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THE USE OF LINEAR PROGRAMMING IN THE OPTIMIZATION OF COAL BLENDS 1/

by

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SUMMARY

In the iron and steel industry, the cost of coal has substantial importance, for it is the raw material that affects most the cost of the final product.

Taking into account the diversification of the supply sources and the large range of coal types, it is very difficult to determine the optimum blend composition to coke by the additional metallurgical processes; thus we turn to operational research techniques.

This paper aims at: 1) determining, among the various coal types, a blend to meet operating needs of the Coking Plant and Blast Furnace Area, while at the same time minimizing the cost of effective coke carbon; 2) serving as a management guide in decisions about the compilation of purchasing contracts of coal and stock control.

PURPOSES

The purposes of this paper can be summarized as follows:

1 - Determining, among the various coal types, a blend to meet operating needs of the Coking Plant and Blast Furnace Area, while at the same time minimizing the cost of effective coke carbon;

2 - Serving as a management guide in decisions about the compilation of purchasing contracts of coal and stock control

DEVELOPMENT

Coal and Coke

In the development of the iron-ore reduction process in blast furnaces, coke will fundamentally play three roles :

a) fuel,

b) reducing agent,

c) charge "permeabilizer".

Therefore, if we propose to produce blast-furnace coke, we should, in the light of these elements, define qualitative and quantitative parameters to be achieved in the Coking Plant operation.

Although blast-furnace operating techniques, such as fuel injection in the tuyeres, air enrichment, high top pressure, use of prereduced material, etc., have been bringing significant reduction results in coke rate, with the increasing world steel demand, there is consequently a raise in coal consumption by the iron and steel industry.

On the other hand, availability of high-quality coal has not followed the same route and so, lower-quality coal must be necessarily introduced in the operation of Coking Plants, seeking to obtain lower coke costs.

It should be pointed out that some Coke Plante, in order to keep the quality of blast-furnace coke at reasonable levels even with the use of lower-quality coal, have introduced new techniques such as coal briquetting, predrying, etc.

Therefore, fundamentally important is the choice of coal so as to have a suitable blend to obtain coke with the desired characteristics for use in blast furnaces.

Furthermore, considering that in the pig iron cost composition, coke is responsible for our conditions to about 60%, in this choice the blend must be one that gives the best cost conditions, since variations in it will deeply affect the economic results of the company.

Effective Coke Carbon

A concept normally used in this choice as related to cost is that of "effective coke carbon" defined as being the remaining carbon that, after the deductions of necessary carbon to melt the coke ash and the flux required for this ash, i.e., it is the carbon available for the process after the needs inherent to the coke itself are complied with.

To calculate the effective coke carbon we have the equation below as found in literature:

$$C = CF - 1.08\ Cz - 3S - 0.038\ CF$$

where:

C =	effective coke carbon	(%)
CF =	fixed coke carbon content	(%)
Cz =	coke ash content	(%)
S =	coke sulfur content	(%)

For our study, alterations should be made in this formula to have it changed into a function of the characteristics of a determined coal i.

Supposing that with the coking of coal i, we will obtain a coke whose characteristics can be calculated approximately through the following relationship:

$$CF = 100 - (Cz + MV)$$

$$S = 0.63\ S_i + 0.20$$

$$Cz = \frac{Cz_i}{R_i}$$

$$R_i = 99 - \frac{5}{6}\ MV_i$$

where:

MV = volatile coke material (fixed at 1%)

S_i = sulfur content of coal i (%)

Cz_i = ash content of coal i (%)

R_i = coke yield: coal, of coal i (%)

MV_i = volatile materials content of coal i (%)

after substitutions are made, we have:

$$C_i = 94,638 - \frac{2,042.Cz_i}{R_i} - 1.89\ S_i$$

C_i being the effective coke carbon obtained from coal i.

Going over to cost, and calling PC_i the Works CIF price, we have:

$$P_i = \frac{1}{C_i} \times PC_i$$

where:

P_i = price of effective coke carbon obtained from coal i.

__Model Setting__

The general problem in linear programming is the choice of an optimum (maximum or minimum) model of a linear function of variables liable to linear restrictions (equations and inequalities).

Holding the objective equation and restrictions, we have built a system of linearly independent equations, forming the matrix that was introduced into the Computer.

It is evidently necessary to take care not to include equations presenting redundancy, for this would lead us to the impossibility of solving the system. So, some metallurgical restrictions are not explicitly included in our matrix, but are inferred to in other equations or inequalities.

So, the equations of our matrix suffice to meet the metallurgical restrictions and requirements of linear programming as well.

Objective Equation

The cost of the effective coke carbon obtained from a certain n coal blend will be:

$$Z = \sum_{i=1}^{n} P_i X_i$$

where:

P_i = price of the effective coke carbon obtained from coal i.

X_i = percentage of coal i in the blend.

We aim at minimizing this function Z, by suitably choosing the coal to enter into the blend composition, as well as the percentages of each coal taking a part in it.

Restrictions used in our Matrix

1. Percentage:

$$\sum_{i=1}^{n} X_i = 1$$

X_i = percentage of coal i in blend No. 14, we used 14 coal types.

2. Low Volatile Minimum:

$$\sum_{j=6}^{8} X_j \geqslant 0.20$$

X_j = percentage of low volatile coal in the blend.

3. Low Volatile Maximum:

$$\sum_{j=6}^{8} X_j \leqslant 0.26$$

4. Volatile Matter of the Blend: Minimum

$$\sum_{i=1}^{n} X_i \, Mv_i \geqslant 0.27$$

M_{vi} = volatile matter content of coal i.

5. Volatile Matter of the Blend: Maximum:

$$\sum_{i=1}^{n} X_i M_i \leqslant 0.29$$

6. Coke Sulfur:

$$\sum_{i=1}^{n} 0.63 \quad S_i \, X_i \quad + 0.20 < 0.80$$

7. Domestic Coal:

$$X > 0.33$$

The restrictions presented here that constituted our model include explicitly many other metallurgical and operating restrictions such as:

- Coking Plant capacity restrictions
- Coke/coal yield
- Ash content and others.

Table 1 MATRIX

Coal / Restrictions	1 A	2 B	3 C	4 D	5 E	6 F	7 G	8 H	9 I	10 J	11 K	12 L	13 M	14 N	bj
Percentage	1	1	1	1	1	1	1	1	1	1	1	1	1	1	= 1
L.Vol.Min.						1	1	1							≥ 0,20
L.Vol.Max.						1	1	1							≤ 0,26
Vol.Matter of Blend Min.	0,347	0,346	0,337	0,287	0,277	0,195	0,201	0,188	0,315	0,340	0,278	0,275	0,250	0,279	≥ 0,27
Vol. Matter of Blend Max.	0,347	0,346	0,337	0,287	0,277	0,195	0,201	0,188	0,315	0,340	0,278	0,276	0,250	0,279	≤ 0,29
Coke Sulfur	0,447	0,472	0,435	0,277	0,380	0,387	0,378	0,409	0,907	0,428	0,529	0,246	0,233	0,605	≤ 0,50
Domestic Coal									1						≥ 0,33
Obj.Equation	38,373	39,088	38,888	39,283	42,082	41,083	41,632	39,535	44,008	40,192	38,922	39,913	[illegible]3,113	45,082	Minimize

Model Solution by the Simplex Method

The solution found was considered satisfactory enough since there was a reduction in cost per ton, in relation to the present blend, and was metallurgically approved.

If we take into account that our present blast furnace consumption is 1000 tons of effective carbon per day and that this value will be increased during the Works expansion phases, any reduction obtained in US$/ton will be very significant.

To solve our matrix we used an IBM/360 computer solution of which is included in the addendum.

Besides the optimum blend (the main purpose of our problem), the program provides us with several valuable reports for eventual decision-making by the management.

Next we will analyze some data of major importance furnished by the computer reports.

COST RANGE REPORT - This report gives variation limits within which the price of each coal can vary and the coal can still continue to be part of the optimum solution, thus it is very useful to the purchasing department.

It also shows which variable - coal - will enter into the optimum solution if the previously cited variation limit is overpassed. In this case, the new variable, playing a part in the optimum solution, will have the initial value supplied by the Matrix.

As for the coals that did not enter into the optimum blend, we have a figure in the REDUCED COST REPORT, showing which cost reduction of these coals will be, so that they can enter into the solution.

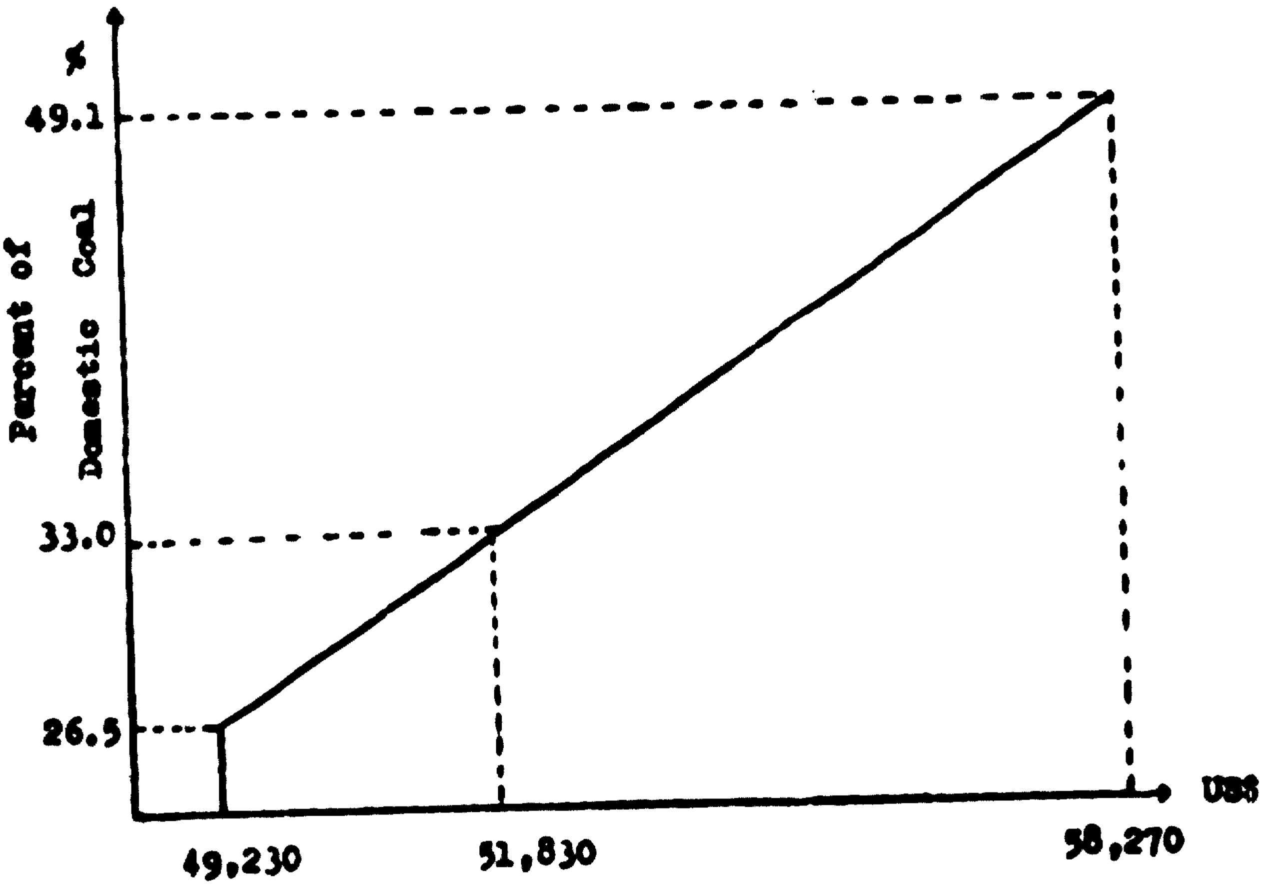
The latest report of the R. H. S. ANALYSIS REPORT program gives data from which we can verify the variation in the total cost of effective coke carbon due to variations in the values of restrictions imposed on the problem.

An analysis of major importance to be carried on with this report data is the influence of domestic coal on the total cost of the blend.

The restriction of domestic coal was set at 33 %, in accordance with requirements of government departments.

We verified from the obtained data that there will be a variation of US$ 0.40 in the total cost of the blend for each 1% of variation in the restriction of domestic coal, and in the same direction, which value is valid in the 26-49% range and taking 33% as the basis as seen on the graph.

Influence of domestic coal on coke cost



Cost of Effective Coke Carbon

Consumption of domestic coal has been the object of various discussions, since it is well known that our coal has the following characteristics:

- Low quality, because of natural conditions;
- Difficult and costly mining and processing, also because of natural conditions;
- A transportation structure (railways, ports and coastal navigation) which strongly contributes to raising its cost when unloaded at the iron and steel works.

Consequently, the cost of its carbon unit is high.

"In Jannuary 1968, the Federal Government issued decree No. 62,113 that stopped all divergences and determined what we could classify as the crystallization phase of the new carboniferous policy, now completely aware in all sectors of comparative thinking, of the economical fact, and the 'last but not the least' of the need for preservation of the social economic structure of the Santa Catarina carboniferous region".

The analysis of the domestic coal policy aims at the following:

a) Preservation of the social-economical structure of the Santa Catarina carboniferous region;

b) National Security;

c) Exchange value balance - Iron and steel-product export;

d) Quality and price of metallurgical coal;

e) Onus distribution. Displacement or diversification of the use of domestic coal;

All the proposed purposes should be achieved by partly displacing the consuming market to the electrical area (thermo-electric) and others, that offer an opportunity for the iron and steel industry to achieve higher productivity in its Blast-Furnaces, and consequently, lower production costs.

Coke Strength

Parameters referring to coke strength are not included among the restrictions of coke quality, for this is a non-linear function of the petrographic composition of the various kinds of coal.

Coke stability, measured according to ASTM Standards because of operating conditions in the Blast-Furnaces, should be higher than 53%.

Therefore, having the classification of coal blends per value, given by "Simplex", we should analyse them in the light of coke stability.

Hence, two ways arise:

a) Box-test

It will be necessary to prepare an amount of samples of the various coals enough to effect box-tests. The blends are laboratory prepared in accordance with the classification order, and coke, obtained from the box-tests will be taken to the drum for measuring ASTM stability which is immediately determined.

b) Petrography

In this case a petrographic analysis of the coal will be necessary, since from its results we can foresee coke stability in accordance with the method developed by Ammosov, Schapiro and Gray.

Obviously, the blends that do not meet this restriction on coke strength will be disregarded while the other are classified according to their economical value.

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ADDENDUM

NCD - LINEAR PROGRAMMING - OPTIMUM COAL BLEND

OPTIMAL SOLUTION REPORT

NUMBER	NAME	ACTIVITY LEVEL
V 4	D	.01837
V 8	E	.20000
V 9	I	.33000
V 11	K	.36680
V 13	M	.08483

UCD - LINEAR PROGRAMMING - OPTIMUM COAL BLEND

OPTIMAL SOLUTION REPORT

NUMBER	NAME	ACTIVITY LEVEL	SIMPLEX MULTIPLIER
A 01	PERCENT	ZERO	45,583 -
S 02 -	BV MIN	ZERO	
A 02	BV MIN	ZERO	1,433
S 03	BV MAX	.06000	ZERO
S 04 -	MV MIN	ZERO	
A 04	MV MIN	ZERO	19,861
S 05	MV MAX	.02000	ZERO
S 06	MAX COQ	ZERO	2,145
S 07 -	C. MAC	ZERO	
A 07	C. MAC	ZERO	39,966 -

MINIMUM OBJECTIVE FUNCTION 51,831

UCD - LINEAR PROGRAMMING - OPTIMUM COAL BLEND

COST RANGE REPORT

NAME	CURRENT COST	HIGHEST COST	HIGH VARIABLE	LOW VARIABLE	LOWEST COST
A	38,373 NB				
B	39,025 NB				
C	38,868 NB				
D	39,283	39,560	V 01	S 06	38,539
E	42,062 NB				
F	41,063 NB				
G	41,632 NB				
H	39,535	41,177	V 06		-INF
I	44,008	INF			-INF
J	40,152 NB				
K	38,922	39,485	S 06	V 12	33,944
L	39,913 NB				
M	40,113	41,581	V 12	V 01	39,735
N	45,082 NB				

UCD - LINEAR PROGRAMMING - OPTIMUM COAL BLEND

CHECK REPORT

NAME	UPPER LIMIT	SOLUTION VALUE	LOWER LIMIT
PERCENT	1.00000	1.00000	1.00000
BV MIN		.20000	.20000
BV MAX	.26000	.20000	
LV MIN		.27000	.27000
LV MAX	.29000	.27000	.27000
INX COQ	.60000	.60000	
C. MAC		.33000	.33000

OBJECTIVE FUNCTION 51,831

UCD - LINEAR PROGRAMMING - OPTIMUM COAL BLEND

REDUCED COST REPORT

VARIABLE NAME	CURRENT COST	REDUCED COST	BASIS VALUE
A	38,373	0,647	37,726
B	39,025	1,313	37,712
C	38,868	0,918	37,950
E	42,062	3,229	38,832
F	41,063	1,642	39,422
G	41,632	2,289	39,343
J	40,152	2,246	37,906
L	39,913	0,385	39,529
M	45,082	6,343	38,739

UCD - LINEAR PROGRAMMING - OPTIMUM COAL BLEND

R.H.S. ANALYSIS REPORT

ROW NAME/TYPE	INCREMENTAL VALUE	DECREMENTAL VALUE	CURRENT RHS	LOWER LIMIT	UPPER LIMIT
PERCENT 0		45,583	1.00000	.98898	1.00265
BV MIN 2	1,433		.20000	.19233	.23470
BV MAX 1	ZERO		.26000	.20000	INF
HV MIN 2	19,881		.27000	.26940	.27327
HV MAX 1	ZERO		.29000	.27000	INF
EMI COQ 1	2,145		.60000	.50364	.60638
C. MAC 2		39,966	.33000	.26520	.49148

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