IMPROVING THE BY-PRODUCTS REUSE IN INTEGRATED STEELMAKING FACILITIES: SCENARIO ANALYSES THROUGH THE COMBINATION OF PROCESS MODELLING, SIMULATION AND OPTIMIZATION TECHNIQUES

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1. Introduction

2. Materials and Methods

3. Results and Discussion

4. Conclusions

5. Future Works
1. Introduction

2. Materials and Methods

3. Results and Discussion

4. Conclusions

5. Future Works

Introduction

Reduced Demand & Economic Crisis

Globalized Market & High Competition between Companies

Diffusion of Industry 4.0 Concept

Increase of Environmental Consciousness

Raise of Raw Materials & Energy Costs

More Stringent Environmental Regulations

New Industrial Revolution
1. Introduction

2. Materials and Methods

3. Results and Discussion

4. Conclusions

5. Future Works
Introduction

Integrated Steelmaking Industries

Solutions are researched to improve the industrial sustainability
Steelworks’ Solid By-Products (e.g. BOF slag, mill scale)

- Can contain valuable materials
- Can substitute raw materials
- Can be Internally or Externally Reused
- Pre-treatments could be required
- Combination of different by-products could be needed
- Their reuse is not optimized

**Introduction**

1. Introduction
2. Materials and Methods
3. Results and Discussion
4. Conclusions
5. Future Works
Only few studies are based on holistic approach that investigate possible by-products reuse routes by taking into account the joint advantages and disadvantages of different pre-treatments and processing.
Improvements have been done by starting from previous works in order to make more holistic investigations about by-products reuse in integrated steelworks.
1. Introduction

2. Materials and Methods

   Conventional Industrial Process Investigation Techniques
   - Theoretical studies
   - Experimental Campaign

   Industrial Process Simulation & Optimization through standard and advanced tools
   - Assessment of non-conventional scenarios difficult to evaluate or test

   Detailed & Holistic Industrial Process & By-Products Route Analyses

   More agile, dynamic and flexible supervision of:
   - all the aspects of the considered processes or routes
   - the interactions among different sub-processes or route
   - processes and related parameters that can be difficult to directly test due to not very known technologies or applications

3. Results and Discussion

4. Conclusions

5. Future Works
Materials and Methods – BOF Pre-treatment model

2. Materials and Methods

Preliminary Results about BOF slag Pre-treatment configurations to obtain a Fe-rich fraction and a Ca an P rich fraction

Improvements

Development of a "digital twin" by Aspen Plus of the suggested configuration in order to:
- evaluate the robustness of the process with different kind of BOF slag
- evaluate the suitability of different types of magnetic separation steps
- investigate possibilities of changes in configuration and in operating conditions

The developed model contains some duplicator blocks to allow evaluating simultaneously:
- different treatment configurations
- different process units

The following parameters can be monitored:
- Distributions of chemical compounds depending on cooling stage and on Particle Size Distribution (PSD) after grinding;
- Composition of the main fractions (e.g. ≤ 2mm and > 2mm) after sieving;
- Compositions of magnetic and non-magnetic fractions after different kind of magnetic separations
  - Manual with neodymium magnet (M)
  - Wet High Intensity (WHI);
  - Wet Low Intensity (LWI);
  - Dry (D)
- Estimation of required energy in the grinding step based on Bond’s Law,
The model has been tuned and validated by comparing results of experimentation carried out on one type of BOF slag.

Examples

Real and simulated cumulative PSDs after grinding

Real and simulated composition of slag fractions after sieving
Materials and Methods – reMIND improved superstructure for by-product reuse optimization

A first reMIND superstructure to allow the optimization of by-products routes in integrated steelworks has been developed.

Starting point

Improvements

Superstructure improvement:
• inclusion of the different BOF slag magnetic separations as in the BOF slag pre-treatment model
• inclusion of three main BOF slag qualities
• removal of the choice of the oily mill scale treatment

The same indicators of the previous superstructure have been considered and are related to: capital and operating costs, revenues, environmental impact, quality of the output products, efficiency of treatment processes. These are the objective functions.

1. Introduction
2. Materials and Methods
3. Results and Discussion
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5. Future Works

Materials and Methods – reMIND improved superstructure for by-product reuse optimization

main improvements

The reMIND improved superstructure allows:

- identifying the best route for by-products reuse
- obtaining indications about the best BOF slag quality to be reused
- suggesting the best BOF magnetic separation depending on the different slag qualities
Materials and Methods – Pellet mixture composition model

An Aspen Plus model has been developed in order to compute the composition of pellet mixture (a possibility to reuse internally by-products) that exploits the indications and by-product combinations obtained by the other two models.
Materials and Methods – Connections between the three models

The three models can be used stand-alone or in cascade

BOF Slag Pretreatment model
- It exploits also real data (e.g. by plant or by experimental trials)

reMIND improved superstructure
- Data from real experimentations or from other simulations can be added

Pellet mixture composition model
- The obtained composition can be exploited to guide pellet production for internal use
Results and Discussion

1. Introduction
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- Efficiency of different magnetic separations for three qualities of BOF slags
- Best routes for the reuse of BOF slags, BOF sludge and mill scale
- Best magnetic separation of BOF slag (not only in terms of efficiency)
- Best BOF slags to be reused
- Estimation of the composition of pellet mixture in the simulated scenarios
- Researched objectives by the joint use of the three models
Results and Discussion

**BOF Slag Pre-treatment Model**

The BOF Slag Pre-treatment Model has been exploited to evaluate the treatment of 3 qualities of BOF slags in the following configuration suggested by previous work:

1. **cooling**
2. **grinding and sieving**
3. **two different magnetic separation steps**
   - for coarse fraction
   - for fine fraction

A simultaneous evaluation of different magnetic separation techniques have been carried out.

<table>
<thead>
<tr>
<th></th>
<th>Mass Percentage</th>
<th>BOF Slag A</th>
<th>BOF Slag B</th>
<th>BOF Slag C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>wt %</td>
<td>41.8</td>
<td>47.3</td>
<td>40.3</td>
</tr>
<tr>
<td>SiO₂</td>
<td>wt %</td>
<td>12.3</td>
<td>12.6</td>
<td>13.4</td>
</tr>
<tr>
<td>Fe₉₅</td>
<td>wt %</td>
<td>22.3</td>
<td>16.7</td>
<td>21.7</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>wt %</td>
<td>1.0</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Others</td>
<td>wt %</td>
<td>22.6</td>
<td>21.8</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Wet High Intensity Magnetic Separation appears the best technique in terms of efficiency to be used for the separation of the magnetic matter from all the three tested BOF slags.
Results and Discussion

After that the results of the last simulations have been included in the superstructure as well as the others already included in the not improved superstructure, the new reMIND superstructure has been exploited for the following two optimization studies.

1. O1 – multi-objective optimization that considers each indicators, except the quality index, in the objective function

2. O2 – global multi-objective optimization

<table>
<thead>
<tr>
<th></th>
<th>External Reuse</th>
<th>Pelletization</th>
<th>Agglomeration</th>
<th>Disposal or Environmental Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOF Slag A</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>0 %</td>
<td>0 %</td>
<td>N.A.</td>
<td>100 %</td>
</tr>
<tr>
<td>BOF Slag B</td>
<td>80 % (WLI)</td>
<td>60 % (WHI)</td>
<td>20 % (WLI)</td>
<td>0 %</td>
</tr>
<tr>
<td></td>
<td>40 % (WHI)</td>
<td>N.A.</td>
<td>N.A.</td>
<td>0 %</td>
</tr>
<tr>
<td>BOF Slag C</td>
<td>21 % (WHI)</td>
<td>0.6 % (WHI)</td>
<td>6%</td>
<td>N.A.</td>
</tr>
<tr>
<td></td>
<td>0.4 % (WHI)</td>
<td>73%</td>
<td>99%</td>
<td>0 %</td>
</tr>
<tr>
<td>BOF Sludge</td>
<td>N.A.</td>
<td>N.A.</td>
<td>100%</td>
<td>0 %</td>
</tr>
<tr>
<td>Mill Scale</td>
<td>N.A.</td>
<td>N.A.</td>
<td>100%</td>
<td>0 %</td>
</tr>
</tbody>
</table>
Results and Discussion

Mass percentage of by-products in pellet mixtures obtained after the optimization studies carried out through the reMIND superstructure

<table>
<thead>
<tr>
<th></th>
<th>O1</th>
<th>O2</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOF Slag A</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>BOF Slag B</td>
<td>30.2 %</td>
<td>60.7 %</td>
</tr>
<tr>
<td>BOF Slag C</td>
<td>9.0 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>BOF Sludge</td>
<td>38.5 %</td>
<td>38.7 %</td>
</tr>
<tr>
<td>Mill Scale</td>
<td>22.2 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>
The obtained **pellet mixtures** have been included in the pellet mixture composition model in order to know their **chemical composition**

<table>
<thead>
<tr>
<th></th>
<th>Fe\textsubscript{tot}</th>
<th>SiO\textsubscript{2}</th>
<th>CaO</th>
<th>C</th>
<th>P\textsubscript{2}O\textsubscript{5}</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>wt %</td>
<td>46.4</td>
<td>5.2</td>
<td>19.5</td>
<td>2.8</td>
<td>0.4</td>
</tr>
<tr>
<td>O2</td>
<td>wt %</td>
<td>33.9</td>
<td>7.6</td>
<td>28.1</td>
<td>3.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Winning formula of previous real trials</td>
<td>wt %</td>
<td>30.9</td>
<td>8.5</td>
<td>29.5</td>
<td>2.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

- The mixture O1 has a higher amount of iron → mill scale is included in the mixture but it is important to take into account results from previous works: **mill scale decreases the quality of pellet**

- The composition of O2 is perfectly in line with the one tested in a previous work → only small differences in terms of iron content
Previous research works on steelworks by-product pre-treatment and reuse have been continued and improved in order to make more holistic analyses. A combination of modelling, simulation and optimization approaches has been exploited. A suite of tools have been provided in order to:

- make scenario analyses on BOF-slags pre-treatments
- find the best destiny of some by-products and wastes coming from steelworks
- calculate the composition of by-products mixture to be used in pellet production for an internal reuse

The tool suite can be easily used by industrial staff in order to make preliminary investigations devoted to extend the borders of experiments and to pave the way to most suitable field tests for the optimization of by-products/waste management.
Conclusions

Scenario analyses have been carried out by using the developed tools

1. The **Wet High Intensity magnetic separation** has shown to be the **most suitable** separation method for iron contained into the BOF slag;

2. **By-products reuse** is often preferred to disposal or environmental recovery;

3. Only some BOF slags appear suitable for pellet production;

4. **BOF sludge** is a good component of pellet mixture;

5. **Mill scale** is preferred to be used directly in sintering process because, although it increases the iron amount in pellets, it affects negatively the quality of pellets (as proved in previous trials);

6. The “global optimized” pellet composition obtained combining the three developed tools is very similar to the composition of “winning pellet formula” real tested in previous experimentations.
The suggestions provided by the “tool package” can lead to more targeted field trials for practices showing a relevant potential for saving natural resources with consequent significant environmental and economic advantages.

Further pre-treatment models for other by-products can be added to the suite.

Optimization superstructure can be increased according to the needs.

Similar approaches and tools can be transferred to other industrial fields.
thank you!

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