# 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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## Abstract

The steel industry is energy intensive, consumes relevant volumes of various resources (e.g. raw materials and water) and produces important amounts of by-products, wastes and emissions. Slags, dusts, mill scales and sludges are the main by-products generated by the steelmaking processes. Frequently, they contain valuable matter that can be internally or externally reused. However, only few studies are related to a holistic investigation of possible by-products reuse routes. Process modelling, simulation and optimization are important to address field tests and to maximize by-products reuse.
This paper presents improvements related to a long-lasting research activity related to slag reuse by deepening aspects, which have been only marginally considered in the past. In particular, an Aspen Plus® based model has been developed to assess different Basic Oxygen Furnace slag pre-treatment configurations or involved techniques. In addition, a previously developed reMIND-based superstructure has been upgraded considering more Basic Oxygen Furnace slag pre-treatments techniques and more qualities of these slags. Finally, a simplified Aspen Plus®-based model of mixing of the different pre-treated by-products has been developed in order to allow the evaluation of the chemical composition of pellets in each scenario starting from the computed mixtures. The developed tools have been exploited to obtain a more holistic view of steelmaking by-products reuse. Different optimization studies have been carried out combining objective functions and different results have been obtained. For instance, the mixture to be pelletized completely changes if the quality of finally product is (or not) considered in the optimization. Moreover, considering the optimization that combines all the considered objective functions, it emerges that the best treatment of slag includes a wet high intensity magnetic separation stage and that only some of the slags qualities are considered in the pellet mixture.

## Keywords

Process simulation, Process Optimization, By-product reuse, Steelmaking Industry, Sustainability.

## 1. Introduction

Over the last few years, the competition between companies has increased, not only for the raw material supply, but also for the obtained products, due to the share of the same market. On the other hand, the increased sensitiveness toward environmental issues and health protection, the ever more stringent environmental regulations as well as the increase of costs of raw materials and energy, have put under pressure companies to achieve a sustainable industrial production [1]. In this context, in order to promote and improve the management and the exploitation of resources [2] as well as the reduction of wastes and emissions, European process industries have spent considerable efforts in terms of innovations and research activities. The main commitments consisted in Prevention, Preparing for Reuse, Recycling, Recovery and Disposal of by-products and wastes coming from production processes. They are in line with the concept of Circular Economy [3], defined as "an industrial economy that is restorative or regenerative by intention and design" [4] [5]. This represents the context where the steel industry operates, being an energy intensive industry, a major consumer of resources and a producer of important volumes of by-products, wastes and emissions. In particular, by-products generated by the steelmaking processes represent 10–15% of the produced steel. The main by-products are represented by slags, dusts, mill scales and sludges, and slags are the 90% by mass of the total by-products generated by ironmaking and steelmaking processes [6]. In order to increase the environmental and economic sustainability of its production processes, the steel industry is committed to find new solutions for increasing the waste and by-products recycling rate [7]. Nevertheless, the "zero-waste" goal has not yet been achieved. Although by-products contain large quantities of valuable matter, that can be internally or externally reused, frequently they are not properly valorized. In this regard, some investigations have already been performed for their internal or external reuse as well as for the related required pre-treatments. In particular, Basic Oxygen Furnace (BOF) slag, after cooling and magnetic separation, is subject to iron recovering [8]. The cooling conditions affect mineral formation and crystallization. The slow cooling of BOF slag promotes the good distribution of crystals, resulting in a fraction with high iron and low phosphorus content [9]. The Fe-richer and P-poorer fraction can be internally recovered as raw material, due to the high content of valuable elements like iron, and used, along with other pre-treated by-products, such as de-oiled mill scales [10], in pellets production [11] or in different field of applications [6]. On the other hand, the not magnetic and P-richer fraction can be used as fertilizer or soil amendment, with good results in particular in lysimeter trials [12] as well as with negligible effects on groundwater pollution [13]. In order to improve the fraction quality, with low content of impurities, the wet magnetic separation can be applied. In addition, the combination of weak magnetic separation with the selective size screening has improved the slag recycling [14]. Furthermore, by applying a strong magnetic field the separation of $Fe_tO$ matrix can be achieved in the crushed BOF slag [15].

Nevertheless, only few studies are based on a holistic approach in order to investigate the possible by-products reuse routes. This takes into account the joint advantages and disadvantages of different pre-treatments and processing. A recent study paved the way on this topic [16], by highlighting the importance of process modelling, simulation and optimization techniques to address real field tests and possibilities to maximize by-products reuse. Starting from this work, this paper presents further achievements on this subject, which have been pursued by deepening some of the topics, included in the approach scheme reported in Figure 1.

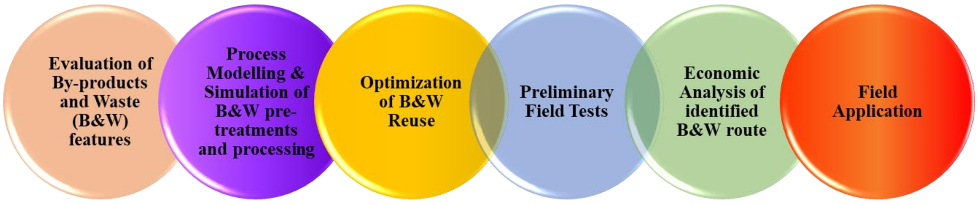



**Fig. 1** Approach scheme to optimize the reuse of by-products and waste in process industries

The work presented in this paper includes the process modelling and simulation, which has been carried out within the projects entitled "Removal of Phosphorus from BOF slag" (PSP-BOF) and "Efficient Use of Resources in Steel Plants through Process Integration" (REFFIPLANT) that are co-funded by the Research Fund for Coal and Steel (RFCS) of the European Union. Such projects aimed respectively at the optimization of by-products reuse scenarios, particularly focused on the BOF slag reuse, and at the efficient use of resources in integrated steel facilities. Starting from the results of a previous work [17], an Aspen Plus®-based model has been developed for assessing different BOF slag pre-treatment configurations, in order to obtain a product that is potentially reusable in the pellet production. This model considers different magnetic separation solutions. Furthermore the reMIND superstructure has been upgraded, compared to the work already done and described in [16]. Models developed by reMIND® software [18] are material flow superstructures, implementing results of the treatment models, in order to evaluate the way to reuse by-products in a more efficient way and to produce high quality raw materials, such as pellets to be used in the sinter plant.

Finally, a simplified Aspen Plus®-based model of mixing of the different pre-treated by-products has been developed. It calculates the chemical pellet composition in each computed mixtures in the analyzed scenarios. The developed tools have been exploited jointly, in order to obtain as a whole a more holistic view of by-products reuse. In this way, further improvement has been obtained with respect to results previously achieved in [16].

The present paper is organised as follows: Section 2 describes materials and methods used in the study; in the Section 3 the main results are presented and discussed, while the Section 4 depicts some concluding remarks.

## 2. Materials and Methods

The methodological approach applied in this and the previous cited works included standard techniques, modelling and simulation tools, and optimization techniques. This allows assessing different scenarios in a holistic way: as already proved in different works [19] [20], the combination of well-known analyses with modelling and simulation tools can lead to take into account the main and the most "hidden" aspects of a process/system or unit configuration in the evaluation of changes of standard operating conditions or in new scenario assessment. Furthermore, by combining by-products and waste management simulations and optimization, the best procedures for their potential internal or external recovery can be determined.

More in detail, considering the work and the results described in [16][17], the BOF slags can be subject to common technologies as well as to new process configurations in order to separate two fractions (i.e. magnetic and non-magnetic). On this subject, different scenarios can be analysed either on field or through the combination of several simulation tools in order to achieve information on the effects of different process configurations as well as of the efficiency of different unit operations (e.g. different magnetic separation units). Consequently, the field trials, including configuration and treatment, can be carried out on the basis of the best achieved results in the simulation phase. In addition, different by-products (i.e. BOF slag fractions, mill scale and BOF sludge) can be combined to obtain valuable secondary raw material (e.g. pellets) or can be internally or externally used with or without pre-treatment. The right by-product destination can be achieved through multi-objective optimization.

Following the previous explained approach and considering the described background, the present work deepens the results obtained in [16][17] by providing more detailed indications about BOF slag treatment and by-products reuse and by providing upgraded tools, which are more suitable to make multiple scenario analyses. For this reasons, two software were used, namely Aspen Plus® and reMIND®.

Aspen Plus® is generally used to develop flowsheeting models starting from data analyses and process knowledge [21]. reMIND® is a Java-based software, which uses the MIND-method (Method for analysis of the INDustrial energy systems) [18] applied to complex superstructures in order to achieve the multi-objective optimization of solid streams by Mixed-Integer Linear Programming,.

In particular, Aspen Plus® has been exploited to develop a "digital twin" of the BOF slag treatment configuration that derives from the investigations described in [17] and tested during the European projects REFFIPLANT and PSP-BOF. The model, here named "ASP_1" provides the combination of cooling, grinding and sieving and of magnetic separation stages. The aim of this model is to allow simultaneous scenario analyses related, for instance, to the treatment of different BOF slag qualities, to different arrangement of process stages or to changes in process units or operating conditions in order to obtain the best results depending on the analysed case studies. According to that, the developed model included each previously listed stage. In addition, some stream duplicator blocks were included in order to evaluate treatment configurations (arrangements of stages) that are different from the one proposed during REFFIPLANT and PSP-BOF projects or different process units (e.g. magnetic separation types). For instance, the following four kind of magnetic separation possibilities have been considered: manual magnetic separation (M) with neodymium magnet, Wet High Intensity (WHI) magnetic separation, Wet Low Intensity (WLI) magnetic separation, Dry (D) magnetic separation. The following parameters can be monitored through the developed model:

- 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;
- Estimation of required energy in the grinding step based on Bond's Law.

After tuning, the results of the tuned model have been compared to the results of experimental trials carried out on one type of BOF slag and the differences with respect to the real case are not significant. For instance, very similar results are obtained for the computation of PSD after grinding and composition of slag fraction after sieving, such as depicted respectively in Figure 2 and Figure 3.

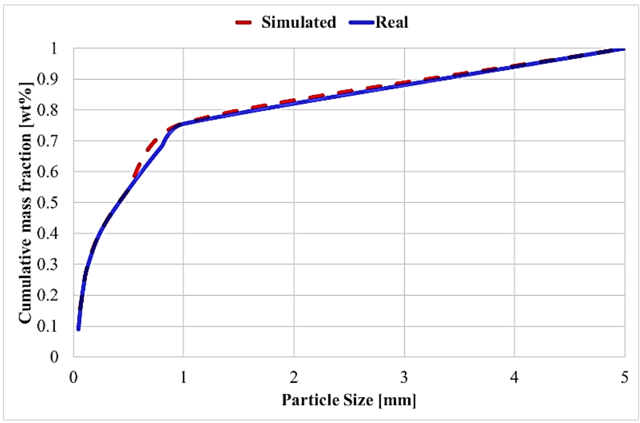
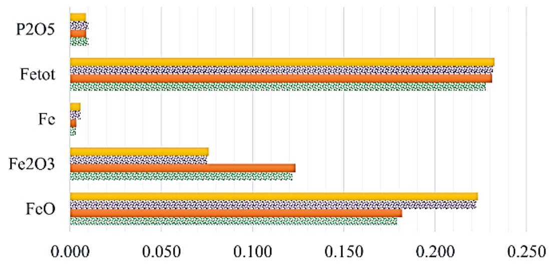



**Fig. 2** Comparison between real and simulated data related to cumulative PSD after grinding




| | FeO | Fe2O3 | Fe | Fetot | P2O5 |
|---|---|---|---|---|---|
| >1mm Real | 0.223 | 0.076 | 0.006 | 0.232 | 0.009 |
| >1mm Simulated | 0.223 | 0.075 | 0.006 | 0.231 | 0.010 |
| <1mm Real | 0.182 | 0.124 | 0.003 | 0.231 | 0.009 |
| <1mm Simulated | 0.179 | 0.122 | 0.003 | 0.228 | 0.010 |

**Mass Fraction**

**Fig. 3** Comparison between real and simulated data related to the composition of slag fractions after sieving

On the other hand, the reMIND® superstructure presented in [16] and devoted to the optimization of main integrated steelworks by-products (i.e. BOF slag and sludge, mill scale) has been improved by including the different BOF slag magnetic separations included also in the ASP_1. Furthermore, three main BOF slag qualities have been included in the superstructure and the treatments of oily mill scale have been removed, because in each optimization carried out in [16] the washing and chemical process is preferred to the distillation and pyrolysis one. The same indicators already included in the superstructure presented in [16] have been exploited and some others have been included to allow the optimization: they represent the objective functions that can be minimized alone or together. They are considered for each stream or treatment and are related to capital and operating costs, revenues, environmental impact, quality of the output products and efficiency of treatment processes. In this way, the reMIND superstructure can provide a more complete multi-objective optimization study, aiming at finding the best solution/configuration for by-products treatment and reuse, by taking into consideration further aspects with respect to the ones considered in the previous works. Indeed, starting from the implementation of the results obtained in the real and simulated case studies in the superstructure, the reMIND model developed in this work allows identifying the best route for by-products reuse, by also giving indications on the best BOF slag quality to reuse as well as on the best BOF slag magnetic separation for the different slags. The obtained superstructure is depicted in Figure 4.

Finally, another simplified Aspen Plus® based model (ASP_2) has been also developed aimed at computing the composition of a possible secondary products (i.e. the pellets), after the optimization of the mixture obtained through the reMIND superstructure. In this way, the final pellet composition can be estimated. It is a very simple model that considers the magnetic fraction of the three slags (and their composition), obtained after the different magnetic separation steps, which is taken into account in the optimization together with the other considered by-products. In addition, the required additives that allow obtaining a good quality pellets are included (i.e. lime and cement). The model includes some mixers and a "design specification block" that adjusts the quantity of required water to obtain a humidity of the slag mixture of about 14 %, representing the humidity that gives best results in real trials [16]. The flowsheet of the model is shown in Figure 5.

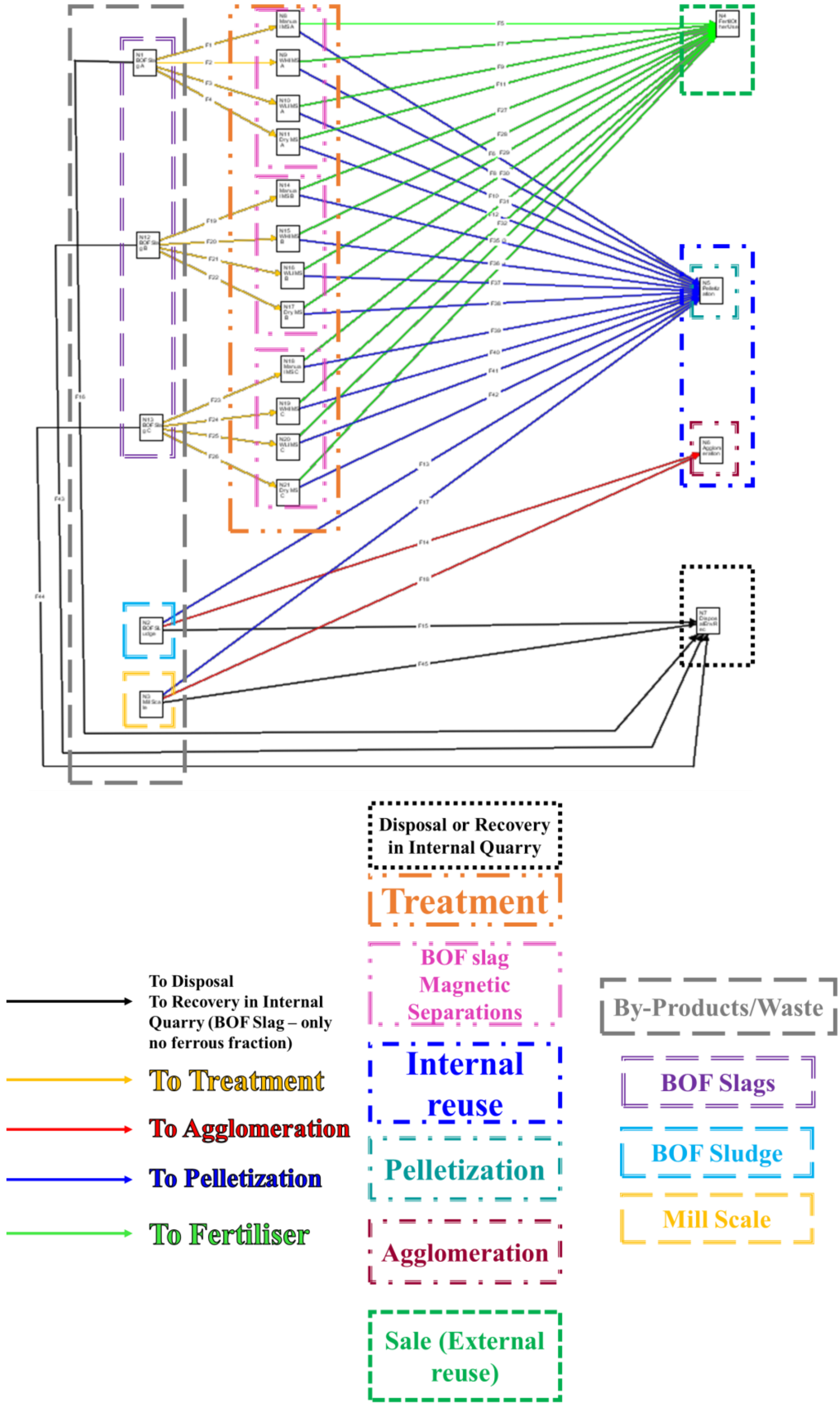



**Fig. 4** reMIND improved superstructure to optimize reuse of by-products and wastes

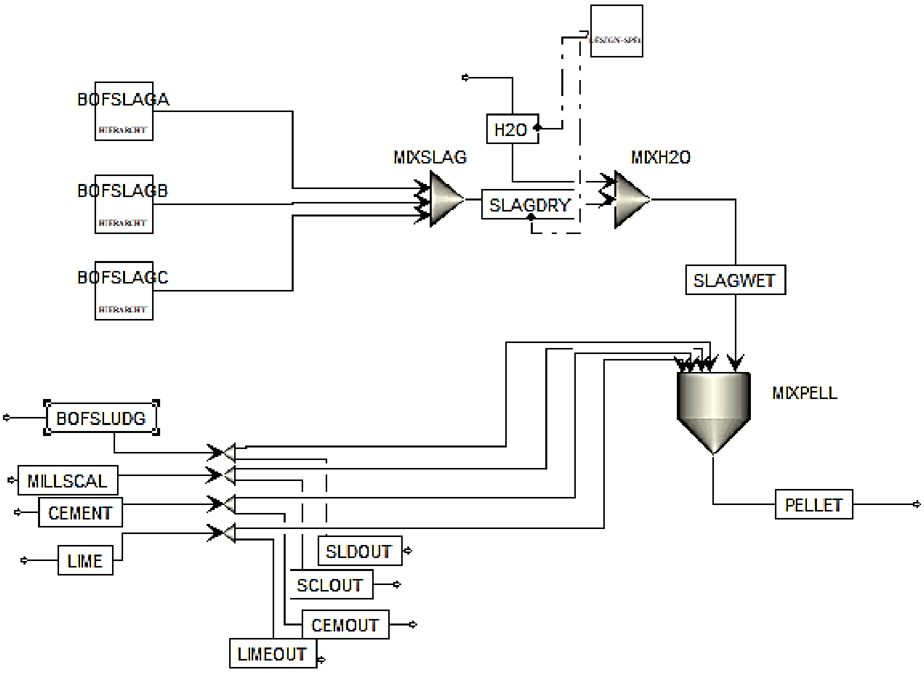



**Fig. 5** Flowsheet of model ASP_2 related to simulation of pellet mixtures

The three presented models can be used stand alone or in cascade: ASP_1 provides data to be used in the reMIND superstructure, which in turn gives information to be used in ASP_2

## 3. Results and Discussion

The three models have been jointly exploited in order to reach the following objectives:

- to collect information about the efficiency of different magnetic separations for three qualities of BOF slags coming from the production of three main steel grades;
- to optimize the routes for the reuse of BOF slags, BOF sludge and mill scale by also selecting the best magnetic separation of BOF slag (not only in terms of efficiency) and by giving information about the best BOF slags to be reused by considering the combination of economic, environmental and quality indicators;
- to obtain an estimation of the composition of pellet mixture in the simulated scenarios.

The ASP_1 model has been used to test a treatment for three BOF slag qualities, whose compositions are reported in Table 1. The treatment combines a sequence of cooling, grinding and sieving and two different magnetic separations steps, one for coarse fraction and one for fine fraction as suggested by the work described in [16] and [17]. In addition, a simultaneous evaluation of different magnetic separation techniques have been carried out. The obtained magnetic separation efficiencies for the analysed techniques are compared in Figure 6.

**Table 1** Composition of the considered BOF slags

| | Mass Percentage | BOF Slag A | BOF Slag B | BOF Slag C |
|---|---|---|---|---|
| **CaO** | wt % | 41.8 | 47.3 | 40.3 |
| **$SiO_2$** | wt % | 12.3 | 12.6 | 13.4 |
| **$Fe_{tot}$** | wt % | 22.3 | 16.7 | 21.7 |
| **$P_2O_5$** | wt % | 1.0 | 1.6 | 1.1 |
| **Others** | wt % | 22.6 | 21.8 | 23.5 |

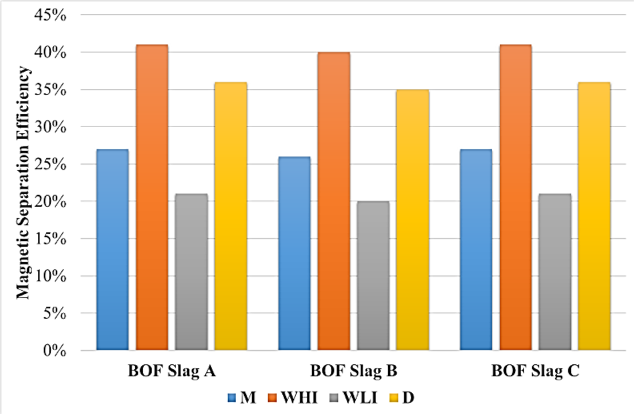



**Fig. 6** Comparison between magnetic separation efficiency with different techniques and for different slags

The WHI magnetic separation allow the separation of a higher magnetic fraction and for this reason it appears the best technique in terms of efficiency to be used for the separation of magnetic matter from all the three tested BOF slags. The composition of magnetic and non-magnetic fractions obtained after the treatments of the three considered slags by using WHI are shown and compared in Figure 7.

The information obtained by the simulation carried out with ASP_1 have been included in the reMIND superstructure together with the one already included in the model presented in [16]; two optimization studies have been thus carried out. The first (O1) is a multi-objective optimization that considers each indicators described in the previous paragraph except quality index, while the other one (O2) is a global multi-objective optimization. The obtained results are listed in Table 2 as by-products/wastes percentage distribution. The environmental recovery or the disposal are always avoided for BOF Sludge, Mill Scale and BOF Slag B that represent in each optimization the most suitable slag for internal and external reuse, followed by BOF Slag C. For both the slags (B and C), WHI magnetic separation is preferred in the global optimization. BOF Sludge is preferred as pellet component, while mill scale appears more suitable for agglomeration according to the O2 results because it decrease the quality of the pellet, as already tested in [16]. On the other hand, mill scale is included in pellet mixture if the quality index of the final product is not considered in optimization. It is clear that two different pellet recipes can be obtained in the two considered multi-objective optimization; they are reported in Table 3.

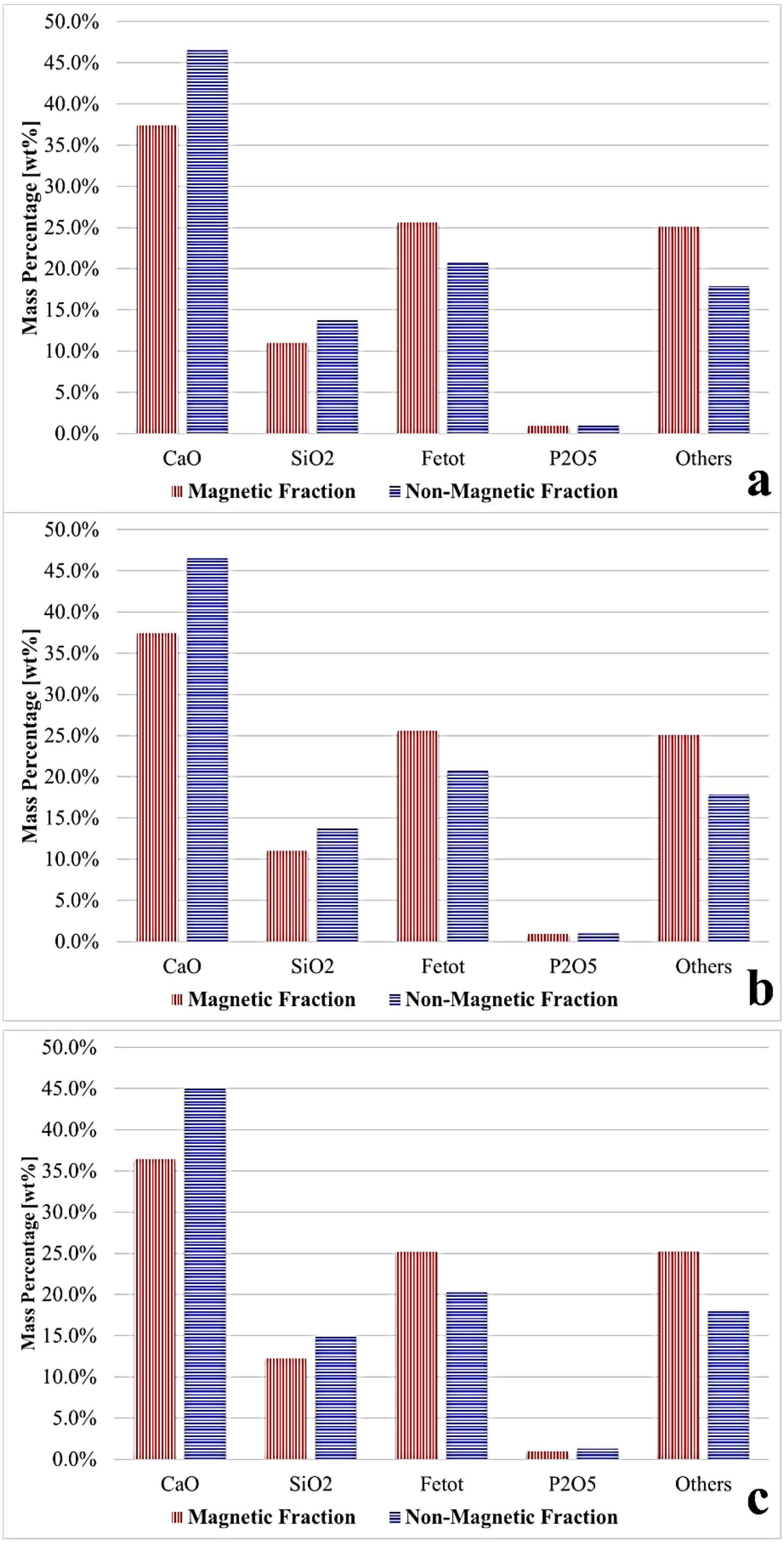



**Fig. 7** Composition of magnetic and non-magnetic fractions obtained after the WHI treatment: a. BOF Slag A, b. BOF Slag B, c. BOF Slag C

**Table 2** Mass percentage distribution of by-products and wastes after two optimizations carried out through reMIND supestructure

| | **External Reuse** | | **Pelletization** | | **Agglomeration** | | **Disposal or Environmental Recovery** | |
|---|---|---|---|---|---|---|---|---|
| | O1 | O2 | O1 | O2 | O1 | O2 | O1 | O2 |
| BOF Slag A | 0 % | 0 % | 0 % | 0 % | N.A. | N.A. | 100 % | 100 % |
| **BOF Slag B** | 80 % (WLI) | 60 % (WHI) | 20 % (WLI) | 40 % (WHI) | 0 % | N.A. | 0 % | 0 % |
| **BOF Slag C** | 21 % | 0.6 % (WHI) | 6% | 0.4 % (WHI) | 0 % | N.A. | 73 % | 99 % |
| **BOF Sludge** | N.A. | N.A. | 100 % | 100 % | 0 % | 0 % | 0 % | 0 % |
| **Mill Scale** | N.A. | N.A. | 100% | 0 % | 0 % | 100% | 0 % | 0 % |

**Table 3** Mass percentage of by-products in pellet mixtures

| | **O1** | **O2** |
|---|---|---|
| **BOF Slag A** | 0 % | 0 % |
| **BOF Slag B** | 30.2 % | 60.7 % |
| **BOF Slag C** | 9.0 % | 0.6 % |
| **BOF Sludge** | 38.5 % | 38.7 % |
| **Mill Scale** | 22.2 % | 0 % |

Starting from these mixtures, the final step of investigation consisted in the evaluation of pellet chemical composition. According to this objective, the found amount of different by-products (Table 3) have been included in ASP_2 model together to fixed amounts of lime and cement corresponding, respectively, to 1 and 7 wt % according to the indications reported in [16]. The simulations give the pellets compositions that are depicted in Table 4; in this table also the chemical composition of the "winning formula" of pellet obtained in [16] is reported.

**Table 4** Chemical composition of pellets obtained by using ASP_2 for the optimized pellet mixtures

| | | **$Fe_{tot}$** | **$SiO_2$** | **CaO** | **C** | **$P_2O_5$** | **Others** |
|---|---|---|---|---|---|---|---|
| **O1** | wt % | 46.4 | 5.2 | 19.5 | 2.8 | 0.4 | 25.7 |
| **O2** | wt % | 33.9 | 7.6 | 28.1 | 3.0 | 0.7 | 26.7 |
| **Previous Optimization [16]** | wt % | 30.9 | 8.5 | 29.5 | 2.1 | 0.6 | 28.4 |

The mixture that includes mill scale (O1) contains obviously a higher amount of iron. However, as already tested and described in [16], the features of mill scale decrease the quality of pellet in terms of hardness and consistency. On the other hand, the composition obtained by considering the result of global optimization (O2) is perfectly in line with the one obtained and tested in [16]; the more relevant difference concerns the iron content but it is not excessive. This fact suggests again that the combination of different simulation tools and an upgraded optimization superstructure leads to valuable results. In addition, the upgrading of developed tools and the addition of new ones allow deeper holistic investigations with respect to the ones presented in [16].

## 4. Conclusions

The work presented in this paper aims at achieving indications about the best route for by-products and waste reuse in integrated steelworks, by exploiting modelling, simulation and optimisation approaches. It also aims at providing information about efficiency of BOF slag treatments, with particular attention on magnetic separation processes, and related to the best BOF slag to reuse, for instance, in order to obtain valuable secondary products for external or internal (e.g. pellets, which composition is computed for different scenarios) reuse. In addition, the developed research activity provides a "tool package" that 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. Therefore, the work already presented in [16] and [17] has been highly improved.

Two Aspen Plus® based model and a reMIND superstructure have been presented and applied in scenario analyses and the following main results have been achieved:

- the WHI magnetic separation has shown to be the most suitable separation method for iron contained into the BOF slag;
- by-products reuse is often preferred to disposal or environmental recovery;
- only some BOF slags appear suitable for pellet production;
- BOF sludge is a good component of pellet mixture;
- mill scale is preferred to be used directly in sintering process because, although it increase the iron amount in pellets, it affects negatively the quality of pellets
- the pellet composition obtained combining the three developed tools is very similar to the composition of "winning pellet formula" tested in [16].

The potential of this "package" has been proved and the provided indications can lead to more targeted field trials for practices showing a relevant potential for saving natural resources with consequent significant environmental and economic advantages.

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issues treated in the present paper lies with the authors; the Commission is not responsible for any use that may be made of the information contained therein.

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