Burden Mix Optimisation for Metallurgical Recycling Processes

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Abstract
The paper presents a hybrid approach for a techno-economic optimisation of the material input mix for a metallurgical recycling process. The approach combines chemical-physical process simulation with economic optimisation models and allows to model chemical-physical coherences adequately while maintaining linearity in the input-output relations of the optimisation model. The paper describes the problem and its background, the general approach, the main development steps, presents results of the optimisation and provides an outlook on further planning tasks as well as further processes on which the approach can be disseminated.

1. Introduction
European environmental legislation concerning wastes and landfills leads to a growing need for treatment processes. For metal-containing wastes metallurgical treatment processes like the utilisation in a blast furnace or the so called Waelz-kiln have been well established. Aim of such processes is the material recovery of metals such as iron and zinc. E.g. the named blast furnace process can be operated with metal containing wastes instead of primary raw materials. Production output is pig iron and a highly concentrated zinc sludge. Though the long-term perspective of such processes is good, in terms of profit and productivity they have to cope with difficulties on a short-term perspective: In the case of the blast furnace process the treatment fees charged by the recycling company for the utilisation of the waste have – at least – to compensate losses in productivity and product quality in comparison with producers of pig iron on a primary raw material basis. In Germany currently

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low prices for landfill are induced by transitional arrangements of the landfill order. Thus, the treatment charge is currently limited approximately to these low prices for landfill. On the other side the world's increasing demand for coke results in rising coke prices while coke is the main cost driver in the process. The rising prices can only be passed partially on the customers of the pig iron because of the mentioned efficiency losses in comparison with processes on a mainly primary raw materials basis. For the utilisation of metal containing wastes in a blast furnace e.g. more than twice as much coke has to be used than in a common blast furnace, while on the other side the products have to compete with the primary processes concerning their quality and prices. It is therefore essential to run such a process as efficiently as possible. A key factor for an efficient operation of the process is the optimisation of the raw material input mix, also called burden mix. A reasonable mix between different metal containing wastes can lead to burdens with comparable high treatment charges and a complementary raw material mix. Thus, high concentrational values can be diluted while high treatment charges for the burden mix can be maintained.

Therefore it is the aim of this paper to develop an approach for the techno-economic optimisation of the secondary raw material input for the process of utilisation of metal-containing wastes in a blast furnace under consideration of environmental aspects. To ease comprehension, the following paragraph depicts the underlying production processes and the planning task first. Afterwards, paragraphs three, four and five focus on the three steps followed in the proposed approach. Paragraph six closes the paper with conclusions and a brief outlook.

2. Problem definition and solution approach

The process we focus on in this contribution is a specially operated blast furnace process for pig iron production consisting of the stages preprocessing, sinter strand, blast furnace and alloying. The raw materials are stored in feed bins and conveyed to a mixing and granulating drum. This raw material mix is given into sinter pallets that move horizontally along the sinter strand. The top layer of the burden mix is ignited and air is sucked through it. While moving slowly horizontally, the burning front moves down. In this burning-front, the materials (i.e. raw materials and supplements) are melted to a certain extent. Recrystallization agglomerates the fine materials. The sintering process ends when the burning front reaches the bottom of the material bed. Afterwards, the cooled sinter is crushed to a predetermined particle size. Together with coke and supplements, it is charged discontinuously into the blast furnace. There the iron oxides are reduced and discontinuously tapped. To achieve a specific pig iron quality, an alloying with supplements in an induction furnace is possible before the iron is finally cast into blooms in a casting machine. The described process flow and the system boundaries are depicted schematically in
Due to the special burden the described process differs from usual blast furnace processes. In particular zinc, alkalis and lead require special attention. The zinc burden is e.g. 300 times and the alkali burden up to five times higher than in other blast furnaces. The zinc, a valuable by-product, is removed from the blast furnace mainly through the top with the blast furnace gas and obtained as a sludge from the gas cleaning system.

We focus on the preparation of one major part of the blast furnace burden, the production of sinter on a sinter strand and the gas cleaning facilities coupled with the sinter strand. Objective is the determination of the cost minimal mix of raw materials for the sinter strand to produce a specified sinter under consideration of technical and economic restrictions.

Like other procedural processes it is essential to model the underlying metallurgical reactions adequately in the economic optimisation. Unlike other optimisation approaches in which the processes are either oversimplified or even neglected and procedural process models which leave it frequently to details and often do not provide the possibility of a comprehensive economic optimisation, the presented hybrid ap-
approach combines chemical-physical process simulation with linear respectively mixed integer linear programming. This enables to deal with comparatively manageable optimisation models while maintaining an adequate modelling of the underlying chemical-physical processes. Our approach consists of three major steps: In the first step, the relevant processes in the sinter strand are modelled in a sequential modular flowsheeting system (cf. paragraph 3). In the second step (cf. paragraph 4) the relevant costs arising in the utilisation of the metal containing wastes as well as the arising revenues for the utilisation of these wastes are determined on a material flow basis. Concerning the sinter strand these are mainly revenues for the treatment of the wastes and costs for coke, other additional raw materials for the sinter process and the gas cleaning as well as resulting by-products. With this data the economic burden mix optimisation model is formulated. Objective of the burden mix optimisation is to determine the cost minimal composition of raw materials for sinter production respecting a technical specification. The third step consist of the implementation of the approach in the integrated decision support system SCOPE (cf. paragraph 5).

3. **Flowsheet simulation of the processes**

Flowsheet simulation is an established approach in process engineering. It is marked by using software-tools for static or dynamic modelling of procedural processes mainly for the development, planning and configuration of processes. Flowsheeting systems already proved to be a valuable tool for simulation of production processes in the metal industry (Rentz et al 1999), (Schultmann/Engels/Rentz 2004). Among other classification criteria, flowsheeting systems can be differentiated by the solution methodology: The *sequential-modular* systems divide the process into single unit operations like mixing, separation, reaction, etc. These are linked and computed sequentially in process flow order. Refeedings are calculated iteratively. The second type of systems solves the flowsheets simultaneously and is also known as the *equation-oriented* approach. This is advantageous for large models with a high amount of refeedings. A major disadvantage of the equation-oriented approach is that the integrity of the model can hardly be checked and further debugging is more difficult than in the sequential modular approach.

Key element of any flowsheeting system is a comprehensive material database. Module libraries for common procedural unit operations provide valuable components for a comparably easy model building while solution algorithms enable the computation of the flowsheets. A graphical user interface controls the interaction with the user. Common systems are *Pyrosim™*, *ChemCad™*, *Designer™* and *Aspen
Plus™, the latter is used in the depicted case. Figure 2 shows a screenshot of a sinter strand flowsheet in Aspen Plus.⁴

The relevant aggregates and processes are modelled in the flowsheeting system and the models are validated by the comparison between simulated and measured data. As an example, Figure 3 displays a comparison between measured and simulated mass flows of gas cleaning dust of the reference company’s sinter strand. With the exception of few outliers the system behaviour correlates highly with measured data.

Figure 2:
Screenshot of a sinter strand flowsheet in *Aspen Plus*

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⁴ For further information on flowsheeting systems the interested reader is referred to (Futterer/Munsch 1990)
The simulation is used to deliver input-output relations for the optimisation models. To derive these relations first, an assumption of the character of the possible input-output function is made. Based on this assumption a complete factor experimental design is elaborated in order to identify the necessary parameters and determine the extent of the parameter variation needed to derive reliable coefficients in the input-output function. According to this experimental design the simulation runs are carried out to compute the data set. Afterwards, multiple linear regression analysis on the data set is used to determine the needed factors. A direct analysis of the measured parameters is not capable of delivering all necessary coherences, as it is impossible from a technical as well as from an economical point of view to carry out the necessary tests in day-to-day business. The following equation (1) gives a linear function stating the input-output relations on the example of the mass flow of gas cleaning dust:

\[ X_{\text{ESP}}^{\text{EXP}} = 0.3638 + 8.1103 \cdot e_{\text{Pb}}^{BM} + 0.4216 \cdot e_{\text{Na}}^{BM} + 0.9016 \cdot e_{\text{K}}^{BM} + 18.3333 \cdot e_{\text{Cl}}^{BM} \] (1)

where \( X_{\text{ESP}}^{\text{EXP}} \) denotes the specific share of the gas cleaning dust referring to one ton of raw material mix and \( e_{\text{Pb}}^{BM} \), \( e_{\text{Na}}^{BM} \), \( e_{\text{K}}^{BM} \) and \( e_{\text{Cl}}^{BM} \) describe the concentration of lead (Pb), sodium (Na), potassium (K), and chlorine (Cl) in the raw material mix of the sinter strand. Equation (1) satisfies the input-output relations with a correlation coefficient of more than 0.98.
Similar equations are derived for the concentration of elements and substances in the relevant mass flows, i.e. the concentrations in the sinter, in the offgas of the sintersand and the precleaned offgas. Further functions are determined for the specific shares of needed raw materials for the gas cleaning facilities and the accruing by-products, each referring to one ton of processed burden mix.

4. Economic modelling and optimization of the burden mix

The underlying planning problem can be characterised as a blending problem. Typically these problems consist of the determination of the optimal blend between different raw materials with different prices and properties to meet certain quality requirements of the mixture while minimizing the purchasing costs. For the formulation of the mathematical model the following identifiers are used\(^5\):

Sets
- \(A\) set of considered aggregates \(a\), \(A = \{SA, ESP, SWS\}\)
- \(M\) set of considered mass flows \(m\), \(M = \{BM, SR, SFIN, SFG, PSFG, CGR, LI, SCG, RSWS, REP\}\)
- \(B \subset M\) set of considered by-products \(b\), \(B = \{SCG, RSWS, REP\}\)
- \(E\) set of considered elements and substances \(e\)
- \(R \subset M\) set of considered raw materials \(r\), \(R = \{BM, CGR, LI\}\)

Parameters
- \(k^{a}_{r}\) cost or revenues for raw material \(r\) of aggregate \(a\) [\(\text{€/t}\)]
- \(k^{a}_{b}\) cost or revenues for by-product \(b\) at aggregate \(a\) [\(\text{€/t}\)]
- \(S\) amount of burden mix that is to be sintered [t]
- \(c^{SIN}_{e}\) minimal concentration of element \(e\) in the sinter
- \(\bar{c}^{SIN}_{e}\) maximal concentration of element \(e\) in the sinter
- \(\underline{x}^{S}_{r}\) minimal share of raw material \(r\) in the burden mix
- \(\overline{x}^{S}_{r}\) maximal share of raw material \(r\) in the burden mix
- \(z^{SIN}_{bas}\) specified basicity of the sinter
- \(\delta_{max}\) maximal number of raw materials to be used for the burden mix
- \(\delta_{r}\) Binary variable indicating whether raw material \(r\) is part of the burdenmix or not
- \(LN\) large number

Decision variables

\(^5\) cf. Figure 1 for the labelling of the aggregates and mass flows.
\( X^a_R \) vector of shares \( x^a_r \) of raw material \( r \) in the material input mix on aggregate \( a \in A \) 

\( X^a_B \) vector of share \( x^a_b \) of by-products \( b \in B \) accruing on aggregate \( a \in A \) referring to one ton of sinter 

\( C^m \) vector of element concentrations \( c^m_e \) of element or substance \( e \in E \) in massflow \( m \in M \)

With these identifiers the model can be formulated as a Mixed Integer Linear Program (MILP): 

Objective function

\[
\text{MIN } \text{Cost}^{\text{BM}} = S \left( \sum_{a=1}^{A} \sum_{r=1}^{R} k^a_r \cdot x^a_r + \sum_{a=1}^{A} \sum_{b=1}^{B} k^a_b \cdot x^a_b \right)
\]  

(2)

Subject to (excerpt)

\[
\sum_{r=1}^{R} x^A_r = 1 \quad (3)
\]

\[
c^B_e = c^A_e \cdot x^A_r \quad \forall e \in E, \forall r \in R \quad (4)
\]

\[
c^E_e = f^E_e \left( C^B \right) \quad \forall e \in E \quad (5)
\]

\[
c^E_e \leq c^E^{\text{SN}} \quad \forall e \in E \quad (6)
\]

\[
c^E_e \leq c^E^{\text{SN}} \quad \forall e \in E \quad (7)
\]

\[
x^a_r = f^a_r \left( C^B \right) \quad \forall a \in A \setminus \{SA\}, \forall r \in R \quad (8)
\]

\[
x^a_b = f^a_b \left( C^B \right) \quad \forall a \in A, \forall b \in B \quad (9)
\]

\[
c^B_{\text{CaO}} / c^B_{\text{SiO}_2} = z^B_{\text{Bas}} \quad (10)
\]

\[
\frac{z^A_r}{x^A_r} \leq \frac{x^A_r}{\delta^A_r} \quad \forall r \in R \quad (11)
\]

\[
x^A_r \leq \delta^A_r \quad \forall r \in R \quad (12)
\]

\[
\delta^A_{\max} \geq \sum_{r=1}^{R} \delta^A_r \quad (13)
\]

\[
x^A_r - LN \cdot \delta^A_r \leq 0 \quad (14)
\]

\[
x^A_r + LN \cdot (1 - \delta^A_r) \geq 1 / LN \quad (15)
\]

\[
x^a_r, x^a_b, c^m_e \geq 0 ; \delta^A_r \in [0;1] \quad (16)
\]
The objective function (2) minimises the costs $Cost^{BM}$ for the utilisation of an amount $S$ of raw material mix under consideration of the raw materials $r$ and the resulting by-products $k$. Equation (3) ensures the consistency of the burden mix. In Restrictions (4) the concentration of elements and substances in the raw material mix is calculated. In equations (5) the chemical specification of the sinter concerning element/substance $e$ in dependence of the specification of the burden mix is calculated. Restrictions (6) and (7) ensure that the concentration of materials in the sinter ($c_{e}^{SM}$) meets the specified bounds ($c_{e}^{SIN}, c_{e}^{SIN}$). In (8) and (9) the specific amount of raw materials for the other considered aggregates and the amount of accruing by-products referring to one ton of burden mix are calculated in dependence of the composition of the burden mix. As an example for technical restrictions the specified basicity of the sinter is ensured by restriction (10). Minimal and maximal shares of raw materials are considered in (11) and (12). Equations (13), (14) and (15) ensure that not more than a maximum number of raw materials are considered for the burden mix\(^6\). Nonnegative and binary values of the decision variables are ensured by equations (16).

5. Implementation and application of the approach

The approach is implemented in the integrated decision support system SCOPE (simulation combined with optimisation in the process industry). The master data needed for the optimisation runs is stored in a MS Access\textsuperscript{TM} database. The database provides input files for the used algebraic modelling system GAMS\textsuperscript{TM}. The results are fed into the MS Access database formatted in a report, providing the optimal input mix, its chemical composition, the tentative sinter composition and the achieved costs.

\(^6\) Equations (14) and (15) linearize the function $\delta_{r} = \begin{cases} 1 & \text{if } S_{t}^{S} > 0 \\ 0 & \text{else} \end{cases}$ needed for restriction (13).

Abandoning the restriction of the number of raw materials and the corresponding equations (13), (14) and (15), parameter $\delta_{r}$ and the binary variables $\delta_{r}, r \in R$ leads to a linear model.
<table>
<thead>
<tr>
<th>Objective function value [€]</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of raw materials sintered [t]</td>
<td>1350</td>
</tr>
</tbody>
</table>

**Share of raw material in raw material mix**

<table>
<thead>
<tr>
<th>raw material</th>
<th>Share [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1301 Sand A</td>
<td>4.83</td>
</tr>
<tr>
<td>3123 Sand B</td>
<td>2.74</td>
</tr>
<tr>
<td>3203 Converter dust A</td>
<td>13.12</td>
</tr>
<tr>
<td>4102 MCW B</td>
<td>61.01</td>
</tr>
<tr>
<td>4314 Blast furnace flue dust</td>
<td>5.28</td>
</tr>
<tr>
<td>8396 Mills scale</td>
<td>0.65</td>
</tr>
<tr>
<td>8406 Pickling residue</td>
<td>12.37</td>
</tr>
</tbody>
</table>

**Raw material mix and sinter specification**

<table>
<thead>
<tr>
<th>Element / substance</th>
<th>Share in raw material mix [%]</th>
<th>Share in sinter [%] (optimisation)</th>
<th>Share in sinter [%] (simulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>13.70</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Fe</td>
<td>48.70</td>
<td>52.00</td>
<td>51.66</td>
</tr>
<tr>
<td>Mn</td>
<td>1.00</td>
<td>0.84</td>
<td>0.86</td>
</tr>
<tr>
<td>P</td>
<td>0.00</td>
<td>0.04</td>
<td>0.042</td>
</tr>
<tr>
<td>Zn</td>
<td>2.70</td>
<td>2.83</td>
<td>2.84</td>
</tr>
<tr>
<td>Pb</td>
<td>0.20</td>
<td>0.13</td>
<td>0.17</td>
</tr>
<tr>
<td>CaO</td>
<td>8.30</td>
<td>8.85</td>
<td>8.83</td>
</tr>
<tr>
<td>MgO</td>
<td>1.30</td>
<td>1.40</td>
<td>1.43</td>
</tr>
<tr>
<td>SiO₂</td>
<td>9.00</td>
<td>9.62</td>
<td>9.58</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.50</td>
<td>1.57</td>
<td>1.59</td>
</tr>
<tr>
<td>Cr</td>
<td>0.10</td>
<td>0.06</td>
<td>0.063</td>
</tr>
<tr>
<td>S</td>
<td>0.24</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.30</td>
<td>0.31</td>
<td>0.28</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.40</td>
<td>0.30</td>
<td>0.28</td>
</tr>
<tr>
<td>Cl</td>
<td>0.20</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C</td>
<td>4.20</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 1: Exemplary results

The optimisation results are starting point for a flowsheet simulation in ASPEN Plus. The simulation allows to determine the deviation between the calculated output results and the actual output. When this deviation exceeds specified tolerances a further optimisation run is started in which the variations of the relative shares of
The raw materials are restricted. This heuristic process is continued until the solution satisfies the set tolerances. Table 1 shows exemplary results of one optimisation run. With the exception of Pb and Na₂O with deviations of 23.5 % and 12.2 % the deviation lies below of 10 %. Similar results in further comparisons confirm that the sinter composition derived by the regression functions complies highly with the sinter composition derived by the simulation. Using the decision support system it is now possible to determine the consequences e.g. of the utilisation of new raw materials, changes in prices or composition of raw materials or for by-products.

6. Conclusions and outlook

The hybrid approach presented combines flowsheet simulation with mathematical optimisation. On the results of thorough simulation runs linear functions describing the input-output relations and concentrations of elements and substances in resulting mass flows are derived. These functions are used in a mixed integer linear program to determine the cost minimal raw material mix for sinter production of the considered metallurgical recycling process. The approach is implemented in the integrated decision support system SCOPE which appears to be valuable tool in day-to-day business in the reference company. Current work of the authors focuses on the simulation of the blast furnace and the connected gas cleaning facilities. Again regression analysis is used to describe input-output relations for these aggregates. The economic optimisation models are extended to cover these aggregates and to model the planning tasks of master production scheduling and determination of adequate treatment charges. Further work should deal with similar processes such as the Waelz-kiln or other parts of the process industries.

Bibliography