Optimization of the charging process in zinc hydrometallurgy

Alexander Peltekov, Doychin Boyadzhiev, Mariusz Kozlowski,
Zlatko Varbanov, Zlatogor Minchev

Problem definition

The main objective is to optimize the charging process in zinc metallurgy with respect to the technological price of the input components' mixture (concentrate build of different charges):

$$L(\vec{x}) = \sum_{j=1}^{n} C_{T_j} x_j \to \min, \tag{1}$$

where C_{T_j} is the technological price of the j-th concentrate and x_j – the quantity of the j-th concentrate in the charge (measured in [%]). Further on, for simplicity C_{T_j} is denoted without the j-th index, i.e. – "C_T".

Calculation of the technological price

After the examples from [1] the technological price C_T could be considered as a triple component:

$$C_T = C_1 - C_2 - C_3. \tag{2}$$

The C_1 component depends on the Zn (zinc) contents in the concentrate as follows:

$$C_1 = \text{if } [(1-p) * Zn < q \text{ then } (Zn - q) * C_D/100 \text{ else } p * Zn * C_D/100], \tag{3}$$

C_D – daily price of Zn on London Metal Exchange (LME);
p – final agreed Zn content at the official LME (85%);
q – minimum deduction of Fe (iron) at the official LME (8%).

The second component C_2 is the correction that depends on the difference between C_D and C_{avg} of *Zn*:

$$C_2 = E_{avg} - (C_{avg} - C_D)/10, \tag{4}$$

where E_{avg} are the average expenses for one tone concentrate processing and transportation, $E_{avg} = 2000$ \$.

The third component C_3 is the penalty for *Fe* contents in the concentrate:

$$\text{if } [Fe < q \text{ then } 0 \text{ else}(Fe - q) * s], \tag{5}$$

where q is the minimum deduction of *Fe* at the official LME (8%) and s – the penalty for 1 % *Fe* contents in the concentrate, $s = 2$ \$.

Methods and techniques

Assuming that the concentrate mixture is a linear combination of the charge components we decided to use the well-known linear optimization techniques including both – real and integer ones. As the input data example could be presented in a table-like form we decided to use the commonly available *MS EXCEL*©2010 product with its build-in SOLVER [2].

The input data arrays that were used contain percentages of the chemical elements, components and groups of a certain imaginary concentrate (see first column of Table 2) in twenty-one real *Zn* concentrates, denoted by "**ZC17-1**" – "**ZC17-21**" (see the first column of Table 1).

Results and future work perspectives

The first task that was solved concerns the creation of a concentrate mixture with "minimal price", keeping in mind the technological constraints for percentages contents of desired variables (noted in the second column of Table 2). The first two variables that have been monitored are *Zn* and S_{tot}. We have assumed the following rule: if the boundary conditions have a positive influence to the concentrate mixture, we use relations like "not less than", whilst the negative influence is denoted by relations like "not more than". The different variables share in the concentrates is limited by the percentages sum (that should be equal to 100%).

In order to achieve similarity in the utilized procedure and for experimental purposes (for other, different but similar optimization problems solving) we put the constraint for the technological price C_T of the desired concentrate contents

Table 1

Concen-trates (in [%])	Charge 1 **Price 543.55**	Charge 2 **Price 549.61**	Charge 3 **Price 558.03**	Charge 4 **Price 560.00**	Charge 5 **Price 559.25**	Charge 6 **Price 558.03**	Charge 7 **Price 560.00**	Charge 8 **Price 557.86**	Charge 9 **Price 558.03**
ZC17-1	12.35		5			5	10.56		5
ZC17-2	12.26	12	15	11.53	15	15	11.95	14	15
ZC17-3								1	
ZC17-4	20.08	17	35	32.32	31	35	29.00	25	35
ZC17-5	7.91	3	5	0.99	1	5	5.25	2	5
ZC17-6	14.84	18	35	1.08	16	35	19.56	23	35
ZC17-7									
ZC17-8									
ZC17-9	6.53	3		16.64	1		8.09	1	
ZC17-10					3				
ZC17-11									
ZC17-12	18.91	17		0.25			9.86	11	
ZC17-13		5		2.45	5			5	
ZC17-14					4				
ZC17-15									
ZC17-16		15	5	30.05	15	5		10	5
ZC17-17		1			2			1	
ZC17-18	1.94	3		4.69	2		3.28	2	
ZC17-19		4							
ZC17-20	4.15	2			3		2.08	4	
ZC17-21	1.04				2		0.38	1	

(following the above rule, and in the present example: not more than 600\$/t, marked by $*$ at the last row of the second column of Table 2) keeping in mind the current *Zn* LME price of 1880\$/t. The LME is a parameter that automatically produces changes in the technological prices of the different concentrate components. We have found out that such mixture exists and this price boundary condition is not producing an unfeasible problem.

The obtained concentrate is of technological price $C_T = 543.55$ \$/t. The percentage distribution of the different components is given in column "Charge 1" of Table 1, and the chemical contents in column "Charge 1" of Table 2.

This solution is a theoretical one and is aiming minimal expected price, but it is not practically applicable because the concentrate building is based on an imperfect transport mechanism ("clamshell excavator") that could make a limited (by means of equal volume size) grabs from the different silos that store the charges. That is why it is practically impossible to build a concentrate with fractional components, e.g. 12.35%, from the first component, 12.26% from the second one, etc.

So, an integer optimization problem has to be solved for the different charge components producing the desired concentrate that have to be of integer type. The resulting solution is of technological price $C_T = 549.61$ \$/t (that is greater than the previous, fractional one, because of this new boundary condition). The quantity of the different charge components is given in column "Charge 2" of Table 1, and its chemical contents in "Charge 2" column of Table 2.

The resulting new solution is practically applicable if the concentrate is built with 100 grabs of the "clamshell excavator" (putting together each grab to one percentage from the concentrate).

This unfortunately is also not always possible taking into account the continuous production process.

So, we tried to find a solution that allows concentrate charges to be aliquot to five, producing in this way the desired ones with twenty grabs (which sounds more applicable in practice).

For this task solving we used twenty-one new, integer variables y_j, putting $x_j = 5y_j$ $(j = 1, 2, \ldots, 21)$. The different concentrates share in the resulting solution is given in column "Charge 3" of Table 1 and its chemical structure in column "Charge 3"of Table 2. The new calculated technological price is: $C_T = 558.03$ \$/t.

As it is clear from the solutions of these three problems that the resulting technological price C_T oscillates in-between 543 \$/t and 558 \$/t. We have to pay attention that the resulting difference is not quite big (less than 3% from the

Table 2

Compo-nents	***Bound***	**Minimal price**			***Bound***	**Minimal Pb + Cu + SiO_2**			***Bound***	**Minimal Fe**		
		Charge 1	Charge 2	Charge 3		Charge 4	Charge 5	Charge 6		Charge 7	Charge 8	Charge 9
Zn	**50**	52.584	52.901	53.305	**50**	53.610	53.486	53.305	**50**	53.522	53.350	53.305
S_{tot}	**31**	31.000	31.081	32.130	**31**	31.506	31.120	32.130	**31**	31.000	31.151	32.130
Pb	**2.5**	2.000	1.922	1.951	**2.5**	1.104	1.819	1.951	**2.5**	1.900	1.973	1.951
Cu	**1**	1.000	0.999	0.998	**1**	1.000	0.997	0.998	**1**	1.000	0.999	0.998
SiO_2	**2.3**	2.300	2.295	2.199	**2.3**	2.300	2.065	2.199	**2.3**	2.300	2.211	2.199
Fe	**8**	8.000	7.992	7.984	**8**	8.000	7.992	7.984	**8***	7.640	7.817	7.984
Se	**20**	6.335	6.270	7.450	**20**	6.953	6.870	7.450	**20**	6.930	6.670	7.450
Hg	**10**	2.392	2.310	2.650	**10**	2.775	2.930	2.650	**10**	2.567	2.600	2.650
Cd	**0.3**	0.254	0.226	0.230	**0.3**	0.196	0.221	0.230	**0.3**	0.249	0.230	0.230
Ni	**15.1**	15.100	14.300	13.500	**15.1**	15.100	14.700	13.500	**15.1**	15.100	14.600	13.500
Co	**100**	69.493	65.540	71.500	**100**	40.916	73.460	71.500	**100**	67.376	73.480	71.500
As	**0.08**	0.064	0.065	0.040	**0.08**	0.064	0.064	0.040	**0.08**	0.064	0.065	0.040
Sb	**160**	159.208	142.310	156.300	**160**	159.000	158.800	156.300	**160**	159.104	154.920	156.300
Ge	**30**	4.792	4.900	5.000	**30**	5.000	4.850	5.000	**30**	4.896	4.800	5.000
Te	**20**	10.685	9.720	8.350	**20**	7.486	7.660	8.350	**20**	9.337	9.110	8.350
Pb + Cu	**3**	3.000	2.920	2.949	**3**	2.104	2.816	2.949	**3**	2.900	2.971	2.949
Pb + Cu + SiO_2	**5.5**	5.300	5.215	5.147	**5.5***	4.404	4.881	5.147	**5.2#**	5.200	5.182	5.147
Sb + Ge	**164**	164.000	147.210	161.300	**164**	164.000	163.650	161.300	**164**	164.000	159.720	161.300
Sb + Ge + As	**808**	808.000	799.510	562.800	**808**	808.000	799.950	562.800	**808**	808.000	806.920	562.800
Mn	**0.45**	0.230	0.228	0.162	**0.45**	0.102	0.201	0.162	**0.45**	0.184	0.218	0.162
CaO	**0.8**	0.531	0.473	0.377	**0.8**	0.239	0.412	0.377	**0.8**	0.434	0.475	0.377
MgO	**0.3**	0.180	0.185	0.167	**0.3**	0.122	0.141	0.167	**0.3**	0.164	0.172	0.167
Al_2O_3	**0.5**	0.386	0.371	0.270	**0.5**	0.185	0.272	0.270	**0.5**	0.311	0.348	0.270
Cl	**0.08**	0.080	0.074	0.013	**0.08**	0.080	0.073	0.013	**0.08**	0.080	0.080	0.013
F	**0.02**	0.010	0.008	0.005	**0.02**	0.005	0.008	0.005	**0.02**	0.007	0.008	0.005
Tl	**0.005**	0.002	0.001	0.002	**0.005**	0.001	0.001	0.002	**0.005**	0.002	0.001	0.002
Price	**600***	543.554	549.608	558.027	**560#**	560.000	559.252	558.027	**560#**	560.000	557.863	558.027

price).

Thus, we posted another optimization goal: "To find concentrate with technological price $C_T \leq 560$ \$/t (the bound is marked by $*$ in Table 2), taking a new boundary condition: minimize $\sum Pb + Cu + SiO_2 \leq 5.5\%$ from the used concentrate mixture (this condition is marked by $*$ in Table 2).

The idea is to keep a reasonable C_T and at the same time to diminish the negative influence of the above mentioned chemical substances. This problem was chosen, because the contents of "$Pb + Cu + SiO_2$" has a negative influence on the concentrate further roasting process and thus should be minimized.

So, we have solved three new integer continuous optimization problems (similar to the already posted above, i.e. aliquot to five) with a new optimization function goal: to minimize the percentage of this components' sum in the concentrate.

The resulting concentrates shares in the different charges are given in columns "Charge 4", "Charge 5" and "Charge 6"of Table 1, and their chemical components – in columns "Charge 4", "Charge 5" and "Charge 6" of Table 2. This generates the percentages of the concentrate negative components to be optimized from 5.3 % to 4.4% in the real optimization case and from 5.2% to 4.9% in the integer one, keeping the same results when the boundary condition for grabs aliquot to five is posted.

Another chemical element that has a negative influence to the *Zn* production process is the *Fe* presence. So we posted the following: minimize the *Fe* content and keeping $C_T \leq 560$ \$/t (the bound is marked by # in Table 2) for $\sum Pb + Cu + SiO_2 \leq 5.2\%$ from the used concentrate mixture. The bounds are marked by $*$ (for "*Fe*") and by # (for "$Pb + Cu + SiO_2$") in Table 2.

Three more similar to the already described optimization problems have been solved and the resulting solutions are given in columns "Charge 7", "Charge 8" and "Charge 9" of Table 1 and Table 2.

A minimal *Fe* discount is noticed for the first two cases, whilst the third (for grabbing aliquot to five) produced no visible changes.

It was also noted that the fourth concentrate, ZC17-4, is used in all of the above mentioned results, but the eight one, ZC17-8, is not.

Further, we have solved three new optimization tasks, limiting the fourth concentrate from above (ZC17-4 $\leq 30\%$) and the eight concentrate from below (ZC17-8 $\geq 5\%$) in order to include it in the resulting concentrate. We do not give the solution details for these three problems. We mark only the results: the real optimization gives $C_T = 548.83$ \$/t, the integer optimization gives $C_T \leq 553.41$ \$/t, and the third one, that uses an integer optimization with grabbing aliquot to five, has not a feasible solution.

Conclusions

By using the proposed methodology the technologists can be oriented on the possible combination of the different concentrates. The consistent application of this methodology can provide an acceptable as chemical composition and technologically feasible in the real production process charge, which is optimal under well-defined criteria and constraints.

References

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