply to many other locations in Europe. The CAPEX related to the space availability as well as to some adaptation measures for the location heavily depends on the particular country and location, thus cannot be a-priori estimated. On the other hand, the installation of an ad-hoc drying system for operation along all the year in Luleå was considered not viable from the economic point of view due to energy costs and the same consideration seem to apply all over Europe at the moment. However, if in the future the technical possibility could arise to recover e.g. some waste heat or other low-grade energy to this purpose, a deep economic analysis could be developed in order to evaluate the viability of such solution. In the present moment, no technical solutions addressing this problem have been envisaged.

Case study on the utilization of LS as a slag former in the BF

The main advantage lies in the fact that the total resource efficiency increases because less virgin limestone is used and the amount of landfilled wastes are reduced. The on-site tests showed that LS can be used as slag former in the BF with no negative effect on the process or product and the main advantage is that the resource efficiency increases since less virgin material is used and also the deposit of secondary materials is decreased. The only obvious effect of LS as slag former in the BF is an increased Al_2O_3 content in BF slag. An amount of 10 kg LS/t_{HM} increases the Al_2O_3 content in BF slag with around 1%. However the access to LS in correct particle size is not sufficient for continuous use as slag former in the BF, therefore it is mostly convenient to utilize the LS when the use of BOF slag is restricted. No additional CAPEX or OPEX are foreseen, while the cost of handling the material is comparable to the one sustained to handle similar by products. Also in this case, such as for the fine grained BOF sludge, the translation of the savings for landfill into an economic value which is valid throughout Europe is not possible, as it highly depends on the location, local regulations, taxes and eventual restrictions for landfilling, local availability of internal or external landfills, manpower and transportation costs.

20 APPENDIX P - Identification of technological and economical constraints and barriers for different EU steelmaking sites (D5.3)

20.1 Solutions impacting on water systems

For ILVA, the case study related to the application of UF and RO order to maximize the reuse of wastewater in the cokemaking area was assessed in close cooperation with the site management. The technological and economical constraints were considered and issues in achieving the different objectives were assessed. The most important constraints for ILVA are:

- Capital expenditure;
- Operating costs;

Therefore, the main barriers are of economic nature and they are common throughout all Europe. On the other hand, their severity depends on the overall situation of the plant, on the price of energy as well as on the cost and availability of the freshwater availability, which is are specific factors of each steelwork and cannot be assessed in general.
No environmental issues are foreseen, as UF and RO are widely recognized as environmental friendly technologies for water treatment. In the case of ILVA the quality of the recovered permeate is high and suitable for most applications, while the quality of the concentrate is suitable to discharge according to the Italian regulations. In general, the amunt of contaminants in the concentrate might represent a barrier, depending on the water body where they are discharged and related local environmental regulations.

For Tata Steel, the 4 case studies were developed with close cooperation with the site management of infrastructure, water supply, environment, BF and HPM plant management. The steps for the implementations were discussed in detail. The technological and economical constraints of the recommended implementation of each of the case studies were considered and issues in achieving the different objectives were assessed. The most important constraints for the Tata Steel UK site are:

- Capital expenditure;
- Running costs;
- Environmental issues;
- Water quality impacting process operation;
- Water quality impacting on health and safety.

Lagoon 1 Water Reuse in BF Gas Wash Systems
This solution, which involves the use of RO and additional pumping costs has the constraint of capital costs of around 1 million £, operating cost of around 0.5 million £/yr with pay back of 1.5 years. Despite the substantial potential benefits in the lagoon 1 water quality, BF GW cooling tower water quality, water conservation and lower cost of maintenance, the constraint of the world/company economic situation and the required capital/operating costs were a barrier.

Pond A Water Reuse in BF Gas Wash Systems
This solution involves the installation of pump and pipeline with total capital investment of around 21,000 £ and operating cost of 63,000 £/yr. This solution achieves great improvements in the lagoon 1 water quality, e.g. 85% reduction in ammonia concentrations. However, although from the cost point of view, this solution was acceptable the environmental, and health and safety constraints caused by the need for disposal of the additional water resulting from the reuse was a serious barrier.

Recycling of the BF GW HC overflow water
In order to reduce environmental concerns caused by the lagoon 1 water quality, reduce pumping costs, dewatering costs, and increase water conservation, the recycling of the blast furnace gas washing HC overflow water was shown to be a very effective solution. However, this recycling deteriorates the quality of the water within the BF GW circuit which leads to a substantial increase in (running) cost of maintenance of the equipment and cooling tower, and risk of health & safety hazard from Legionella disease. Therefore, a suitable water treatment, that consisted of MF and RO, was selected and simulation studies carried out to reduce this impact.

As a result of implementing the above water treatment other constraints are introduced, e.g. capital costs and running costs of the RO and MF. Additionally, the cost of development of a specifically designed magnetic filter is a further constraint. These costs will be paid back by the benefits including the recovery of Fe-rich sludge suitable for recycling through the sinter plant.

HPM-Ancholme System Water Recovery & Control
This solution achieves the following benefits:

- Maximum water recovery from HPM in the Ancholme water system;
- Energy cost savings;
- Stable supply pressure (~ 4 bar) leading to better water availability and avoiding over-pressures;

This solution involves the installation of a new control scheme with some changes to pumps and valves, and it is estimated to require a capital investment of approximately 20,000 £. The total savings are estimated to be approximately 49 k£/y with a PBP of 5 months. Again, this solution was of great interest to the Tata Steel management, but, due to the current (2015) economic situation, it is postponed.

As far as the on-site trials pursued at SSAB on the recirculation of the water coming from the BF gas cleaning system are concerned, an increased concentration of NH_4, Chloride or Ca as the recirculation increases is a limiting factor and a represents a technical barrier to the recirculation. A treatment stage is needed in order to treat the overflow of the clarifiers. The insertion of a RO filter in order to treat the overflow from the clarifier, i.e. between the clarifier and the cooling tower, would create space to recirculate the untreated decanted sludge water from the BF sludge basin to basin 5. This solution, on the other hand, has an impact on the economic side, due to the quite high CAPEX and OPEX related to RO.

20.2 Solutions impacting on materials recycling

Case study of pellet from BOF SLAG for sinter plant use.
This case study concerned the production of pellets to be recycled in the sinter plant, thus it applies only to steelworks where such plant is in operation.
The main non technical barrier in Italy for the recycling of by-products inside the steel cycle though pellet production is represented by the constraints related to Italian regulation on by-products management and the complexity of the authorization procedure. Similar regulations apply to the rest of Europe, but the procedure required for authorization can be shorter.
From the economic point of view, the production of pellets at industrial scale (not in an experimental pilot plant) requires a big mixing machine and a big pelletizer disc in order to treat big amount of byproducts (many tons). For this reason, the CAPEX related to the implementation of such solution can be not negligible and can be recovered through time by savings achievable through an enforced recycling and valorization of by-products − not only BOF slag − with also related disposal saving costs. Pelletizing is a process showing a few constraints and many advantages such as:

- It provides a de-dusted and compacted material;
- It needs a natural binder as lime and cement;
- It shows a fast production breakdown;

In conclusion, pellettization cannot be defined an expensive process.

The main barriers related to the implementation of both the selected process integrations solutions for resource efficiency that were tested at the SSAB steelwork in Luleå are related to:

- Operating costs
- Increased presence of harmful compounds in BOF sludge and LS

Case study on recycling BF flue dust into the BF
A capital investment has recently been made, and no additional capital investments are required. The material that is injected in the BF and is no more used in the briquetting plant can be replaced by a scrap mix. No technical barriers are foreseen, due to a limited effect on the BF slag rate, HM quality and Zn balance.

Case study on the use of fine grained BOF sludge to prepare briquettes to be fed to the BF.
Capital investments are not required, as a briquetting plant is already available in the SSAB steelwork in Luleå. However, as such plant in Luleå has already reached its maximum production, this solution can be implemented only if injection of BF flue dust is jointly implemented as well, as it allows to make some capacity of the briquetting plant available and to increase the total recycling. This consideration is obviously not general and cannot be extended in a straightforward way to other plant, but it is an aspect to consider when a briquetting plant is intensively exploited.
The test trials show no particular effect on energy consumption and product quality. However, for the briquetting of fine grained BOF sludge a big issue is represented by the need to dry the material. Drying of fine grained BOF sludge outdoors on the ground is a low-cost and energy-effective method (although it requires some space) but it is challenging in the sub-arctic climate of Luleå. Acceptable moister content (18 wt%) was reached during the tests but the material was still rather wet. A more continuous solution of drying could be investigated, but economic restrictions is a barrier for the investment and operating costs may concern also energy. Another issue is briquetting of fine-grained materials with high moisture content which can be limited during winter (in the sub-arctic climate of Luleå) since the material can freeze. This problem should not arise in other regions of the EU which are characterized by a warmer climate. Wet material can also cause problems with sticking in the briquette plant and may be a generic problem regardless of climate.
Another problem that can occur when fine grained materials are handled, is the dust emissions i.e. diffusion of materials to the surrounding environment due to wind. Some protective measures should be foreseen, in order to avoid this phenomenon. This might have an impact on investment costs.
A technical barrier may be the chemical composition of the briquettes, e.g. zinc and iron affecting the BF process in general and the zinc balance in particular. No clear effect could be seen regarding the Zn content either in the briquettes with BOF sludge or in the produced BF dust and BF sludge during the trial. However, there was a slight trend of increased Zn content in the briquettes at the end of the trial campaign. If there was a minor enrichment of Zn in the recycled BF dust, this could result in a gradual increase of Zn in the briquettes. The Fe content in the briquettes is somewhat lower during the tests than the year before and is probably due to a lower share of desulphurization scrap. The desulphurization scrap has a few percent higher Fe content than the BOF sludge. This may also explain why there is larger amount of pellets and scrap charged to the BF during the trials than the year before. However the briquettes just before the trial have similar Fe content as during the trials and the consumption of iron carriers are in the same level before after and during the trials.

Case study on the use of LS as slag former in the BF

The main technical barrier is represented by the fact that the quantity of LS in a suitable particle size is not sufficient for a continuous use. Moreover it is most beneficial to utilize the LS when low amount of BOF slag is used, due to the restrictions of P and V. This primarily depends on the characteristics of the iron ore pellet types charged to the BF. Otherwise, as much BOF slag as possible should be recycled to the BF since it contains around 20% of Fe that consequently will be recycled. From the economic point of view, this means finding a trade-off between the savings on iron ore that could be achieved by using BOF slag and the cost for landfilling the LS (whose production is of 20 Kton/y): the trade-off obviously depends also on the price of iron ore as well as on the available alternatives for reuse of BOF slag.

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The overall aim of the project is to improve efficiency of resources (materials, water, energy) in integrated steelmaking plants both by minimising them at source and by finding integrated solutions for recycling, reuse, treatment of waste water, slag, sludge and dust. To achieve this aim, the following objectives are pursued:

- To undertake detailed investigations, at total site and individual process levels, to provide the required information for developing novel Process Integration (PI) solutions for resource efficiency;
- To investigate solutions for improved water efficiency at source and available PI options for water systems, evaluate the impacts on energy minimisation and CO_2 footprint, and quantify saving potentials;
- To investigate solutions for improving material efficiency at source through reuse, recycling, and/or treatment of slag, dust and sludge, in order to identify PI options for a more flexible steel making system through low cost and higher utilisation of secondary raw materials;
- To develop a set of new design frameworks for generating alternative process solutions that will lead to the implementation of PI measures and practical decision-support tools which exploit multi-objective optimization techniques for evaluating the feasibility of different solutions;
- To assess the engineering, practical aspects and resource efficiency improvements associated with the implementation of the proposed PI solutions by undertaking on-site experimental activities at pilot scale and identifying the constraints for different EU sites.

The project aims to show how to exploit PI methods and techniques together with multi-criteria optimisation to identify overall solutions minimising the steelmaking ecological footprint.

Publications Office

ISBN 978-92-79-65646-0
doi:10.2777/052290