COST EVALUATION OF LIQUID METAL PRODUCTION IN ELECTRIC FURNACES – METHODOLOGY DEVELOPMENT

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1 INTRODUCTION

At present the uniform methodology that focuses on possibilities of cost reduction in liquid metal production is being developed, so called “technical and economic analysis”. The methodology builds on earlier works in this area almost since the sixties of twentieth century. The aim of the article is to familiarize professional public with development and application of the method that focuses especially on determination, monitoring and evaluation of cost and chosen technological characteristics in liquid metal production in electric furnaces (EAF, EIF). The method should be a tool for uncovering of cost reserves, possible savings and their analysis in partial periods of liquid metal production. The applied production process is being considered in order to find a way to costs reduction and at the same time preserving all of the functions. To assess a liquid metal production method are used especially the tools of statistical analysis. Individual phases of the “technical and economic analysis” are in detail described in the following paragraphs of the article.

2 TECHNICAL AND ECONOMIC ANALYSIS [1]

Technical and economic analysis is realized in nine basic steps. Procedure of the analysis is as follows:

1. Introductory analysis;
2. Decision on the subject of investigation (number of melts, steel grade, type of furnace etc.);
3. Data collection from the melting papers into electronic form;
4. Cost model development;
5. Division of the cost evaluated melts into partial selective complexes according to:
   a. melters;
   b. furnaces;
   c. working shifts;
   d. days per week;
   e. etc.
6. Statistical analysis:
   a. testing for outliers;
   b. testing for normality;
   c. calculation of the basic statistical characteristics;
   d. graphical evaluation;
e. assessing of the statistical significance of differences between mean values;
f. choosing and calculation of the statistical dependencies.

7. Evaluation of the technical and economic analysis results;
8. Proposal of the next procedure;
9. Conclusion of the technical and economic analysis.

2.1 Introductory analysis

The first step of the analysis, so called introductory analysis, predates technical and economic analysis in full range (in the above mentioned nine steps). Introductory analysis serves as a tool for an opening look into foundry that indicates on which areas we should focus on. Introductory analysis is in foundries realized in a smaller number of melts (30 – 40). On the basis of results of introductory analysis, foundries decide whether they should perform the technical and economic analysis in bigger number of melts (200 – 300) focusing on concrete areas of liquid metal production (to refine the results of the introductory analysis).

2.2 Decision of the subject of investigation

At the beginning of technical and economic analysis (step 2 – 9) foundry chooses, what the subject of its investigation will be. Submission of technical and economic analysis usually results from conclusions of the introductory analysis. Foundries usually choose:

a) furnace (EAF or EIF);

b) grade of liquid metal (steel or cast iron of specific grade);

c) number of evaluated melts (usually 200 – 300 melts);

d) other criteria results from concrete conditions in the foundry.

In dependence on number of evaluated melts, tasks and possibilities of the foundry, way of separation into partial selective complexes is decided as a next step. Foundry usually divides melts into partial selective complex according to:

$\S$ melters (for findings, if economical or technological differences exist between melters);

$\S$ furnaces (for findings, what furnace is economically or technologically more favourable);

$\S$ work shifts (for findings, if economical or technological differences exist between morning, afternoon or night shift);

$\S$ number of charging baskets (for findings, if it is economically or technologically more favourable to charge by one or two charging baskets);

$\S$ other criteria (sequence of melts on the work shift, days per week etc.).

After the division of subject of investigation, data collection from the melting papers into electronic form follows.

2.3 Data collection from the melting papers into electronic form
When collection data we are starting from partial melting papers, given to us by liquid metal producer. Transcription of the date from melting papers is usually made by representatives of the foundry. In case that foundry or steel works have not any melting papers (these cases are known too), required items from melting papers are continuously filled into electronic form directly in the melting house.

From the melting papers, we usually collect:

a) Weight of metal charge and its partial items (components) [kg/melt];

b) Weight of metallic and non-metallic ingredients and its partial items [kg/melt];

c) Electric energy consumption [kWh/melt];

d) Weight of liquid metal [kg/melt];

e) Time of partial period of melt [min/melt];

f) Number of conducted operations (temperature measuring within meltage, liquid metal analysis within meltage, etc.) [-];

g) Liquid metal temperature (last temperature measured in the furnace, temperature into ladle furnace after cast of liquid metal) [°C];

h) Liquid metal analysis [in % of evaluated chemical elements].

Of course, we know basic information about furnace (EAF, EIF), steel grade, date and time of meltage, work shift and melters. Except for the above data, we need information about prices of used items (components) and energies.

After the data collection cost model development follows.

2.4 Cost model development [2]

Cost model is based on the incomplete working cost (IWC) calculation. I.e. cost model takes into account only those costs directly related to the production of liquid metal and the manufacturing centre directly impressible. Cost model excludes e.g. halls lighting, depreciations, overhead administrative expense, etc. Costs are always set to a calculation unit (for example tonne of liquid metal, etc.). Due the mentioned model, individual melts are costly evaluated (using data obtained from the melting papers and prices of used items /components/ and energies). Calculations of partial items of the cost model are for example mentioned in [3].

Cost model of IWC of liquid metal production usually has this form:

A) MATERIAL COSTS:
   - Metal charge costs;
   - Metallic and non-metallic ingredients costs;

B) COST OF PROCESSING:
   - Energy used for melting (e.g. electric energy, gas, oxygen, argon etc.);
   - Cost in proportion of melting time (personal cost, furnace lining cost etc.);
   - Other cost of processing (measuring of liquid metal temperature etc.).

INCOMPLETE WORKING COSTS OF LIQUID METAL PRODUCTION

In next steps we work on a fact that IWC of liquid metal are divided in two main groups - material costs and costs of processing. In the context of the material costs, the ones of the metal charge and ingredients (metallic and non-metallic) are considered. Within processing costs we evaluate costs of melting energy (e.g. electric energy), costs in proportion of meltage time...
(personal costs, lining costs, costs of graphite electrodes etc.). In the next step, we evaluate other processing costs (costs of liquid metal temperature measurement, cost of metal analysis etc.). In this way, for example, we find out what are the IWC of concrete steel grade production. What proportion of these costs consists of metal charge, metallic ingredients, electricity etc. From this information we obtain a detailed overview of the costs performance of each melt.

On the basis of tasks of the foundry (result from the introductory analysis and subject of investigation), custom cost model is developed. *Cost model is connected with electronic form described in chapter 2.3.* All costs and technological indicators are calculated in the spreadsheet program Excel.

So we can say that *the programmed model works as follows:*

- a) in the first sheet of the Excel (electronic form) are data from the melting paper filled;
- b) in the second sheet of the Excel (cost model) are all items of cost model automatically calculated;

*Main advantages of the programmed model are:*

- a) automatic calculation of costs and selected technological indicators save work and time;
- b) using computers, programmed model allows continuously monitoring and evaluation of costs, directly at a melting house.

After the calculation of all costs of liquid metal production, division of the cost evaluated melts into partial selective complexes follow.

### 2.5 Division of the cost evaluated melts into partial selective complexes

To perform *statistical analysis*, it is necessary to *divide the individual cost evaluated melts to partial selective complexes*. The selective complexes should always be compared under strictly comparable conditions. We have the means, e.g. comparison of IWC expended on liquid metal production of melter A (working on the furnace EAF1, night shift, charging at one charging basket) with a IWC expended on liquid metal production of melter B (working on the EAF1, night shift, charging at one charging basket) [2].

It means that the selective complexes evaluated by melters should be:

- § melted on the same furnace;
- § melted the same grade of liquid metal;
- § melted at the same work shift (e.g. only night shift);
- § charging by same number of charging baskets;
- § etc.

At the same time, we should pay heed to fact that for each selective complex was available at least 20 - 30 values (that the results of statistical analysis were meaningful).

An example of the comparison of two partial selective complexes of melts under strictly compared conditions is introduced at fig. 1.
Criteria, by which it is possible to compare evaluated melts in foundries, are of a wide range. Selection of significant criteria is up to representatives of the foundry and specialists in the field of metallurgy and energy. The statistical analysis follows.

### 2.6 Statistical analysis

Within the technical and economic analysis, **statistical analysis is performed at six basic steps**. While performing the statistical analysis, statistical software is used.

#### 2.6.1 Testing for outliers

As it was stated above, **testing for outliers** within technical and economic analysis we use a box diagram, so called **boxplot**. It states whether within a compared group there is one, which significantly differs from the others. In case of finding such melts, these outliers are excluded from the complex in order to statistically evaluate them further, so that the results of statistical analysis are not distorted. After outliers identification, the causes of these outliers are searched.

We can find the following values from the boxplot:

- minimal value of the complex – $X_{min}$;
- maximal value of the complex – $X_{max}$;
- first quartile – $Q_1$ … (25% of evaluated values of the complex is lower or equal this value);
- third quartile – $Q_3$ … (75% of evaluated values of the complex is lower or equal this value);
- median – $Me$ … (50% of evaluated values of the complex is lower or equal this value).

After testing the outliers, the normality test is relised.

#### 2.6.2 Testing for normality

When testing we consider, whether the division of the selective complex is normal (caused by the Gaussian curve). For hypothesis testing, we choose either Ryan – Joiner test (used for small complexes $3 \leq n \leq 50$), or Anderson – Darling test (meant for larger complexes in number).

In statistical softwares, p-value is a criterion for assessing, whether the tested data are normally divided or not. If then:
\( p \leq 0.05 \Rightarrow \text{data have not a normal distribution}; \)
\( p > 0.05 \Rightarrow \text{data have a normal distribution}. \)

The decision on the normality of the tested data is necessary for the further steps in statistical evaluation. In case the data are:

- **Normally distributed** – when evaluating the mean values we work with the arithmetic means
- **Not normally distributed** – when evaluating the mean values we work with the medians.

After assessing, whether the tested complex has a normal distribution, the third step of the analysis follows, i.e. the calculation of the basic statistical characteristics.

### 2.6.3 Calculation of the basic statistical characteristics

When we exclude the outliers and test for the normality, the basic statistical characteristics are calculated.

Within the technical and economic analysis we set these characteristics:

- **a)** **Minimal and maximal value of the selective complexes;**
- **b)** **Mean values:**
  - \( \text{arithmetic mean}; \)
  - \( \text{median}. \)
- **c)** **Variability indexes:**
  - \( \text{dispersion (variance)}; \)
  - \( \text{standard deviation}; \)
  - \( \text{range}; \)
  - \( \text{variation coefficient}. \)
- **d)** **Upper and lower value of confidence intervals of the mean.**

The individual selective complexes are via these characteristics compared in detail.

The basic statistical characteristics are also accompanied with in-depth graphical evaluation, which is described in the following chapter.

### 2.6.4 Graphical evaluation

The melting selective complexes are evaluated graphically as well, via:

- **a)** **Boxplots** (chapter 2.6.1);
- **b)** **Frequency histogram**;
- **c)** **Confidence intervals of mean.**

*Frequency histograms we use to make it easier for us to compare the distribution of the data in the selected complex.* In our case we consider the distribution of the meltings evaluated by the incomplete working costs calculation both for melter A (Fig. 2a) and melter B (Fig. 2b).
From the figure 2a it is obvious that the meltings of the melter A range from 12 500 CZK/t to 16 000 CZK/t. The majority of melter A’s meltings is evaluated for 14 000 CZK/t. The melter A, over the melter B, has one of the meltings situated in the left hand part of the frequency histogram - 12 500 CZK/t.

Melter B’s meltings are placed within the interval of 13 000 – 16 000 CZK/t, with one “more expensive” in the right hand part of the histogram amounting to 17 000 CZK/t. Most of the melter B’s meltings (13) are evaluated similarly for 14 000 CZK/t.

Another used graphical tool is the confidence intervals of arithmetic means (Fig.3).

**Fig. 3:** Confidence intervals of arithmetic means of melter A and melter B

By these confidence intervals we find out which intervals would the IWC of production of this steel range with the probability of 95 per cent by the melter A and B. All of this is under a condition that from the basic selective melting complex for the analysis by random selection of we would use a different selective X melting complex.

In the following chapter it is assessed, whether the obtained differences within the mean values of both melting complexes are significant.

2.6.5 Assessing of the statistical significance of differences between mean values

Thanks to using the above mentioned statistical characteristics, we are able to compare the individual selective complexes. The emphasis is put on the differences between mean values of the compared complexes and their variability. From the common practice we know the cases in which the average costs of selective complexes are compared. The obtained result reaches for example the amount of 300 CZK/t of molten metal. However, by this kind of statement, the evaluation very often ends. This procedure is not really ideal and moreover, it can be misleading.
Within the technical and economic analysis we use the hypotheses testing in order to evaluate the significance of difference between the mean values, by the following two tests:

a) **Two sample t-test** (comparing arithmetic means – in case of normal data distribution);

b) **Wilcoxon test** (comparing medians – in case that selective complex has not a normal distribution).

The evaluating criterion leading to decision whether the tested variance is significant is the p-value. If:

- $p \leq 0.05 \Rightarrow$ between mean values there is statistically significant difference;
- $p > 0.05 \Rightarrow$ between mean values there is no statistically significant difference.

Only on the basis of the above mentioned results, we can state whether there is or is not statistically significant result (i.e. the one, which is not caused by a coincidence – high changeability).

If the statistically significant difference was found among the compared complexes, the impulse to deal with this specific situation is urged. The causes of the found difference we search in the individual parts of calculation model. First, the material costs are analysed in detail and then the processing costs. We keep the same procedure, even if there were no differences within the selective complexes found – just to be sure.

The last step of the statistical analysis is finding the correlation within the selective indicators (changeable).

### 2.6.6 Choosing and calculation of the statistical dependencies

**Within the technical and economic analysis the dependencies are also considered among the selected costs and natural indicators.**

**Criteria for decision of the dependence among the compared indicators are:**

a) **Correlation coefficient R** – if:

- $R = 1(-1) /near 1 (-1)/ \Rightarrow$ there is a significant dependence among compared indicators;
- $R = 0 /near 0/ \Rightarrow$ there is a insignificant or zero dependence among compared indicators.

b) **P-value** – if:

- $p \leq 0.05 \Rightarrow$ there is a dependence among compared indicators;
- $p > 0.05 \Rightarrow$ there is no dependence among compared indicators.

On executing all the mention steps, the conclusion and evaluation of the results follow.

### 2.7 Evaluation of the technical and economic analysis results

**In the first step of evaluation we compare all findings detected within technical and economic analysis.** For example:

- basic statistical characteristics (described in chapter 2.6.3);
- graphical evaluation (chapter 2.6.4);
- statistical significance of difference between mean values (chapter 2.6.5);
- statistical dependencies (chapter 2.6.6).

**In the next step of evaluation we are looking for causes of the findings:**
If the difference among selective complexes is found in the incomplete working cost of liquid metal production (which is the first criterion we are evaluation), we look for the cause:

a) First, we search the material costs (the individual components of charges and ingredients);
b) Then, we search within the group of processing costs (costs of graphite electrodes, personal costs, costs of furnace lining, costs of liquid metal temperature measurement, cost of liquid metal analysis)

The particular procedure of evaluating costs (using the p-value) is described by diagram issued e. g. in [4].

The procedure is lead till setting the concrete problems that are necessary to deal with. For example:

 § optimalization of the composition of metal charge and metallic ingredients;
 § assessment of the influence of various energetic regimes;
 § optimalization of the working regimes;
 § ensuring of standardization of the course of melt;
 § etc.

2.8 Proposal of the next procedure

After the performing of technical and economic analysis in full range all findings are concentrated and we are often trying (with specialists in the field of metallurgy, energy and refractory materials) to specify targeted recommendations that will bring the costs effect into foundry.

2.9 Conclusion of the technical and economic analysis

Technical and economic analysis is concluded by final report in which all the significant findings are in detail described, which were in the analysis detected. Final report also contains proposal and recommendations how the detected problems eliminate and by elimination contribute to costs reduction in foundries.

3 CONCLUSION

Submitted article focuses especially on particular phases of statistical evaluation of cost and selected natural indicators and following decision steps by using the method of technical and economic analysis.

The main aim of the method of technical and economic analysis is to develop a very effective tool for searching of the source of savings and other reserves (cost, technological) in foundries and steelworks. The method should lead directly to mark the source of savings and to quantification of possible benefit.

We can conclude that in 2008 technical and economic analysis in KRÁLOVOPOLSKÁ SLÉVÁRNA, Ltd was finished. During 2008 – 2009, so called introductory analysis were in six foundries performed. Technical and economic analysis at full range is at present realised in foundry DSB EURO, Ltd.
LITERATURE:


[4] www.metalurgie-ekonomika.wz.cz/index3.htm, 10. 4. 2010, 10:00 (to browsing the algorithm it is necessary to have installed a PDF browser, e.g. Acrobat Reader).