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EVOLUTION OF CHARGING PROGRAMS FOR OPTIMAL BURDEN DISTRIBUTION IN THE BLAST FURNACE

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Abstract

The burden distribution in the blast furnace affects the efficiency of the upper part of the process and is, therefore, associated with smoothness of operation, coke rate and productivity. A burden distribution model is applied in this work to evolve charging programs fulfilling a goal given by the designer by evolving (mainly) angles for the rotating chute. The charging program is based on a genetic algorithm. It is demonstrated that the method can make efficient progress in the complex search space, finally designing charging programs that produce distributions of ore and coke which closely fit the target patterns. The technique holds promise for application in the ironmaking industry for evolving novel charging programs.

Key words: burden distribution, genetic algorithm, blast furnace, ironmaking

1. INTRODUCTION

The blast furnace is the principal process unit in the primary steelmaking process (Omori, 1987). It acts as a shaft-like countercurrent heat exchanger and chemical reactor and produces molten ("pig") iron which is converted to steel in the downstream processes of the steel plant. The furnace is charged with agglomerated iron ore (sinter or pellets) and coke and supplied with hot (possibly oxygen-enriched) air, blast. The oxygen in the blast reacts with coke in the lower part of the process and produces a hot gas that on its ascent heats, reduces and melts the descending ores.

The gas distribution in a blast furnace is very important parameter for the operation of the process. Control of gas distribution can mainly be achieved by adjusting the ratio of ore and coke and the particle size along the radius of the furnace. This is realized by selecting an appropriate *charging program*, which consists of a sequence of (typically 5-20) dumps of burden that is repetitively charged. Most of the charging programs used are the result of experience and some empirical knowledge. However, as every dump can be charged at about ten different discrete radial positions, there are a huge number of potential combinations to evaluate in a charging program. As the potential alternatives may exceed a million, it is clearly impossible to carry out an exhaustive search through all combinations even with a mathematical model. This is one of the reasons why it is motivated to develop strategies for finding charging programs which can allow better control of the furnace.

The paper presents an approach, where a burden distribution model is used to evolve charging programs yielding a desired distribution of ore and coke along the furnace radius using genetic algorithms as an optimization tool. The method is demonstrated to provide an intelligent search that produces solutions

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that largely mimic the target patterns for the distributions. In this paper six different formulations are used, and the ways in which the evolutionary algorithm evolves the chute positions in the charging program are illustrated.

2. BURDEN DISTRIBUTION MODEL

A two-dimensional burden distribution model was developed simulating the charging and the descent of burden in the upper part of a blast furnace. The simplified model can simulate the general behavior of layer formation and descent in blast furnaces with bell-less top charging. The layer formation depends on the furnace dimensions, chute angle, burden surface profile and material properties and their order.

2.1. Burden charging model

The charging model is based on earlier work (Saxén & Hinnelä, 2004; Mitra et al., 2012). With reference to figure 1, the material dump is discharged from the hopper to the downcomer to enter the chute, from where it falls freely and finally distributes on the bed surface. For the case of simplicity, angular symmetry in the cylindrical geometry was imposed, which makes the problem two-dimensional. Thus, for a certain dump, the chute is essentially fixed. The burden trajectory calculations were simplified with the assumption of point mass. In the simulation, the stock level (i.e., bed surface) at a particular radial position is measured and the hopper discharge starts when the stock descends below a limit. The dump falls from the hopper through the downcomer, hits the chute and loses all its velocity perpendicular to the chute. Thereafter it slides along the chute to fall on the burden surface.

Hattori et. al. (1993), Radhakrishnan and Ram (2001) and Xu et al. (2011) have developed similar models and considered various parameters like air-drag, size distribution and shape factors, but these were neglected in the present study to make the model simple and fast. Still, the evolution of the velocity along the chute can be adjusted by changing the value of the friction coefficient. The heap that is formed on the bed is described as a combination of two straight lines whose apex lies on the falling trajectory (cf. figure 1). For more details, the reader is referred to Saxén and Hinnelä (2004) and Mitra et al. (2012).

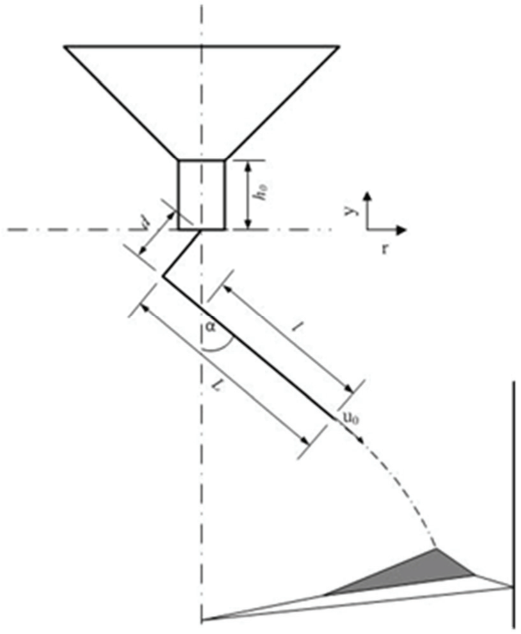

Fig. 1. Schematic of burden distribution model, where d, h_0, l, L are the dimensions of the system, α is the chute angle and u_0 the particle velocity after leaving the chute.

2.2. Burden descent model

The burden descent model is similar to the strategy applied by Park et al. (2011), where a method is developed to consider the effect of the widening shaft along with the descent of the layers. We assume that a layer maintains its basic shape as it descends along the throat and shaft of the furnace. It is assumed that no mixing takes place and there is negligible effect of the gas flow. The walls are assumed to be smooth so their effect on the layers is neglected. The main emphasis was put on ensuring that all the crucial points in the layers (intersection points, apexes) maintain their relative radial positions and that the layer keeps its volume throughout the descent. In addition, the relative thickness of a layer along the radius also remains the same throughout the descent. The descent of the individual points is

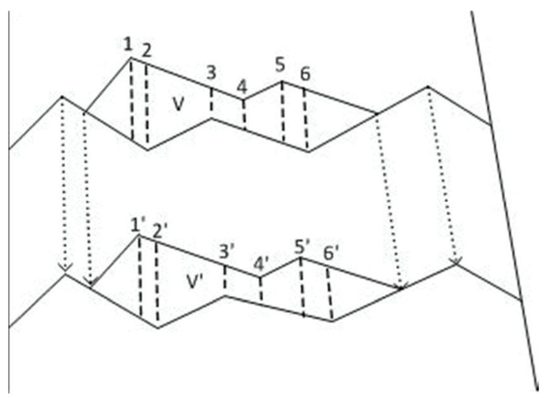

Fig. 2. Burden descent strategy.

proportional to the velocity, for which a radial distribution is assigned at a particular vertical height. For example, in figure 2 the ratios between the layer heights at 1-6 remain same and so does the volume of the layer ($V = V'$) as it descends.

2.3. Sensitivity analysis

In order to understand the complexity of the design of a charging program, a simple example was created. First, a reference charging program, table 1, was introduced. In this program, four coke dumps (or "rings") and a center-coke dump are followed by four pellet dumps. The program was designed to create a quite uniform layer of coke, followed by a center coke dump, the primary role of which was to prevent the forthcoming pellet dumps from entering into the center of the furnace. (This makes it possible for the gas to flow in the furnace center at a high temperature and a high velocity, which has been found to yield a stable and efficient operation of the shaft.) Finally, the four pellet dumps enter with a high chute angle close to the wall.

Table 1. *Reference charging program for sensitivity analysis.*

Dumps	1	2	3	4	5	6	7	8	9
Material	C	C	C	C	CC	P	P	P	P
Mass (t)	1.75	1.75	1.75	1.75	0.40	7.50	7.50	7.50	7.50
Angle (°)	29.9	32.7	37.5	39.6	15	41.7	41.7	41.7	41.7

In the analysis, each dump (except the fifth, the center coke) was charged with eight different chute angles among the eleven possible (cf. table 2), while the other dumps in the program were charged as indicated in table 1. For the coke dumps the chute angle positions 2-9 were used, while positions 4-11 were applied for the pellet dumps. The difference of the angle sets for coke and pellets was motivated by the lower angle of repose of pellets, which makes this material more apt to enter the furnace center. Figure 3 shows how the shifting of a single layer (or dump) affects the burden distribution and the radial distribution of the share of ore in the bed. It may be observed from the behavior of the first four dumps that they are the most influential to the profile, while the last four dumps do not affect the profile to the same extent. In each of the cases, shifting the chute position by one step brings about a gradual change of the profile, which may be predicted with reasoning. However, if multiple dumps are moved, it is extremely difficult to predict the net change in the profile.

Table 2. *Chute positions and corresponding charging angles.*

Chute positions	1	2	3	4	5	6	7	8	9	10	11
Charging angles (°)	15	26.7	29.9	32.7	35.1	37.5	39.6	41.7	43.7	45.6	47.4

3. GENETIC ALGORITHM FORMULATION

Genetic algorithms have gained popularity for solving complex combinatorial optimization problems and have already found applications in steelmaking (Santos et al., 2003; Chakraborti, 2005; Agarwal et al., 2010; Mitra et al., 2011). The problem of evolving charging programs in the blast furnace was earlier tackled by Pettersson et al. (2005), but the setup was different and a blast furnace with bell-top charging equipment was considered in their work.

In this study the classical simple genetic algorithm, based on the work by Holland (1975), was used for optimization. The goal was to evolve a charging program that produced a desired distribution of the share of ore, $x(r)$, in the bed. Two types of problem formulations were considered, either with or without the center coke mass as a variable. In general, the chromosomes were binary coded such that each variable was represented by a binary sequence of zeros and ones (figure 4). Three bits were used to represent the chute position of each of the charged rings. As in the sensitivity analysis of subsection 1.2, chute positions 2-9 and 4-11 were applied for coke and pellet dumps respectively. The center coke dump was fixed at position 1, but in cases where the center coke was included among the search variables extra genes were added to express four different masses of center coke, 100 kg, 200 kg, 300 kg and 400 kg. One point tournament crossover was carried out between each chromosome and the best fit in a randomly chosen pool. The fitness function, E, was expressed as the root mean of the squares of errors between the target, x_i, and the current profile, $\hat{x}_i$, where $i = 1,\ldots N$ are the points along the radius for which the value of target x is given. Thus, the best individual is the one corresponding to the smallest value of E.

Bitwise mutation was carried out with a probability of 4% to ensure diversity in the solutions. Selection was based on the elitist scheme, where the best individual from the previous generation was added to the population pool. A total of 150 generations were simulated for each case with an initial population of 100 individuals (i.e., charging programs). The chromosome representations are presented in figure 4.

4. RESULTS AND DISCUSSIONS

Six different scenarios were studied, mimicking general requirements in actual blast furnace conditions. The charging programs with the possible variables are presented in table 3.

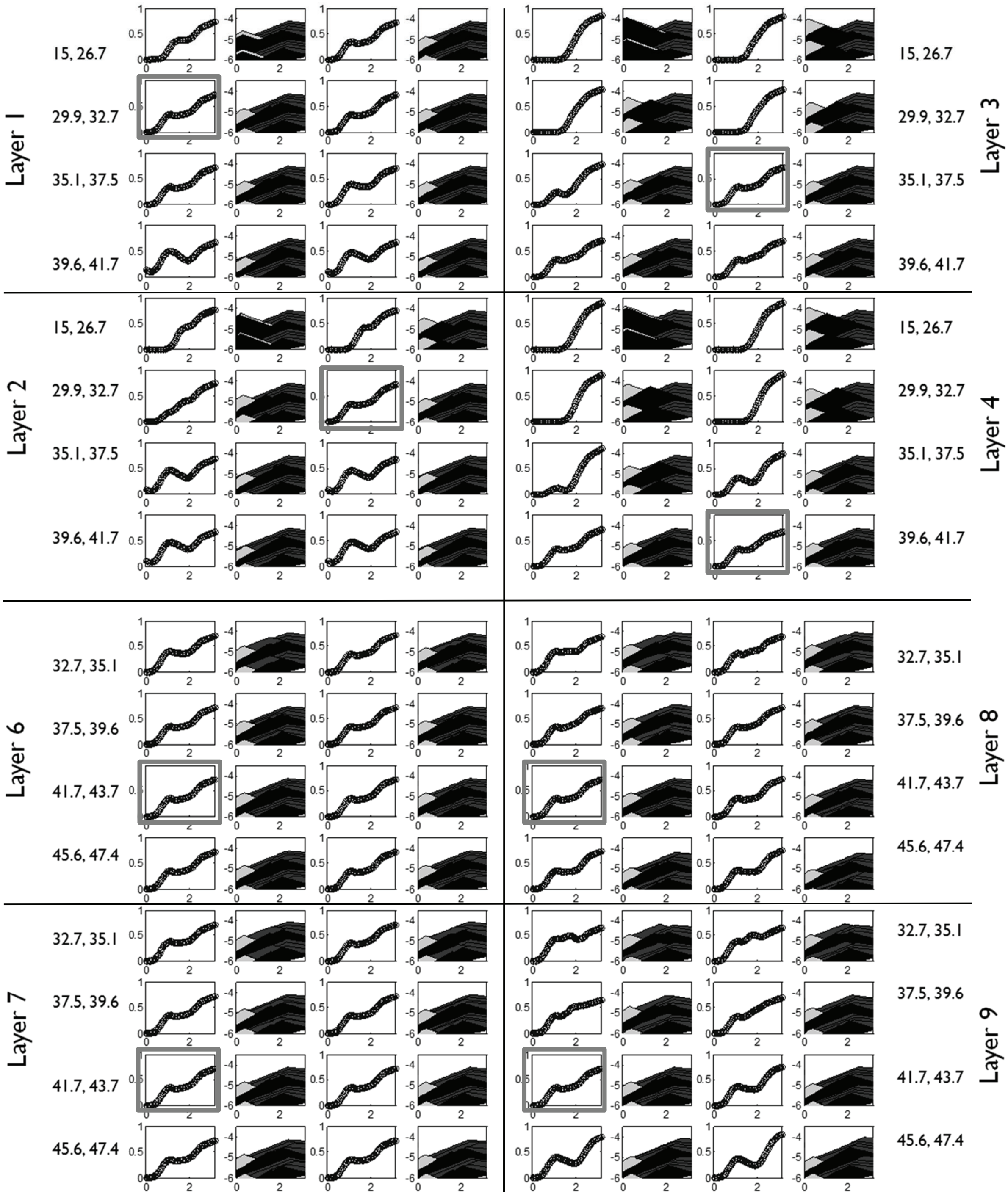

Fig. 3. Sensitivity of shifting a layer (dump) in the charging program. The left subpanel for each case shows the radial distribution of the share of ore in the bed, and the right subpanel the burden distribution. Coke dumps are depicted in black, center coke in light gray and pellet in dark gray. Figures enclosed by squares indicate the profile of the reference program (cf. table 1).

Chromosome	3 bit	3 bit	3 bit	3 bit	3 bit	3 bit	3 bit	3 bit
Ring number	1	2	3	4	6	7	8	9

Chromosome	3 bit	3 bit	3 bit	3 bit	2 bit	3 bit	3 bit	3 bit	3 bit
Ring number	1	2	3	4	CC	6	7	8	9

Fig. 4. *Chromosome formulation without (top) and with (bottom) center coke* ***mass as a search variable.***

Table 3. *Charging programs for the cases (C: coke, CC: center coke, and P: pellets).*

Case	Variable	Dump								
		1	2	3	4	5	6	7	8	9
Case a-d	Material	C	C	C	C	CC	P	P	P	P
	Mass (t)	1.75	1.75	1.75	1.75	0.40	7.50	7.50	7.50	7.50
	Chute position	2 - 9	2 - 9	2 - 9	2 - 9	1 (fixed)	4-11	4-11	4-11	4-11
Case e	Dump	1	2	3	4	5	6	7	8	9
	Material	C	C	C	C	CC	P	P	P	P
	Mass (t)	1.75	1.75	1.75	1.75	0.10-0.40	7.50	7.50	7.50	7.50
	Chute position	2 - 9	2 - 9	2 - 9	2 - 9	1 (fixed)	4-11	4-11	4-11	4-11
Case f	Dump	1	2	3	4	5	6	7	8	9
	Material	P	P	C	C	CC	P	P	C	C
	Mass (t)	7.50	7.50	1.75	1.75	0.40	7.50	7.50	1.75	1.75
	Chute position	4-11	4-11	2 - 9	2 - 9	1 (fixed)	4-11	4-11	2 - 9	2 - 9

Case a: Four coke rings, one center coke and four pellet rings. The target is 50% ore all over the radius, allowing the chute to vary in the eight different positions for every ring.

Case b: Similar to Case a, but using a different target with a higher coke at the center. This would enforce a central gas flow in the blast furnace.

Case c: Similar to Case b, but lower share of coke at the wall. This protects the wall from excessive heat load and losses.

Case d: Similar to Case b, but higher share of coke at the wall. This state would prevent the formation of scaffold (buildup material) at the wall.

Case e: Target as in Case a, but allows the center coke masses to vary.

Case f: Target as in Case a, but charged with alternate pairs of rings of pellet and coke.

Table 4 and figure 5 present the final results of the optimization, i.e., for the best individual in the final generation. In Case a, the coke rings are uniformly distributed, while the first two pellet dumps enter with quite low chute angle. The error is relatively large because it is impossible to get a uniform ratio of ore and coke due to the presence of the centre-coke dump and with other coke layers near the centre but pellet layers at the periphery. Therefore, for Case b a much better approximation is obtained. This result must be considered appropriate, keeping in mind the constraints of the problem. The coke dump pairs are split into one entering close to the center and another close to the wall. The target patterns of Cases c and d, which were required to increase or decrease the share of coke at the wall, respectively, are also seen to been fitted well, with an error of $E = 0.06\text{-}0.07$. Also note that the solution for Case c is very similar to that of Case b, and that Case d shows similar general features in that the coke is split into two pairs dumped closer to the center and closer to the wall, respectively. In Case e the fact that the mass of center coke can be reduced leads to a flatter profile in the centre, so the error is halved compared to Case a. Finally, in Case f it is possible to get very flat profile with a very low approximation error, because the alternate pellet and coke charging enables a uniform distribution. The arising burden distribution is illustrated in figure 6, which shows how an ingenious shifting of the coke layers can lead to a uniform ore share over the radius. However, some of the layers are seen to be extremely thin which may be difficult to achieve in a real furnace where mixing and percolation effects occur.

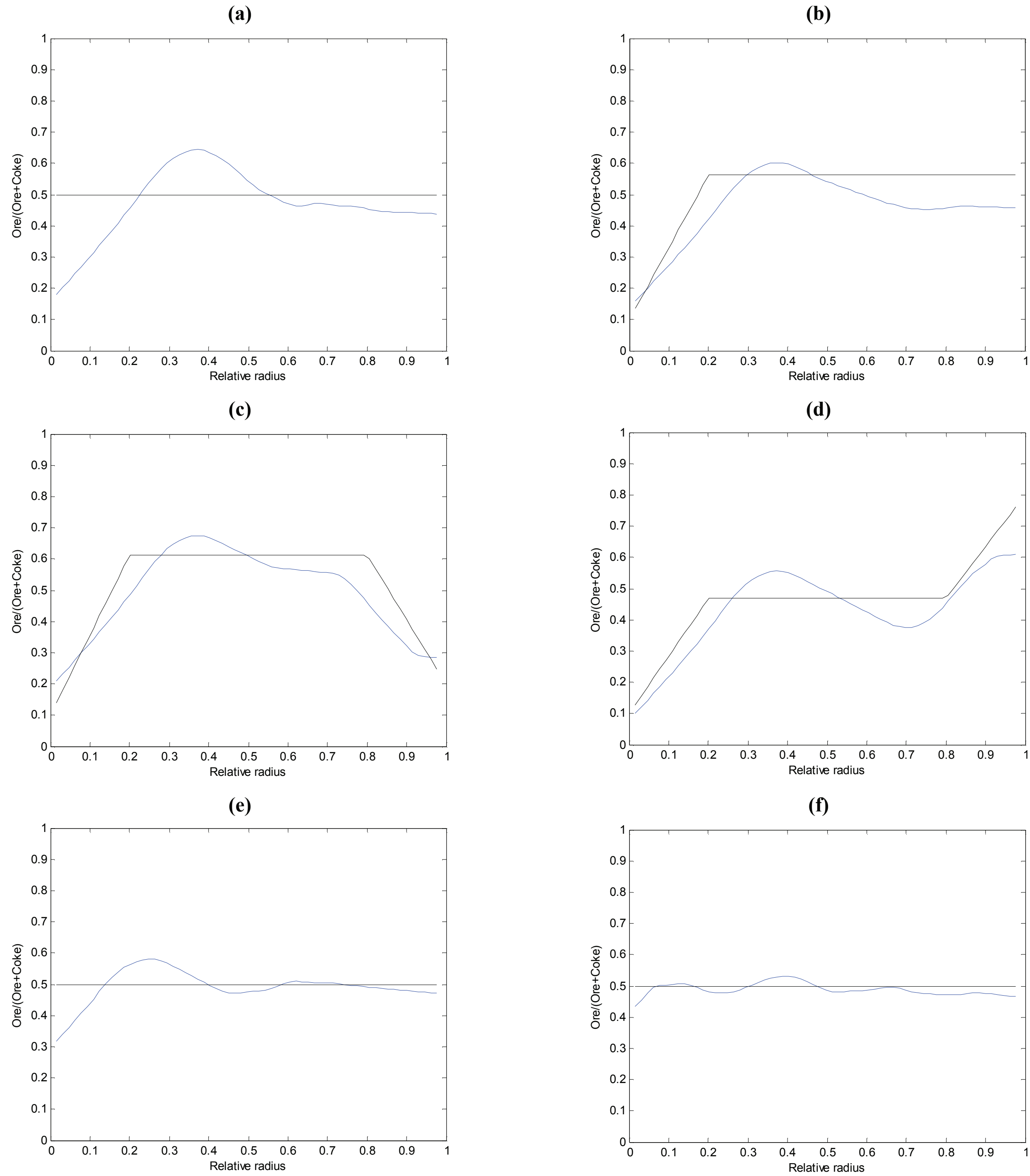

Fig. 5. Radial distribution of the share of ore for the best individual of the final generation for six different targets: (a) 50% ore share all along the radius, (b) like Case a, but more coke at the center to promote central gas flow, (c) like Case b, but with less coke at the wall, (d) as Case b, but with more coke at the wall, (e) as Case a, but allowing variable center mass of center coke dump, and (f) like Case e, but charging alternate pellet and coke dump pairs.

5. CONCLUSIONS AND FUTURE WORK

A burden distribution model describing the charging process in the blast furnace has been applied in a design task, where a given charging sequence has been optimized with respect to angles of the rotating chute and, in some cases, also the mass of center coke. The target for the burden distribution was a given radial distribution of the share of ore in the bed, and a genetic algorithm was use to tackle the combinatorial optimization problem. By studying the results, it was found that reasonable charging programs were evolved with the technique, and that at most 100 generations of a population of 100 individuals were needed to find a converged solution. Inspection of the programs evolved revealed novel solutions that would be very hard to find by experience or by trial and error. It should be stressed that the combinatorial nature of the problem does not allow for an exhaustive search through all possible combinations. Future work will be focused on the possibility to include other goals, e.g., a target for the gas flow distribution. This would require an extension of the model to simulate gas flow patterns, simultaneously considering thermal conditions in the blast furnace shaft.

Table 4. *Optimized charging programs and their performance (root mean square error, E). Values expressed in boldface are optimized ones.*

Case	Variable	Dump									*E*
		1	2	3	4	5	6	7	8	9	
a-d	Material	C	C	C	C	CC	P	P	P	P	
a-d	Mass (t)	1.75	1.75	1.75	1.75	0.40	7.50	7.50	7.50	7.50	
a-d	Chute position	2 - 9	2 - 9	2 - 9	2 - 9	1	4-11	4-11	4-11	4-11	
a		**3**	**5**	**7**	**9**	1	**6**	**4**	**9**	**9**	0.1075
b		**3**	**5**	**9**	**8**	1	**11**	**9**	**7**	**8**	0.0829
c		**3**	**5**	**9**	**8**	1	**11**	**9**	**9**	**11**	0.0642
d		**5**	**6**	**9**	**9**	1	**11**	**11**	**8**	**9**	0.0689
e	Mass (t)	1.75	1.75	1.75	1.75	**0.10**	7.50	7.50	7.50	7.50	
e	Chute position	**4**	**9**	**4**	**6**	1	**4**	**6**	**7**	**6**	0.0519
f	Material	P	P	C	C	CC	P	P	C	C	
f	Mass (t)	7.50	7.50	1.75	1.75	**0.40**	7.50	7.50	1.75	1.75	
f	Chute position	**4**	**6**	**7**	**9**	1	**10**	**9**	**5**	**5**	0.0200

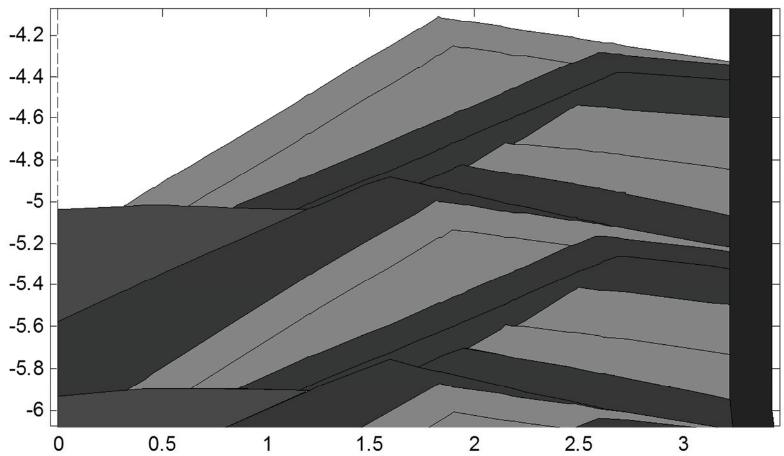

Fig. 6. *Burden distribution for the best individual of the final population in Case f; dark grey layers correspond to ore and light grey layers to coke.*

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ROZWÓJ PROGRAMÓW ZAŁADUNKU WSADU DLA UZYSKANIA OPTYMALNEGO ROZKŁADU TEGO WSADU W WIELKIM PIECU

Streszczenie

Rozmieszczenie wsadu w wielkim piecu wpływa na wydajność procesu w górnej części pieca, a tym samym na płynność tego procesu, wskaźnik zużycia koksu oraz wydajność. W niniejszej publikacji opisano model rozmieszczania ładunku, który umożliwi opracowanie programów ładowania wsadu, realizujących konkretny cel postawiony przez projektanta, tj. zmianę kątów położenia obrotowej rynny zsypowej. W programie wykorzystano algorytm genetyczny. Przedstawiona metoda może skutecznie pomóc w procesie przeszukiwania złożonych przestrzeni rozwiązań dla tego zagadnienia i docelowo w opracowaniu programów załadowania wsadu, które doprowadzą do rozmieszczenia rudy oraz koksu zgodnie z przyjętymi założeniami. Technika ta ma szanse wdrożenia w przemyśle stalowniczym przy opracowywaniu nowatorskich programów ładowania wsadu.

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