The example of an assessment and selection of the optimal variant of technological process of iron smelting

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Abstract. The example of an assessment and selection of the optimal variant of technology smelting from set of existing alternatives on the basis of the method developed by the author is presented.

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Key words: pig iron smelting; desirability function; methods of optimization.

Introduction

This article is devoted to an actual problem of a choice of optimal variant of technological process from the plurality of existing alternatives. Many Russian researchers have long been engaged with this problem (Adler,Y.P. *et al.*, 1976; Demin, D.A. *et al.*, 1995; Girshovich, N.G.,1978; Kartashova, T.M. and B.I.Shtarkman, 1970; Novik, F.S. and Ya.B.Arsov., 1980; Novik, F.S. *et al.*, 1972; Novik,F.S., 1979; Puryaev, A.S., 1997; Shtarkman, B.P., *et al.*, 1969; Shtarkman, B.P., T.M. Kartashova, I.M.Monich and I.N.Rasminsky, 1969). The method of an assessment and selection of the optimal variant of technological process is offered by the author.

The developed and described method of an assessment and selection of variant of technological decisions (technological process) which was presented in the book (Puryaev, A.S. 2004) for the best understanding it is shown on a conditional example of an assessment and a selection of technology process of iron smelting. It is presented below.

Task

It is necessary to define optimum option of technological process of iron smelting when developing the modernization project of existing smelting bay of gray-iron foundry.

Initial data

1. The restrictions and desirable levels in the private parameters of optimization set by the technologist and the decision-maker are presented in the table 1.

Table 1. The restrictions and desirable levels in the private parameters of optimization

Parameters	Technical - technological				Technical and economic
	Pig iron grade	Technolo-gical melt tempe-rature, ^0C	Content of sulphur after smelting, 10^{-2} %	Group the complexity of the casting on the grounds of 1,3,5,6-10	Productivity, tonne/hour
Value	any	1600	0,035	3,4,5	25
Status of parameter and value level	strict *	strict min	strict max	strict *	strict *

Techno - economic			Ecological					Social
Type of production process, tonne / hour	Specific productivity of labor, tonne / (man×hour)	Cycle of melting and holding, hour	Heat radiation, watt/м^2	Noise, decibel (A)	Vibra-tion, decibel	Dust, kg/ tonne	Harmful substances, mm^3/ tonne	Coefficient of labor protection working by techno-logical process
Large-scale production	3.0	4.0	1500	80	100	9	240	0,3
strict*	desirable min	desirable max	desirable max	desirable max	desirable max	strict max	strict max	desirable min

Qualitative		Economic		
Complex index of FEQ, mark	Other qualitative parameters, mark	Internal rate of return (IRR), %	Capital investment (CI), mln. RUB	The period of payback (PP), years
3.0	3.0	20	250	6
desirable min	desirable min	strict min	strict max	strict max

Remarks. The values of the parameters, noted symbols * are presented in the form of designations (the type, the name, the brand) or in the form of an interval or separate values of the discrete sizes measured in ordinal scales. Therefore, in this case, value level (minimum, maximum) isn't set. The admissibility of variant solutions is defined otherwise (see below).

2. Alternative options multitude of technological process of iron smelting (available) with their private values of optimization parameters is presented in the table 2.

Table 2. Alternative options multitude of technological process of iron smelting

№	Option techno-logical process of melting iron	Private optimization parameters							
		Technical - technological				Technical and economic			
		Pig iron grade *	Max. techn. melt tempe-rature, ^0C	Min. content of sulphur after smelting, $\times 10^{-2}\%$	Group * (category) the complexity of the casting on the grounds of 1,3,5, 6 –10	Produc-* tivity, tonne / hour	Type* of production process, tonne / hour	Specific productivity of labor, tonne / (man×hour)	Cycle of melting and holding, hour
0	1	2	3	4	5	6	7	8	9
1	IF	any	1600	4	1,2,3,4	0,5-28	IP, SP, FP	4,0	3,0
2	EAF	—"—	1650	4	1,2,3,4	0,5-25	IP, SP, FP	5,3	2,0
3	IICF - IICFM	—"—	1600	2	1,2,3,4 5,6	0,5-28	SP,FP,LP, MP	3,2	4,0
4	IICF - IIHFM	—"—	1600	2	1 - 6	0,5-28	—"—	3,2	3,5
5	IICF - EAF	—"—	1650	2	1 - 6	0,5-25	—"—	4,0	4,0
6	EAF - IICFM	—"—	1600	2	1 - 6	0,5-28	—"—	4,0	3,0
7	EAF- IIHFM	—"—	1600	2	1 - 6	0,5-28	—"—	4,0	2,5
8	EAF - EAF	—"—	1650	2	1 - 6	0,5-25	—"—	4,2	2,7
9	IICF - IIHFM - AFM	—"—	1600	2	1 - 6	0,5-28	—"—	2,7	3,5
10	IICF - IICFM - AFM	—"—	1600	2	1 - 6	0,5-28	—"—	2,7	4,0
11	IICF - EAF - AFM	—"—	1650	2	1 - 6	0,5-28	— "—	2,8	4,0
12	EAF - IICFM - AFM	—"—	1600	2	1 - 6	0,5-28	—"—	2,8	3,0
13	EAF- IIHFM - AFM	—"—	1600	2	1 - 6	0,5-28	— "—	2,8	2,5
14	EAF - EAF - - AFM	—"—	1650	2	1 - 6	0,5-28	—"—	3,2	2,7

№	Private optimization parameters										
	Ecological					Social	Qualitative		Economic		
	Heat radiation, watt/ $м^2$	Noise, decibel (A)	Vibra-tion, deci-bel	Dust, kg/ tonne	Harmful sub-stances, mm^3/ tonne	Coeffi-cient of labor protect-tion working by techno-logical process, mark	Complex index of FEQ, mark	Other quail-tative para-meters, mark	Inter-nal rate of return (IRR), %	Capi-tal investment (CI), mln. RUB	The period of payback (PP), years
	10	11	12	13	14	15	16	17	18	19	20
1	500	70	70	0,3-5,0	10-30	0,3	3,0	2,5			
2	560	100	80	5-10	120-150	0,2	3,0	2,5			
3	1000	80	70	1-9	20 - 60	0,3	3,5	3,0	20,5	210	5
4	1000	80	70	1-9	20-60	0,32	3,6	3,0	22	210	5,5
5	1200	100	80	6-10	20-60	0,28	3,5	3,0	18	220	5,7
6	1200	100	80	6-10	200-300	0,25	3,6	3,0			
7	1200	100	80	6-10	200-300	0,25	3,7	3,0			
8	1300	105	85	6-10	200-350	0,26	3,7	3,0			
9	2000	80	70	1-9	20-60	0,32	3,6	3,2	28	230	9

10	2000	80	70	1-9	20-60	0,31	3,5	3,2	23	250	4
11	2100	100	70	6-10	20-60	0,28	3,5	3,2	20	300	4,5
12	2100	100	80	6-10	200-300	0,25	3,5	3,2			
13	2100	100	80	6-10	200-300	0,24	3,6	3,2			
14	2200	105	85	8-12	200-350	0,26	3,7	3,2			

1. IF – Inductive Furnace; EAF – Electric Arc Furnaces; IICF-IICFM – Inductive Iron-smelting Crucible Furnace – Inductive Iron-smelting Crucible Furnace for Mixing; IICF-IIHFM – Inductive Iron-smelting Crucible Furnace – Inductive Iron-smelting Hot air Furnace for Mixing; IICF-EAF – Inductive Iron-smelting Crucible Furnace – Electric Arc Furnaces; EAF-IICFM – Electric Arc Furnaces – Inductive Iron-smelting Crucible Furnace for Mixing; EAF-IIHFM – Electric Arc Furnaces – Inductive Iron-smelting Hot air Furnace for Mixing; EAF-EAF – Electric Arc Furnaces – Electric Arc Furnaces; IICF-IIHFM-AFM – Inductive Iron-smelting Crucible Furnace – Inductive Iron-smelting Hot air Furnace for Mixing – Automatic Filling machines; IICF-IICFM-AFM – Inductive Iron-smelting Crucible Furnace – Inductive Iron-smelting Crucible Furnace for Mixing – Automatic Filling machines; IICF-EAF-AFM – Inductive Iron-smelting Crucible Furnace – Electric Arc Furnaces– Automatic Filling machines; EAF-IICFM-AFM – Electric Arc Furnaces – Inductive Iron-smelting Crucible Furnace for Mixing – Automatic Filling machines; EAF-IIHFM-AFM – Electric Arc Furnaces – Inductive Iron-smelting Hot air Furnace for Mixing – Automatic Filling machines; EAF-EAF-AFM – Electric Arc Furnaces – Electric Arc Furnaces – Automatic Filling machines.

2.The parameters of optimization contain conditional and approximate values in the table 2. Reflection's adequacy of reality by them isn't guaranteed. It's intended for evident demonstration of essence offered methodical to the recommendation.

2. The symbols: *IP* – individual production; *SP* – small-scale production; *FP* – full production; *LP* – large-scale production; *MP* – mass production.

Solution

1. The definition of quantity of possible variants of technological process of iron smelting on the following groups of private optimization parameters: technical and technological, technical and economic, ecological, social, group of qualitative parameters.

For definition of private desirability of parameters optimization the mechanism of the translation Y_i in Y_i' in the form of the straight-line equations originally is defined

$$y_i' = a \times y_i + b \tag{1}$$

Two control points established on preference of the technologist and the decision-maker (the control points) are presented in the table 3 for each private parameter of optimization. The first control point coincides with restriction.

Table 3: The reference points of private parameters

Control points	Max.techn. melt temperature		Min. content of sulphur after smelting		Specific productivity of labor		Cycle of melting and holding		Heat radiation		Noise	
	°C	*d*	*%*	*d*	*tonne / (man× hour)*	*d*	*hour*	*d*	*watt/ м²*	*d*	*decibel (A)*	*d*
1	1600	0.37	0.035	0.37	3.0	0.37	4.0	0.37	1500	0.37	80	0.37
2	1650	0.7	0.02	0.8	4.0	0.7	3.0	0.7	500	0.8	10	0.8

Continuation of table 3

Control points	Vibration		Dust		Harmful substances		Coefficient of labor protection working by technological process		Complex index of FEQ		Other qualitative parameters	
	decibel	*d*	*kg/ tonne*	*d*	*мм³*	*d*	*w/d **	*d*	*mark*	*d*	*mark*	*d*
1	100	0.37	9.0	0.37	240	0.37	0.3	0.37	3.0	0.37	3.0	0.37
2	70	0.8	1.0	0.8	10	0.8	0.65	0.8	4.0	0.8	4.0	0.8

Remarks:

1. The reference points for the parameters noted by a symbol * in the table 2, aren't established. The admissibility of these parameters is defined otherwise (see below).

2. * w/d – without dimension.

Next, the coded values of control points is determined by a formula:

$$y' = -\ln\ln\left(\frac{1}{d}\right) \tag{2}$$

This formula is derived from the formula of the Harrington's function of desirability:

$$d = e^{-e^{-y'}} \tag{3}$$

presented in book (Puryaev, A.S., 2004). The results are presented in the table 4.

Table 4: The coded values of reference point (Y')

Control points	Max.techn. melt temperature		Min. content of sulphur after smelting		Specific productivity of labor		Cycle of melting and holding		Heat radiation		Noise	
	^oC	Y'	%	Y'	tonne / (man× hour)	Y'	hour	Y'	watt/ $м^2$	Y'	decibel (A)	Y'
1	1600	0	0.035	0	3.0	0	4.0	0	1500	0	80	0
2	1650	1.03	0.02	1.5	4.0	1.03	3.0	1.03	500	1.5	10	1.5

Continuation of table 4

Control points	Vibration		Dust		Harmful substances		Coefficient of labor protection working		Complex index of FEQ		Other qualitative parameters	
	deci-bel	Y'	kg/ tonne	Y'	$мм^3$	Y'	w/d	Y'	mark	Y'	mark	Y'
1	100	0	9,0	0	240	0	0.3	0	3.0	0	3.0	0
2	70	1.5	1.0	1.5	10	1.5	0.65	1.5	4.0	1.5	4.0	1.5

Remarks: Calculated values of Y' are rounded to two decimal places.

The conversion functions received on two control points are presented in the table 5.

Table 5: Conversion functions Y_i in Y_i'

Parameter of optimization	Function $y' = a \times y + b$	Parameter of optimization	Function $y' = a \times y + b$
Max. technological melt temperature	$y' = 0.02 y - 32.96$	Vibration	$y' = - 0.05y + 5$
Min. content of sulphur	$y' = -100y + 3.5$	Dust	$y' = -0.19y + 1.69$
Specific productivity of labor	$y' = 1.03y - 3.09$	Harmful substances	$y' = -0.0065y + 1.5652$
Cycle of melting and holding	$y' = -1.03y + 4.12$	Coefficient of labor protection working by technological process	$y' = 4.286 y - 1.286$
Heat radiation	$y' = -0.0015y + 2.25$	Complex index of FEQ	$y' = 1.5y - 4.5$
Noise	$y' = -0.02y + 1.71$	Other qualitative parameters	$y' = 1.5y - 4.5$

Remarks: The coefficients a and b of the equations are rounded to the ten-thousandths place.

The desirability table of the first five groups of private parameters of optimization is received by the conversion. It is presented below (Table 6).

Table 6. The desirability table of the first five groups of private parameters of optimization

№	Option techno-logical process of melting iron	Desirability of the private optimization parameters																
		Technical - technological				Technical and economic				Ecological					So-cial	Qualitative		Generalized desira-bility -D^*
		d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8	d_9	d_{10}	d_{11}	d_{12}	d_{13}	d_{14}	d_{15}	d_{16}	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	IF	0.37	0.37	0.0	0	0.37	0	0.70	0.70	0.80	0.48	0.80	0.74	0.79	0.37	0.37	0.12	0
2	EAF	0.37	0.70	0.0	0	0.37	0	0.91	0.88	0.78	0.26	0.69	0.46	0.60	0.22	0.37	0.12	0
3	IICF-IICFM	0.37	0.37	0.80	0.37	0.37	0.37	0.44	0.37	0.62	0.37	0.80	0.62	0.76	0.37	0.62	0.37	0.475
4	IICF-IIHFM	0.37	0.37	0.80	0.37	0.37	0.37	0.44	0.55	0.62	0.37	0.80	0.62	0.76	0.40	0.67	0.37	0.491
5	IICF-EAF	0.37	0.70	0.80	0.37	0.37	0.37	0.70	0.37	0.53	0.26	0.69	0.43	0.76	0.34	0.62	0.37	0.474
6	EAF - IICFM	0.37	0.37	0.80	0.37	0.37	0.37	0.70	0.70	0.53	0.26	0.69	0.43	0.0	0.29	0.67	0.37	0.0
7	EAF - IIHFM	0.37	0.37	0.80	0.37	0.37	0.37	0.70	0.81	0.53	0.26	0.69	0.43	0.0	0.29	0.70	0.37	0.0
8	EAF - EAF	0.37	0.70	0.80	0.37	0.37	0.37	0.75	0.77	0.48	0.23	0.62	0.43	0.0	0.31	0.70	0.37	0.0
9	IICF - IIHFM -AFM	0.37	0.37	0.80	0.37	0.37	0.37	0.26	0.55	0.12	0.37	0.80	0.62	0.76	0.40	0.67	0.48	0.436
10	IICF - IICFM - AFM	0.37	0.37	0.80	0.37	0.37	0.37	0.26	0.37	0.12	0.37	0.80	0.62	0.76	0.38	0.62	0.48	0.422
11	IICF - EAF - AFM	0.37	0.70	0.80	0.37	0.37	0.37	0.29	0.37	0.09	0.26	0.80	0.43	0.76	0.34	0.62	0.48	0.412
12	EAF - IICFM - AFM	0.37	0.37	0.80	0.37	0.37	0.37	0.29	0.70	0.09	0.26	0.69	0.43	0.0	0.29	0.62	0.48	0.0
13	EAF - IIHFM - AFM	0.37	0.37	0.80	0.37	0.37	0.37	0.29	0.81	0.09	0.26	0.69	0.43	0.0	0.27	0.67	0.48	0,0
14	EAF - EAF - AFM	0.37	0.70	0.80	0.37	0.37	0.37	0.44	0.77	0.06	0.23	0.62	0.0	0.0	0.31	0.70	0.48	0.0

Remarks:

1. The parameters of optimization have the following designations of the desirability: pig iron grade – d_1; maximum technological melt temperature – d_2; maximum content of sulphur after smelting – d_3; group the complexity of the casting on the grounds of 1, 3, 5, 6-10 – d_4; maximum productivity – d_5; type of production process – d_6; specific productivity of labor – d_7; cycle of melting and holding – d_8; heat radiation – d_9; noise – d_{10}; vibration – d_{11}; dust – d_{12}; harmful substances – d_{13}; coefficient of labor protection working by technological process – d_{14}; complex index of functions execution quality (FEQ) - d_{15}; other qualitative parameters – d_{16}.

2. The desirability noted by a symbol * (d_1, d_4, d_5, d_6) are defined by check of compliance of value set by the technologist (an interval of values) areas of values for each decision variant, i.e. if set value or an interval of values of parameter "*i*" completely belongs to area of values of decision version, this option is admissible to the private parameter of optimization "*i*" and $d_i = 0.37$, $d_i = 0$ otherwise.

3. Desirability D^* defined by the formula: $D^* = \sqrt[16]{d_1 \times d_2 \times d_3 \times \ldots \times d_{16}}$.

Next, it is necessary to check compliance between indicators of statistical sensitivity (variation coefficients) natural values of parameters and their desirability. This procedure of check is carried out for values of all private parameters, except designated by a symbol * in the table 2. The values of variation coefficients are presented in the table 7.

Table 7. The values of variation coefficients

Coefficient of variation	Private optimization parameters						
	Max. techn. melt tempera-ture	Min. content of sulphur after smelting	Specific productivity of labor	Cycle of melting and holding	Heat radiation	Noise	Vibration
1	2	3	4	5	6	7	8
η_y	0,0154	0,3177	0,2210	0,2100	0,4131	0,1280	0,0788
η_d	0,3364	0,4237	0,4355	0,3032	0,7204	0,2472	0,0958
Coefficient of variation	Private optimization parameters						
	Dust	Harmful substances	Coefficient of labor protection working by technological process	Complex index of FEQ	Other qualitative parameters	Generalized parameter of optimization	
	9	10	11	12	13	14	
η_y	0,2882	0,7967	0,1273	0,0644	0,0790		
η_d	0,3644	0,9045	0,1628	0,1767	0,3217	1,2028	

Table 7 shows that the values of the variation's coefficients of private desirability and of generalized desirability higher than those of optimization parameters, i.e. *selected desirability scale (generalized and private) are not less sensitive to changes than the optimization parameters* ($\eta_d \geq \eta_y$).

So, admissible options on the first five groups of private parameters of optimization are *1)IICF-IICFM (D = 0.75), 2) IICF-IIHFM (D = 0,491), 3) IICF-EAF (D = O,474); 4) IICF- IIHFM -AFM (D = 0.436), 5) IICF-IICFM-AFM (D = 0.422) ; 6) IICF-EAF-AFM (D = 0.412).*

2. Definition of optimal version of the decision from set of the admissible

It is originally necessary to define values of private optimization parameters of economic group (*IRR, CI, PP*) when using each admissible option, in the modernization project of the smelting sector. Assume that the calculation of parameters were performed and the values obtained are recorded in the table 2.

Further by the set restrictions of the customer (table 1) it is determined private desirability of economic group parameters (*IRR, CI, PP*). This procedure of definition is absolutely identical to the procedure stated in the section 1 of this decision (the control points for each parameter originally are established, their coded values are defined, the conversion functions for each parameter are defined, the private desirability are calculated and check of compliance of desirability scales on statistical sensitivity is carried out). All these intermediate calculations are presented in the corresponding tables.

Table 8: The reference points of parameters and their coded values

Control points	Internal rate of return (*IRR*)			Capital investment (*CI*)			The period of payback (*PP*), years		
	%	*d*	*y'*	*mln. RUB*	*d*	*y'*	*years*	*d*	*y'*
1	20	0,37	0	250	0,37	0	6	0,37	0
2	28	0,8	1,5	200	0.8	1,5	4	0,8	1,5

Table 9: Conversion functions y_i in y_i'.

Optimization parameters	Conversion equation
Internal rate of return (*IRR*)	$y' = 0{,}1875 \times y - 3{,}75$
Capital investment (*CI*)	$y' = -0{,}03 \times y + 7{,}5$
The period of payback (*PP*)	$y' = -0{,}75 \times y + 4{,}5$

Table 10: The sixth group's desirability of private optimization parameters

№	Admissible options of technical process of iron smelting	Desirability		
		IRR d_1	*CI* d_2	*PP* d_3
1	IICF - IICFM	0,40	0,74	0,62
2	IICF - IIHFM	0,50	0,74	0,50
3	IICF - EAF	0,0	0,67	0,45
4	IICF - IIHFM - AFM	0,80	0,58	0,0
5	IICF - IICFM - AFM	0,57	0,37	0,8
6	IICF - EAF - AFM	0,37	0,0	0,72

Table 11: Variation coefficients

Variation coefficients	Private optimization parameters		
	IRR	*CI*	*PP*
η_y	0,1570	0,1456	0,3156
η_d	0,6015	0,5581	0,5519

So, these scales of desirability are suitable for processing of statistical data.

The optimum version of the technological decision (from a position of primary managing subject) is determined by criterion:

$$D = \sqrt[4]{D^* \times d_1 \times d_2 \times d_3} \quad \rightarrow \quad \max \qquad (3)$$

d_1, d_2, d_3 – the private desirability of economic group parameters (*IRR, CI, PP*);

D^* – generalized desirability of private optimization parameters of the first five groups (from the table 6).

Calculation is presented in the table 12.

Table 12: The generalized desirability function of admissible options of technological smelting processes

№	Admissible options of technical process of iron smelting	Desirability				
		total 5 groups	Economic parameters			Generalized parameter
		D^*	*IRR* d_1	*CI* d_2	*PP* d_3	*D*
1	IICF - IICFM	0,475	0,40	0,74	0,62	0,543
2	**IICF - IIHFM**	**0,491**	**0,50**	**0,74**	**0,50**	**0,549**
3	IICF - EAF	0,474	0,0	0,67	0,45	0,0
4	IICF - IIHFM - AFM	0,436	0,80	0,58	0,0	0,0
5	IICF - IICFM - AFM	0,422	0,57	0,37	0,8	0,517
6	IICF - IICFM	0,412	0,37	0,0	0,72	0,0

Conclusion

The optimal variant of technological process of iron smelting (from a position of the decision-maker or the customer) is **IICF-IIHFM duplex process** because it is most in the best way corresponds to all complex of restrictions (***D = 0,549***).

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