PROCESS OPTIMIZATION IN METALLURGY BASED ON TECHNOLOGICAL MAPS

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1   INTRODUCTION

It is a fundamental property of every process, including a technological one, that one or more outputs are attached to it, with the outputs being influenced or regulated by inputs. A target or optimal value is set for each of the outputs, and tolerances are defined for controllable inputs. The inputs can be adjusted within their defined tolerance. The usual objective is to make such adjustments to the inputs that the process outputs are as close as possible to their target values. There are many methods that try to determine process input settings. However, some of the inputs must fairly often be changed for different reasons when the process is still running, which results in the optimal state of the process being interrupted. In this paper, we describe how to determine an optimal region for the regulation of inputs in metallurgy, the region being called a process regulation map. This map provides one with enough room for process regulation. If the regulation is done within the optimal region, a change in the settings of the process inputs will not affect the optimal state of the process. To find the map, we shall use the Design Expert software.

To find the regulation map, the following steps will be taken and discussed:

1. Process outputs $Y1, ... , Ym$ to be monitored are defined.

2. Inputs $A, B, C, ... $, which might affect the defined outputs, are selected.

3. Effects of the selected inputs are evaluated.

4. Regression-based relation(s) between output(s) and the influential inputs are found.

5. Contour graphs are identified by making cuts through the surface of the regression functions.

6. The optimal region in each contour graph is detected.

7. The regulation map is obtained by intersecting the individual optimal regions.

To describe the steps above in a greater detail, we shall exploit the design of experiments theory (Myers, Montgomery and Anderson-Cook, 2009) which suits our needs best in the context of metallurgy. Another example of using the theory in metallurgy can be found in (Raszka, 2001). Design of experiments is based on the principle that the nature of a process can be learnt well by observing how the process outputs react to different settings of the process inputs. Changes made to the inputs are performed schematically, the scheme being prescribed by an experimental plan. Such a plan is set up with the inputs being observed only at two levels – an upper level, denoted *+1*, and a lower level, denoted *-1*. Let us note in this context that there are other approaches to process analysis, as well, including those that are based on simulations (Zgodavova and Bober, 2012) or those that focus primarily on handling the problem of noise occurence in a process (Tošenovský, Tošenovský and Kudělka, 2013).

2 DEFINITION OF OUTPUTS AND CONTROLLABLE INPUTS

To make the ideas more concrete, we shall work with a specific output Y of a metallurgical process, which is going to be the number of castings fabricated by the technique of continuous casting implemented at a steelmill. Apart from this variable, we shall also be preoccupied with the process variability S^2 as an output since it is recommended that the process be stable, i.e. its variance be minimal. As far as the potentially influential inputs are concerned, we consider the following factors: casting speed (m/minute), steel overheating (°C), amount of castings on the catalytic converter (tons), casting streams (internal, external) and steel brand.

To find effects of the inputs on the outputs, an experimental plan is to be created. Normally, when five inputs are considered as in our case, $2^5 = 32$ possible settings of the two-level inputs exist in the full experimental plan, i.e. *32* possible scenarios or runs to launch the process. However, when a full plan is to be carried out, there is usually the problem that engineers supervising the process do not allow all the runs of the plan to be performed. The reason for that might be the fact that such a procedure could be too costly, it could last too long or, as is often the case, the engineers know beforehand that some of the runs are certain to lead to unsuccessful experimental results, or may even damage the production. Therefore, an experimental plan is often reduced in terms of how many of its runs are actually realized. Neither in our case was the process of steel casting carried out *32* times. The experimental plan which was actually realized is shown in Table 1. Table 2 presents then the explanation of the coded variables used to denote the levels of the inputs. The results of such an experiment can usually be obtained since everything about the factory process in question is monitored and documented by the factory itself for its own further reference.

Table 1 shows that in the first run, for instance, all the inputs were set at their lower level, coded *-1*. The resulting average output was $Y_1 = 158.5$ castings. Since the corresponding variability S^2 differs substantially from one run to another, it is recommended for practical reasons that its logarithmic transformation $log\ S^2$ be used instead to describe the variability. Therefore, this characteristic was also calculated.

Table 1 – Partial experimental plan

Run i	A	B	C	D	E	Y_i	S^2	$logS^2$
1	-1	-1	-1	-1	-1	158.5	84.5	1.926857
2	1	-1	-1	-1	-1	54.5	40.5	1.607455
3	-1	1	-1	-1	-1	135	242	2.383815
4	1	1	-1	-1	-1	158.5	312.5	2.49485
5	-1	-1	1	-1	-1	124.5	40.5	1.607455
6	1	-1	1	-1	-1	53.5	364.5	2.561698
7	-1	1	1	-1	-1	59.0	2.0	0.30103
8	1	1	1	-1	-1	57.5	12.5	1.09691
9	-1	-1	-1	1	-1	180.5	0.5	-0.30103
10	1	-1	-1	1	-1	140	1458	3.163758

Table 2 - Process factor levels used

Factor	Symbol	Level *-1* of the factor	Level *+1* of the factor
Casting speed	A	[4.1, 4.5)	[4.5, 4.9)
Steel overheating	B	≤ 40	> 40
Amount of castings	C	≤ 7500	> 7500
Casting streams	D	1, 8, 5, 4	2, 3, 6, 7
Steel Brand	E	Type 1	Type 2

3   EVALUATION OF INPUTS

Effects the inputs have on the output *Y* are shown in Table 3. Effect of a factor equals the average change in the output *Y* caused by shifting the level of that factor from its lower level to its upper level. For instance, a negative sign of an effect means the level of the output dropped in average when the level of the corresponding factor changed from *-1* to *+1*. To calculate these effects, it is imperative that all variables in question are properly measured, otherwise distortions transferred from one mathematical step to another in this analysis can accumulate, resulting in false conclusions (Zgodavova, 2010).

Table 3 - Evaluation of factor effects

Factor	Effect	Sum of Squares	P-value of Effect	Contribution (%)
A	-13.94	1554.03		2.483
B	**23.44**	**4394.53**	**0.036**	**7.022**
C	**-39.13**	**12246.13**	**0.001**	**19.568**
D	-1.13	10.12		0.016
E	**-40.63**	**13203.13**	**0.000**	**21.097**
AB	12.94	1339.03		2.139
AC	-4.75	180.50		0.288
AD	-5.00	200.00		0.319
AE	13.13	1378.13		2.202
BC	-1.88	28.13		0.045
BD	-2.00	32.00		0.051
BE	**25.00**	**5000.00**	**0.003**	**7.989**
CD	8.44	569.53		0.910
CE	**23.31**	**4347.78**	**0.037**	**6.947**

Table 3 includes a so-called *contribution*, i.e. the share by which a factor contributes to the change of *Y*. This characteristic might even be more eloquent than the effect itself. It is clear from the table that more factors are influential, but the factors *C, E* are the most influential ones. These two inputs therefore represent the core of our analysis. The third column of table 3 shows the sum of squares which is can be calculated for any regression model, and is used for the calculation of the *contribution*. The p-value in the fourth column of the table results from testing the factors. If *p < 0.05*, the corresponding factor is significant, the nivel of the test being five per cent. The table contains only the p-values of the significant factors and interactions.

4   REGRESSION MODELS

In the fourth step of our procedure, the following regression model was found for the output *Y* (its graph is depicted in Figure 1).

$$Y = 82.4 + 11.7B - 19.6C - 20.3E + 12.5BE + 11.7CE \tag{1}$$

Table 3 showed that factors *C* and *E* were the most influential. The other factors are set at the levels depicted by the legend of Figure 1. The levels are coded: *A = B = D = 0*, which denotes the center of the tolerance intervals required for the factors. Figure 1 depicts equation (1) and sections along the *E-C* plane (the contour graphs).
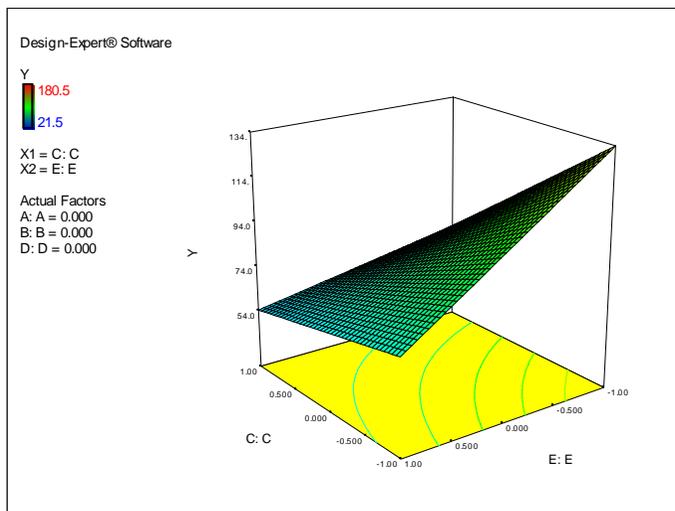
Figure 1 – 3D graph of the output Y and the contour graphs of Y for model (Myers, Montgomery and Anderson-Cook, 2009)

Basic characteristics related to this model are shown in Table 4. The characteristics include the sample standard deviation and the sample mean of *Y*, the coefficient of variation C.V., three types of correlations and the PRESS characteristic assessing the presence of influential points.

Table 4 – Characteristics for model (Myers, Montgomery and Anderson-Cook, 2009)

Std. Dev.	29.99	R-Squared	0.63
Mean	82.41	Adj R-Squared	0.55
C.V. (%)	36.39	Pred R-Squared	0.43
PRESS	35432.76	Adeq Precision	8.07

The contour graph contains, just like a geographical map, lines which link the points in the domain of the function that give the same value of the output *Y*.

A second regression model was also found for $logS^2$. It takes the form (its graph is in Figure 2).

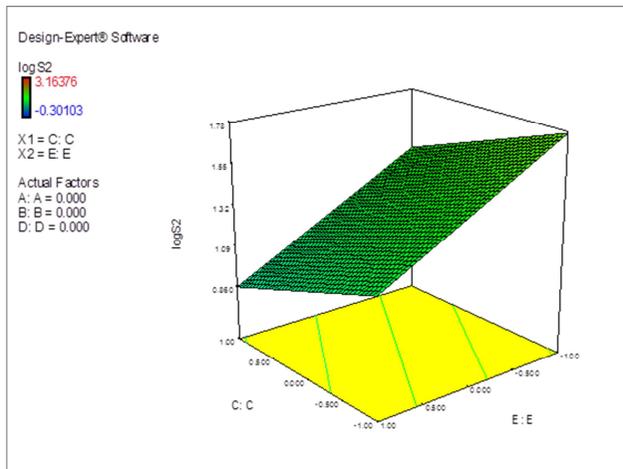$$logS^2 = 1.32 - 0.171C - 0.284E - 0.369AE - 0.281BC \qquad (2)$$

Figure 2 – Variability logS^2 of the output, as a function of the factors E and C

5 PROCESS MAP

The last step in our construction of the regulation map is the intersection of the contour graphs of *Y* and *log S^2*. To do so, we need to set limits for *Y* and *logS^2*. Let us set, for instance, the following limits: $65 \leq Y \leq 180$ and $-0.3 \leq log\ S^2 \leq 1.20$. Levels of the other individual factors *A*, *B* and *C* are set to zero again. Figure 3, the final graph generated by the Design Expert software, depicts the region of the optimal process regulation. In this region, both *Y* and *log S^2* are close to their required specification.
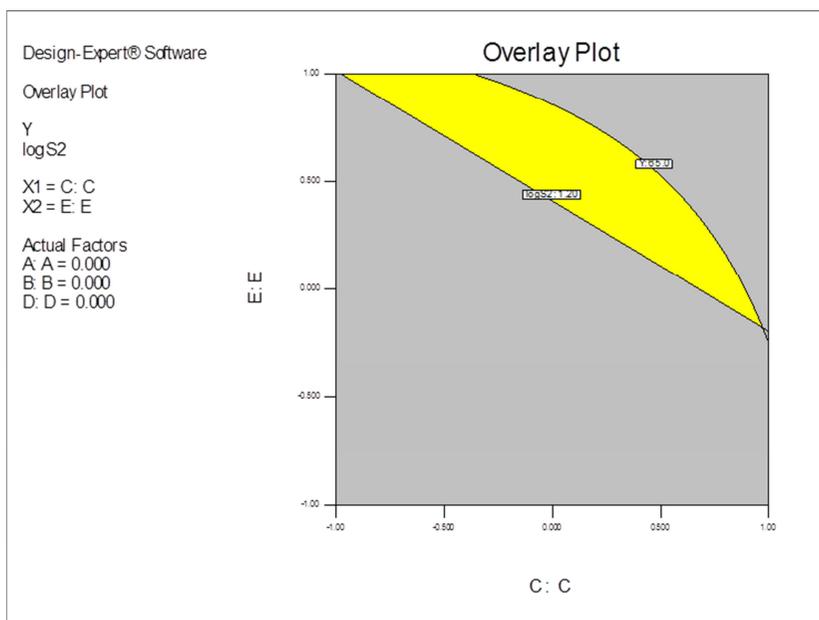

Figure 3 – Area of regulation for optimal Y and minimal logS^2, B = 0

When the specification for *Y* and *log S*^{2} does not change, but *B* is at its lower level *-1* (see Fig. 4), the regulation region changes completely. Therefore, it is necessary to weigh the setting of all the inputs. The settings are often defined by requirements of engineers.
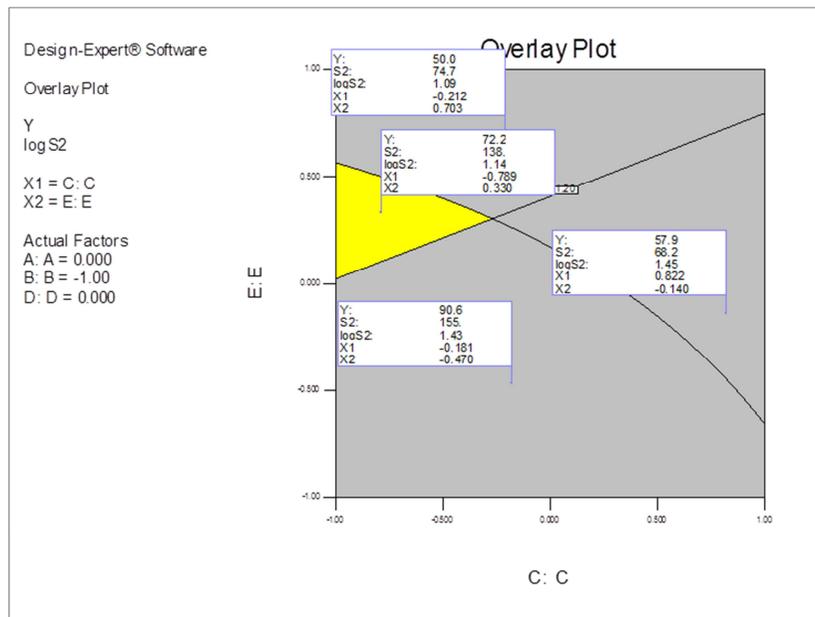

Figure 4 – Variability log S2 of the output, as a function of the factors E and C

Figure 4 contains flags with information about the settings of the inputs (*X1 = C, X2 = E*) and the corresponding outputs *Y*, *S*^{2} and *log S*^{2}. Such flags can be erected at any spot in the map. Contour lines may also be attached to the graph.

6   CONCLUSION

The methodology just described may be used even for a greater number of outputs, so that the intersection of optimal regions serves as the area for the best possible process regulation with respect to all monitored characteristics. These characteristics (outputs) may include costs, as well. The calculation of the optimal region is more convenient for practical management than the commonly calculated optimal values of process inputs. Software packages calculating regulation regions are also enriched with characteristics that evaluate the acquired levels of outputs.

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