Gold-mine productivity as affected by the average wet-bulb temperature of the underground working places

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SYNOPSIS

Objective justification on economic grounds for expenditure aimed at improving the quality of the underground working environment requires a suitable measure of any improvement in productivity that would result under routine working conditions. For this purpose, a composite production criterion is suggested, as well as its correlation under actual operating conditions with various factors directly affecting productivity and the environment. Of the environmental factors, wet-bulb temperature appears to be the major factor affecting productivity. The production data given indicate that a decrease in the wet-bulb temperature of 1 °C can be expected to result, on average, in some 3 to 4 per cent increase in productivity; in the higher temperature ranges, this percentage could be much higher.

SAMEVATTING

'n Objektiewe regverdiging op ekonomiese gronde vir uitgawes wat 'n verbetering in die gehalte van die ondergrondse werkomgewing beoog, vereis 'n geskikte maatstaf van enige verbetering in die produktiwiteit wat in roetinewerksomstandighede daaruit kan voortspruit. 'n Saamgestelde produksiekriterium tesame met sy korrelasie onder werklike bedryfstoestande met verskillende faktore wat die produktiwiteit en die omgewing raak, word vir die doel aan die hand gedoen. Van die omgewingsfaktore het die natboltemperatuur blykbaar die grootste uitwerking op produktiwiteit. Die produksiedata wat verstrek word, toon dat 'n daling van 1 °C in die natboltemperatuur na verwagting 'n verbetering van gemiddeld 3 tot 4 persent in die produktiwiteit tot gevolg sal hê; hierdie persentasie kan in die hoër temperatuurbestekke veel hoër wees.

Introduction

Because of the ever-increasing depths of working places and the associated higher rock temperatures, the gold mines in South Africa are faced with a need for increasing efforts to improve the quality of the underground working environment. Regular data on the quality of this environment include dry- and wet-bulb temperatures, wet kata-temperatures, air velocities, etc., and derived measures such as cooling power.[1] The environment has at least to be of a quality that is conducive to health. A further improvement could be justified on economic grounds to ensure the optimum trade-off between additional costs for refrigeration and/or ventilation on the one hand, and higher productivity on the other hand. Such an approach presupposes that productivity will rise as the environment, and more specifically the working temperature, is improved. This supposition can be accepted as valid in view of the results obtained in any elementary study of the relationship between seasonal variations in productivity and working temperatures on a mine. It was also confirmed as far back as 1961 in a research project[2] conducted by the Research Laboratories of the Chamber of Mines; this was a planned experiment and not based on routine production data.

To quantify the relationship between productivity and environment for use in the justification of refrigeration and ventilation projects on economic grounds and *on the basis of production data*, the following approach is suggested:

(*a*) the use of a single realistic measure for production;
(*b*) the inclusion of all the main variables that could have a significant effect on the environment or production, and
(*c*) the collection of adequate real data to ensure that a meaningful relationship can be established.

Unit of Production

Tonnage milled, tonnage broken, and gold produced are the more commonly used units of production in the South African gold-mining industry. Gold produced would be the obvious measure if the effects of variations in grade could be allowed for properly, and if the ratios of tons milled to tons broken (i.e., the activities absorbing the major production facilities) and to gold produced remained constant. As these conditions can never be met in practice, the following is proposed:

(1) for stoping — the major gold-producing activity — the unit should be square metres broken; this measure is independent of variations in grade but is directly related to gold production;
(2) for sweepings — a not insignificant gold-producing activity — the unit should be square metres swept converted to equivalent square metres stoped by use of a factor related to the relative work contents of a square metre swept and a square metre broken;
(3) for development — where reef development is also a direct gold-producing source and, together with off-reef development, is essential in providing access to new stoping units — the unit should be the equivalent square metres broken, also based on a relative work-content factor.

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The addition of the three above amounts provides the total equivalent square metres broken as a single measure of the effective level of production. The factors used in (2) and (3) will not be entirely objective but, provided the relative levels of the square metres for sweepings, development, and stoping do not vary drastically over the period studied, and provided the measure is not used for comparisons between different mines, changes to these factors within realistic ranges should not have a significant effect on the total equivalent square metres as a *relative* production measure for the same mine from month to month.

Factors Affecting Production

Apart from the average wet-bulb temperature of the working places in a mine (stopes and development ends), the quality of the environment can also be monitored by the wet kata-temperature and air velocity. Furthermore, a table recently published by Steward and Whillier[1] can be used to derive the composite measure of 'cooling power' of the air. Apart from the quality of the environment, production levels should naturally also be well correlated with the *numbers of productive workers* underground. The novices have been accepted as effectively unproductive for a limited period and have been excluded for periods ranging from 2½ to 3½ months. The production teams comprising the rockbreakers as team leaders and the underground labourers as team members are directly involved in the activities of breaking stope square metres, sweeping stoped areas, and advancing development ends. All the other underground and surface employees can be viewed as an 'overhead' work force required to provide the production teams with the required supervisory, back-up, and follow-through facilities.

If data are collected over a long period and for different mines or mine sections, a number of factors will also affect production levels, e.g., depth and spread of working places, degree of mechanization, widths and dips of orebodies mined, hangingwall conditions, etc. In the shorter term, the effects of these factors on the same mine should be small, and probably time-dependent; if so, this can be catered for, at least partly, by the incorporation of any trend in productivity linked to time. If

TABLE I

BASIC DATA FOR HARTEBEESTFONTEIN GOLD MINE, JANUARY 1975 TO MARCH 1978

Month No.	Rock breakers	Average wet-bulb temperature °C	Equivalent m² broken	Underground labourers: Total	Excluding novices for periods of (months): 2½	3	3½	Wet kata	Variances: Wet kata	Variances: Wet bulb	Air velocity in stopes m/s	Cooling power W/m²
1	142	30,2	105 854	11 732	11 339	11 217	11 098	11,1	—	—	1,15	317
2	138	30,5	101 709	11 486	10 947	10 732	10 756	11,1	—	—	1,17	305
3	135	30,6	100 583	11 542	10 706	10 545	10 627	10,1	—	—	1,13	297
4	134	29,5	94 660	11 445	10 486	10 279	10 241	11,4	—	—	1,19	351
5	133	29,0	91 490	11 003	9 853	9 439	9 423	12,8	—	—	1,30	383
6	130	28,7	98 118	11 318	9 690	9 305	9 368	13,5	—	—	1,40	405
7	128	28,4	102 444	12 359	10 496	10 233	10 082	13,9	—	—	1,19	399
8	132	28,2	105 452	12 654	11 073	10 791	10 245	13,3	—	—	1,06	395
9	129	29,0	106 833	12 404	10 968	10 624	10 197	12,5	—	—	0,99	354
10	129	29,0	101 787	12 455	10 732	10 263	10 205	12,6	—	—	1,02	357
11	132	29,6	96 404	12 539	10 656	10 400	10 091	11,3	—	—	1,09	338
12	134	29,9	94 487	12 381	10 852	10 774	10 164	10,9	—	—	1,08	324
13	132	30,4	91 883	11 841	10 802	10 431	9 863	10,6	—	—	1,14	307
14	133	30,6	90 419	12 545	11 049	10 451	10 537	10,6	—	—	1,18	301
15	139	30,8	93 785	14 198	12 064	11 868	11 908	10,0	—	—	1,06	283
16	142	29,9	95 905	14 454	12 679	12 493	11 937	10,9	—	—	1,08	324
17	141	29,4	101 372	14 468	13 490	13 277	12 294	11,0	—	—	0,85	323
18	145	28,9	109 628	14 595	13 596	13 397	13 204	12,0	—	—	0,89	348
19	145	28,2	112 239	14 575	13 491	13 232	13 118	12,5	—	—	0,95	382
20	150	28,3	111 407	14 227	13 063	12 816	12 637	12,7	—	—	0,93	376
21	151	28,6	109 345	13 209	12 197	12 197	11 798	12,2	—	—	0,87	357
22	150	29,4	101 383	12 549	11 757	11 460	11 239	11,2	—	—	0,99	338
23	146	29,1	91 728	11 893	10 941	10 584	10 447	11,8	—	—	1,15	366
24	141	30,0	81 450	11 169	9 705	9 551	9 705	10,7	—	—	1,06	318
25	136	30,3	74 194	10 883	8 939	8 018	8 344	10,9	12,7	2,6	0,94	295
26	129	31,0	79 164	13 593	11 217	10 993	10 503	9,1	8,4	2,0	0,94	264
27	132	30,4	86 631	15 219	12 926	12 924	12 617	10,4	8,3	2,1	1,05	300
28	133	29,8	93 410	14 911	14 440	14 422	12 598	11,0	11,0	2,5	1,04	325
29	135	29,1	99 012	14 677	14 458	14 280	14 009	12,1	9,5	3,6	1,06	357
30	135	28,3	101 343	15 060	14 644	14 622	14 640	12,2	8,9	3,7	0,97	381
31	144	28,9	108 485	14 920	14 321	14 125	14 285	11,8	8,6	3,9	0,94	353
32	145	29,4	110 574	15 045	14 405	14 204	14 048	11,4	9,4	3,9	0,99	338
33	143	29,9	104 706	14 482	13 536	13 387	13 491	9,6	9,3	4,0	0,91	309
34	141	30,2	104 481	14 217	13 380	13 246	12 987	9,8	10,1	3,9	1,00	304
35	143	30,0	102 552	13 957	13 199	13 010	12 796	10,9	8,6	2,9	1,09	321
36	139	30,6	92 374	13 354	12 654	12 603	12 355	10,5	6,6	2,4	1,03	289
37	135	30,6	86 092	12 990	12 400	12 292	12 131	9,6	9,2	2,4	0,90	278
38	138	31,1	88 913	14 093	13 716	13 658	13 337	9,3	10,0	3,0	0,95	260
39	136	30,6	93 991	14 511	14 096	14 014	13 993	9,8	10,3	2,2	1,32	310

TABLE II

ANALYSIS OF DATA GIVEN IN TABLE I

	Corr. coeff. with m²	Regression coeff.	Standard error of regr. coeff.	Mean
(1) Average wet-bulb temp., °C	−0,624	−4 010,1	970,0	29,65
(2) Underground labourers excl. novices for $3\frac{1}{2}$ months	0,426	4,151	0,684	11 623
(3) Month no.	−0,170	−523,8	97,5	20
(4) Rockbreakers	0,435	359,4	134,1	137,8

Multiple correlation coefficient = 0,878
Y-intercept for regression formula = 129 448,5 m²/month
Mean of m² distribution = 97 853 m²/month

Regression formula:

m² broken = 129 448,5 − 4 010,1 (temp. °C) + 4,151 (U/G labourers less novices) − 523,8 (month no.) + 359,4 (rockbreakers).

Standard error of regression estimate = 4606,0
= 4,7 % of mean m².

Regression coefficients as percentages of the mean m²:

Average wet-bulb temperature = 4,1 % (standard error 1,0 %)

Month number = −0,54 %

the months covered by the data used are numbered consecutively, and the month number as a further independent variable is correlated with the dependent variable of production, any net trend in productivity with time should become evident.

Data and Analysis

The main data on the quality of the underground environment available on a regular basis for mines cover the average wet-bulb temperature of the working places, the wet kata-thermometer readings, and the air velocity along stope faces; more recently, data on the spread of wet-bulb and wet-kata readings across the individual working places have been recorded monthly. From the wet-bulb and air-velocity figures, the corresponding monthly cooling power of the air in watts per square metre can be derived.[1] The monthly temperature and other data figures for the Hartebeestfontein Mine for the period January 1975 to March 1978 are recorded in Table I. The data were subjected to a stepwise multiple-regression analysis with square metres broken as the dependent variable and all the other data listed for the period of 39 months as independent variables without

TABLE III

BASIC DATA FOR A GROUP OF 27 LARGE GOLD MINES, JANUARY 1975 TO MARCH 1978

Month no.	Rock-breakers	Average wet-bulb temperature °C	Equivalent m² broken	Underground labourers excluding novices for (months):			Monthly turnover for underground labourers %
				$2\frac{1}{2}$	3	$3\frac{1}{2}$	
1	2 395	29,2	1 435 126	162 049	158 889	158 787	11,13
2	2 365	29,4	1 426 697	162 467	159 072	158 862	11,61
3	2 325	29,4	1 440 691	161 909	158 368	159 716	10,95
4	2 377	28,9	1 458 149	163 315	159 175	156 981	12,82
5	2 362	28,7	1 499 182	165 817	161 858	159 015	11,41
6	2 357	28,1	1 558 513	172 003	169 044	164 908	8,52
7	2 341	28,0	1 580 544	178 471	175 633	170 181	7,63
8	2 369	28,1	1 566 435	178 532	175 041	170 603	9,43
9	2 336	28,4	1 539 327	174 145	169 981	168 216	10,23
10	2 369	28,4	1 511 149	169 574	165 392	163 881	11,40
11	2 355	28,7	1 446 629	165 617	161 989	158 619	10,61
12	2 331	29,1	1 385 693	160 718	158 543	152 378	7,82
13	2 323	29,2	1 376 827	158 489	151 893	150 108	17,01
14	2 335	29,3	1 408 000	169 482	162 243	162 215	16,18
15	2 388	29,2	1 445 926	175 411	170 572	171 050	12,34
16	2 367	28,9	1 455 822	181 242	177 846	168 033	9,69
17	2 373	28,6	1 487 722	189 979	186 723	175 490	8,60
18	2 406	28,2	1 537 973	192 007	188 160	182 319	9,11
19	2 425	27,9	1 545 004	191 821	188 153	185 011	8,61
20	2 460	28,0	1 527 558	184 808	180 667	178 286	9,75
21	2 444	28,1	1 516 966	181 726	181 726	174 020	0,41
22	2 444	28,6	1 472 091	178 934	175 377	171 585	10,23
23	2 421	28,9	1 375 456	173 093	169 116	164 799	12,47
24	2 376	28,8	1 283 042	158 379	156 138	158 379	10,45
25	2 336	29,0	1 260 136	156 761	146 964	149 634	21,90
26	2 340	29,5	1 326 078	183 320	177 426	175 356	13,73
27	2 378	29,3	1 404 591	187 192	184 150	182 699	8,87
28	2 444	29,1	1 449 898	196 596	192 105	176 994	12,55
29	2 447	28,7	1 497 385	209 712	207 165	197 906	7,66
30	2 454	28,0	1 532 443	206 966	204 515	200 867	8,90
31	2 477	28,3	1 572 741	213 314	210 772	204 321	8,85
32	2 491	28,3	1 597 348	212 398	208 733	207 294	12,19
33	2 478	28,8	1 584 750	214 966	212 996	210 051	9,83
34	2 502	29,1	1 586 513	211 813	209 538	206 717	10,39
35	2 492	29,3	1 526 133	206 714	204 173	199 372	12,29
36	2 473	29,4	1 422 131	196 862	194 902	192 908	10,70
37	2 435	29,6	1 419 449	197 755	193 857	193 194	16,06
38	2 456	29,9	1 478 218	212 996	211 940	207 904	8,65
39	2 518	29,5	1 500 545	223 226	221 794	219 292	9,19

any transformations. The following independent variables were selected in the sequence listed in Table II, and the remaining variables were rejected on the basis of a minimum F value of 4 for acceptance of a variable and a maximum F value of 3,9 for removal of a variable.

The data for a second analysis covered only the last 15 months for the above 4 variables plus the variance in wet-bulb temperature across the individual working places, but was too limited; in fact, only the independent variables nos. (2), (3), and (4) in Table II were accepted. Thus, the only environmental factor selected as significant was wet-bulb temperature.

Following the analysis for the Hartebeestfontein Mine, a similar analysis was done by the Chamber of Mines of South Africa over the same period for a group of 27 large gold mines but accepting only wet-bulb temperature as the main measure of the quality of the environment. An additional variable of monthly turnover of underground labourers was included.

However, this new variable was rejected as contributing no significant additional information towards the explanation of variations in production levels. In this case, for the number of underground labourers, the exclusion of novices was selected on a 3 months' basis. The basic data are recorded in Table III, and the results of the analysis in Table IV. The high multiple-correlation coefficient indicates that the four independent variables explain almost 90 per cent ($r^2 = 0,89$) of the total variability in the monthly production levels.

The close agreement for the group of 27 mines between the actual number of square metres broken and that estimated from the above regression formula is evident from Fig. 1.

The analysis was also done for the individual mines (excluding turnover rate) and resulted in the skew distribution shown below for the temperature regression

TABLE IV

ANALYSIS OF DATA GIVEN IN TABLE III

	Corr. coeff. with m²	Regression coeff.	Standard error of regr. coeff.	Mean
(1) Average wet-bulb temp., °C	−0,567	−48 526	9 982,2	28,82
(2) Underground labourers excl. novices for 3 months	0,575	4,663	0,517	180 580
(3) Month no.	0,045	−6 738,3	804,7	20
(4) Rock-breakers	0,466	277,6	172,1	2 404,2

Multiple correlation coefficient = 0,941
Y-intercept for regression formula = 1 496 571 m²/month.
Mean of m² distribution = 1 472 789 m²/month.

Regression formula:
m² broken = 1 496 571 − 48 526 (temp. °C) + 4,663 (U/G labourers − 6 738,3 (month no.) + 277,6 (rockbreakers).
Standard error of regression estimate = 29 514,6
= 2,0 % of mean m².
Regression coefficients as percentages of the mean m²:
Average wet-bulb temperature = −3,2 % (standard error 0,7 %)
Month number = −0,45 %.

TABLE V

SUMMARY OF REGRESSION FORMULAE

		Hartebeest-fontein	27 mines
Mean of m² broken	(C)	97 853	1 472 789
Y-intercept		132,3 %C	84,5 %C
Temperature, °C	(T)	−4,1 %C.T	−3,3 %C.T
Month no.	(M)	−0,54 %C.M	−0,45 %C.M
Rockbreakers	(R)	+359,4R	+277,6R
Underground labourers	(B)	+4,151B	+4,663B

coefficient expressed as a percentage of the average total of monthly square metres:

Category limits, %	1	2	3	4	5	6	7
Frequency	5	5	4	8	3	–	– 2

The regression formulae for the Hartebeestfontein Mine and for the group of 27 mines are summarized in Table V. It should be noted that the number of underground labourers excluded novices for 3½ months for Hartebeestfontein and 3 months for the 27 mines. Furthermore, the conversion factors from sweepings and development to equivalent centares broken varied from mine to mine. The regression coefficients for temperature and month, expressed as percentages of the average square metres broken, are nevertheless of the same order for Hartebeestfontein and the group of 27 mines; for temperature, the category 1 to 5 per cent included 20 of the 27 individual mines.

If a new ventilation project concerns a specific mine section, conditions could differ from those for the mine as a whole and, if at all possible, a similar regression analysis should be conducted on specific data from that section. Where feasible, the possibility should also be investigated of a nonlinear regression of production on temperature; it seems obvious that the slope (estimated at above 3 to 4 per cent) for wet-bulb temperatures in the range from say 28 to 31°C should steepen at the upper end of the temperature range, and should approach zero at some temperature below the ranges analysed for Hartebeestfontein and for the group of 27 mines. This was confirmed by work[2] conducted by the Research Laboratories of the Chamber of Mines; this work indicated a zero slope at 28°C and a slope of 3½ to 4 per cent at 31°C. A non-linear approach was attempted for the data of the 27 mines by transforming temperature (T) to $e^T/10^{12}$; the multiple correlation coefficient was only slightly reduced from 0,942 to 0,929, and the regression coefficient for temperature as transformed was −13 226,7, indicating a slope of 1,3 per cent at 28°C and 9,6 per cent at 30°C. The regression coefficients for the individual 27 mines also show some positive correlation with the corresponding 27 average wet-bulb temperatures; however, in view of the limited data the trend is not significant ($r = 0,25$).

Conclusions

The above analyses indicate that, within the ranges and the limitations of the available data, wet-bulb temperature is the most significant measure of environmental quality. They also indicate that a change of 1°C in average wet-bulb temperature affects productivity by

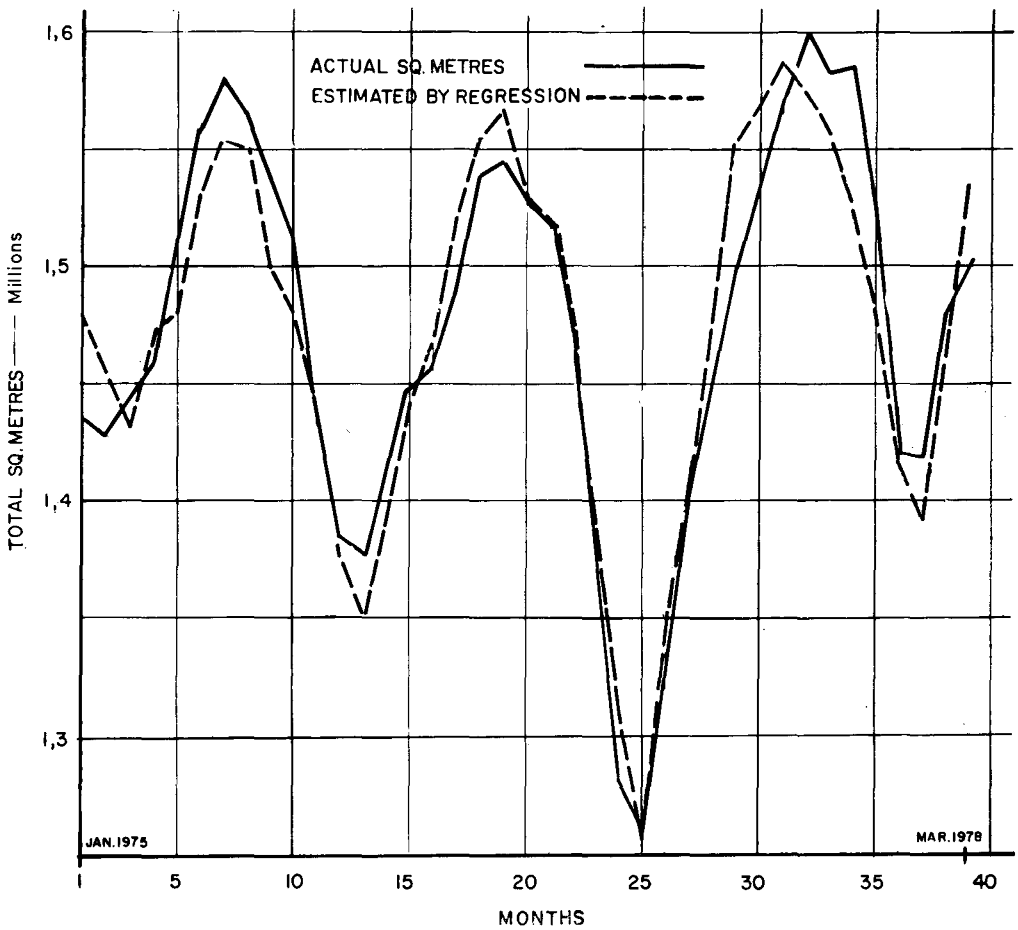

Fig. 1—Total equivalent square metres broken for a group of 27 gold mines

an estimated average extent of some 3 per cent. The extent, if any, to which the percentage for a mine or section will vary within and outside the temperature ranges observed cannot be stated with confidence on the basis of the available data, although it seems logical that, at temperatures of 30°C and higher, the percentage should be higher. A quantitative approach based on production data is thus suggested for the economic analysis of any new ventilation or refrigeration project.

Also, from this analysis it seems that, on balance,

(*a*) productivity declined over the period studied by some ½ per cent per month;

(*b*) the marginal productivity of one additional underground labourer is small (4 to 5 m^2 per month) whereas that of an additional rockbreaker is large (some 300 m^2 per month).

The indicated decline in productivity is serious, and warrants continued study and analysis. The marginal productivities of underground workers should not be accepted at their relative levels without qualification. The rockbreaker and his team should be seen as a workers' unit, and the combined figure of additional centares produced by an additional *team* then becomes meaningful, i.e., the number of rockbreakers should rather be seen as the *number of production teams*.

There appears to be considerable scope for further analyses along these lines.

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