VIEIRA, F.M.C.C. Utility-based framework for optimal mine layout selection, subject to multiple-attribute decision criteria. *Application of Computers and Operations Research in the Minerals Industries,* South African Institute of Mining and Metallurgy, 2003.

Utility-based framework for optimal mine layout selection, subject to multiple-attribute decision criteria

F.M.C.C. VIEIRA
CSIR Miningtek, Auckland Park, Gauteng, South Africa

Four mining alternatives for exploiting an ultra-deep orebody were assessed through a multidisciplinary evaluation process which involved: the generation of a 3D geological model; the design and scheduling of life-of-mine layouts; the analysis of anticipated ventilation and cooling conditions; the study of rock-related risks of mining in ultra-deep stress environments; the logistic implications of transporting men, rock and materials; and, lastly, the economic implications of each option. Once results from the integrated mine design assessment were available, mine planners were faced with an important problem to solve: how to identify the optimal mine design alternative when numerous assessment measures and multiple decision criteria needed to be considered simultaneously? To address this 'multiple-attribute decision problem' and arrive at the 'optimal layout for ultra-depth', a generic decision methodology that uses principles of 'utility'was applied. The methodology assumes that 'single-value risk estimators' do not account for the inherent variability of real conditions. Therefore, risk estimators were represented by statistical distributions of their incremental changes, where applicable. The stochastic variables, once defined, are used as inputs in the 'utility'-based layout decision scheme. This 'utility'-based decision methodology offers a framework for mine design decisions to be made objectively, when complex trade-offs between multiple risk domains need to be considered simultaneously. Upon applying it, one of the layouts emerged as the preferred alternative

Keywords: Utility; mine design; multiple-attribute decision; layout selection

Introduction

Suppose that you are to decide which of four mining layout alternatives is the best option for extracting an ultra-deep orebody. Based on preliminary studies you have determined that all alternatives are implementable from an engineering viewpoint. Consider that strict guidelines are to be met by the optimal layout for ultra-depth, and that these include fulfilling five 'fundamental objectives' as follows:

- *Life-of-mine production output*—the layout must enable the best production output over the life-of-mine
- *Rock engineering*—the layout design must comply with best practice rock engineering criteria, in order to minimize rock related risk (seismicity, falls-of-ground, pillar failures, etc)
- *Ventilation, cooling and refrigeration*—the layout must be efficient and cost effective from a viewpoint of ventilation, cooling and refrigeration engineering
- *Logistics*—men, materials and rock: logistic systems for cleaning and transport of men, materials and rock must enable optimal delivery
- *Economics*—the layout must be viable from a financial viewpoint, i.e. to be the lowest cost producer yielding the highest return on investment.

Suppose that for each of the above fundamental objectives, a number of attributes were identified (Table II) and that compliance criteria have been specified (e.g. maximize, minimize). Consider that specialized studies have been conducted and that 'levels' of each attribute were determined using various approaches (numerical modelling, back analysis, expert knowledge, etc). Some attribute levels would have been determined as 'point estimate' figures (deterministic levels) and others defined stochastically, by a representative probability distribution; the mean and standard deviation; maxima and minima (uniform distributions), etc.

Suppose that certain attributes could only be specified qualitatively by using descriptors such as 'best', 'worst', 'high', 'low', etc. For each of the available mining alternatives you have compiled a decision analysis matrix that contains assessment data relevant to formulating a decision (e.g. Table III, Table IV, Table VI, Table VII, Table VIII). Your task is now to determine which of the mine design alternatives is best, when all objectives and respective attributes are considered simultaneously. Can you do it?

There are many trade-offs that should be considered when making mine design decisions involving multiple constraints such as those above. The 'real world' of decision-making in mining engineering is full of complex multiple-attribute decision problems, involving various trade-offs. Decisions based on single objectives are unrealistic, and should be discarded. Choosing a layout based on rock-engineering objectives alone, for example, would mean little should relevant (often conflicting) objectives such as the impact on production output, ventilation, cooling and refrigeration systems (VCR), logistics and financial viability not be considered simultaneously.

The description of a realistic mine design decision problem is presented here. Various computer applications were used to assess the different design alternatives. The

Table I
Sample of a decision analysis matrix (weighted objectives)

Objectives →		O_1	O_2	O_j	O_n	
Relative weights →		w_1	w_2	w_j	w_n	Relative utility
Attributes →		x_1	x_2	x_j	x_n	
Alternatives	a_1	p_{11}	p_{12}	p_{1j}	p_{1n}	$U_1 = \sum_j p_{1j} w_j$
	a_2	P_{21}	p_{22}	p_{2j}	p_{2n}	$U_2 = \sum_j p_{2j} w_j$
	$\vdots$					$\vdots$
	a_i	p_{i1}	p_{i2}	p_{ij}	p_{in}	$U_i = \sum_j p_{ij} w_j$
	$\vdots$					$\vdots$
	a_m	p_{m1}	p_{m2}	p_{mj}	p_{mn}	$U_m = \sum_j p_{mj} w_j$

a_i = the ith alternative, $i = 1$ to m
O_i = the ith objective, $j = 1$ to n
x_j = the jth attribute of objective j (singular case of one attribute for each objective)
w_j = the relative weight of importance to objective O_i, $j = 1$ to n
p_{ij} = the probability of attaining the objective O_i through alternative a_i (measured by attribute x_j)
U_i = the overall relative utility of alternative a_i to attain objectives O_i

Table II
Attributes and criteria selected

Rock engineering		**Ventilation cooling and refrigeration**	
Regional loading (VER) over 3 mining years (MJ x 10^6)	Min	Wet-bulb temp. (°C)	Min
P (APS < 2.5 x UCS) on all designed regional pillars	Max	Heat load (kW/ktpm)	Min
Benefit of backfill reducing APS on planned pillars (%)	Max	Refrigeration requirement (kW)	Min
P(ERR < 30 MJ/m^2) on all active faces planned	Max	Air requirements (kg/s/ktpm)	Min
Inferred maximum event magnitude on active faces	Min	Air power (kW/ktpm)	Max
Inferred cum. seismic energy on active faces (J x 10^6)	Min	VCR power consumption (MWE/yr)	Min
Probability of ESS peak above 45 MPa (slip precursor)	Min	VCR systems OPEX (Rm/t)	Min
Probability of slip ride on features (slip above 11 cm)	Min	Independence of vent districts	Best
Benefit backfill in reducing positive ESS lobes (%)	Max	Potential for concentration of ventilation	Best
Cumulative seismic moment of slip events (Nm x 10^6)	Min	Potential for in-stope vent control	Best
Maximum inferred magnitude of slip events on features	Min	Potential for multi-shift blasting	Best
Footwall stress relaxation index (s) along tunnel paths	Min	Ventilation short-circuiting avoidance	Best
Footwall stress orientation index (o) along tunnel paths	Min	In-stope air cooling potential	Best
Range of influence of RCF variability (m) along tunnels	Min	Air contaminants control	Best
RCF variographic index ($D = \gamma(d)_{min}$) along tunnels	Min	Escape and evacuation ease	Best
Likelihood orepass failure as caused mining sequence	Min	Fire risk control potential	Best
Logistics: men, materials and rock		**Production**	
Personnel utilization/lease	Min	LOM area mined (km^2)	Max
Total locomotives/lease (conventional tramming)	Min	Regional extraction (%)	Max
Material cars/stope/month	Min	Build-up period (yrs)	Min
m^2/ material car	Max	Stoping/development ratio over LOM (m^2/m)	Max
Average km-t/loco	Max		
Face cleaning rate (t/hr)	Max	**Economics**	
Gully cleaning rate (t/hr)	Max	Gold produced (t)	Max
Tramming output (t/x.cut/month)	Max	NPV (Rm)	Max
Avg. length monowinch (m)	Min	IRR (%)	Max
		PBP (yrs)	Min

geological model, mine design model and life-of-mine scheduling were carried out using CADSmine; rock engineering evaluations were done using MINSIM, MAP3D and MINF; the ventilation, cooling and refrigeration studies were conducted using VUMA; and the economic implications were studied in MinEcon. Highlights of the results are briefly discussed to present the complexity of multidisciplinary solutions. Faced with a multiple objective, multiple criteria, multiple attribute decision dimension, a utility-based framework is proposed to structure the decision problem and then select the optimal alternative.

Description of the decision problem

The Iponeleng orebody

The geological model of a typical ultra-deep Ventersdorp Contact Reef orebody, derived from the interpretation of a 3D reflection seismic survey constrained by information from shallower mining and boreholes[3], was considered.

Table III
Summary of production results

Objective	Production performance						
Weight	0.3		0.4		0.2		0.1
Attributes	BUP (yrs)		LOM reserves mined (km^2)		Regional extraction (%)		LOM stope/dev ratio (m^2/m)
	Min	Max	Mean	St. dev.	Mean	St. dev.	Mean
Alternative							
LSP	5	7	12.04	1.21	68.0	7.0	29.5
SGM	9	10	10.48	1.12	59.5	6.5	70.5
SDD	5	7	8.56	0.88	48.0	5.0	69.75
CSDP	6	6	11.32	0.84	64.0	2.0	69.75

Table IV
Summary of ventilation, cooling and refrigeration performance results (quantitative analysis)

Objective	Ventilation, cooling and refrigeration performance (quantitative)												
Weight	0.15		0.15		0.10		0.10		0.10		0.20		0.20
Attributes	Wet Bulb Temp. (°C)		Heat Load (kW/ktpm)		Refrigeration requirement (kW)		Air requirements (kg/s/ktpm)		Air power (kW/ktpm)		VCR systems operating cost (Rm/t)		VCR elec.t power consump. (MWE)
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Avg.
Alternative													
LSP	20	29	100.2	103.5	120.6	132.4	3.91	3.99	21.5	27.1	783	820	75.7
SGM	20	29	69.4	88.4	106.9	116.9	4.14	6.24	27.7	28.1	699	790	67.5
SDD	20	27.5	94.4	123.5	118.9	127.8	6.85	6.89	52.5	54.0	824	845	79.6
CSDP	20	28.2	72.1	73.7	101.1	115.1	3.58	3.95	23.1	24.8	640	750	72.6

VCR = Ventilation, cooling and refrigeration

Table V
Summary of ventilation, cooling and refrigeration performance results (qualitative analysis)

Objective	Ventilation, cooling and refrigeration (qualitative)								
Weight	0.13	0.13	0.13	0.08	0.11	0.15	0.05	0.11	0.11
Attributes	Potential for creating independent ventilation districts	Degree of concentration of ventilation areas	Relative ease of in-stope vent control	Potential for multi-shift blasting	Potential for avoiding short-circuiting	Potential for in-stope air cooling	Potential to minimize build-up in air contaminants	Ease of escape and evacuation	Potential to minimize fire risk
Alternative									
LSP	B1	B1	W2	W2	B1	W1	S1	B1	W2
SGM	B1	S1	S1	B2	W2	W2	S1	S1	S1
SDD	S1	W1	B1	B1	S1	B1	B1	S1	S1
CSDP	S1	W2	S1	W2	S1	W2	S1	S1	S1

B1 = best; B2 = better; S1 = satisfactory; W1 = worse; W2 = worst

Table VI
Economic attributes

Objective	Economic performance							
Weight	0.3		0.4		0.1		0.2	
Attributes	Gold produced (t)		NPV (Rm)		IRR (%)		PBP (yrs)	
	Mean	St. dev.	Min	Max	Min	Max	Min	Max
Alternative								
LSP	696.83	57.69	21	56	10.10	10.26	14.5	16
SGM	593.66	33.70	-81	63	9.96	10.25	16	17.5
SDD	602.55	44.12	143	388	10.64	11.91	13	15
CSDP	716.16	15.46	531	632	12.12	12.33	12.75	14.5

BUP = Build Up Period; NPV= Net Present Value; IRR = Internal Rate of Return; PBP = Pay Back Period

Table VII
Summary of logistics performance results

Objective	Logistics: Transport men, material and rock (qualitative)								
Weight	0.20	0.05	0.15	0.10	0.05	0.09	0.09	0.22	0.05
Attributes	Personnel required/ lease	Number of locomotives/ lease	Material cars per stope/month	m^2/ material car	Average (km-t/loco)	Face cleaning rate (t/hr)	Strike gully cleaning rate (t/hr)	Tramming output (t/x.cut/month)	Operating length of monowinch (m)
Alternative									
LSP	3625	174	131 -165	17.5 - 19.2	7087	28 - 31.5	10.1-15	6372	84 - 96
SGM	2388	108	164	22.0	10173	29 - 34	10.6 - 21.4	16065	100
SDD	2756	160	89	15.5	9492	24.0	70.0	5685	235
CSDP	2786	147	284	14.5	4110	41.8	12.9 - 25.7	18975	139

Table VIII
Rock engineering principal and partial objectives, related attributes and weights

	k_i	w_i	Alternatives →	LSP		SGM		SDD		CSDP	
				Min	Max	Min	Max	Min	Max	Min	Max
Principal objective: Sustainable rock engineering systems		Objectives 1: Regional stability effectiveness									
	0.2	0.2	Regional loading (VER) over 3 mining years (MJ x 10^6)	3.12	5.20	5.04	7.14	1.04	1.28	2.18	4.87
		0.5	P (APS < 2.5 x UCS) on all designed regional pillars	0.70	0.80	0.88	0.91	0.97	0.99	0.89	0.95
		0.3	Benefit of backfill reducing APS on planned pillars (%)	8.0	22.0	2.0	14.0	1.0	3.0	1.5	11.0
		Objectives 2: Active face stability effectiveness									
	0.4	0.5	P(ERR < 30 MJ/m^2) on all active faces planned	0.62		0.65		0.88		0.51	
		0.2	Inferred maximum event magnitude on active faces	2.30		2.65		2.61		2.90	
		0.3	Inferred cum. seismic energy on active faces (J x 10^6)	30.00		43.49		27.48		39.20	
		Objectives 3: Mining adjacent to geological features									
	0.3	0.2	Probability of ESS peak above 45 MPa (slip precursor)	0.68		0.80		0.86		0.78	
		0.2	Probability of slip ride on features (slip above 11 cm)	0.85		0.50		0.00		0.12	
		0.2	Benefit backfill in reducing positive ESS lobes (%)	26.0		18.0		5.0		16.0	
		0.2	Cumulative seismic moment of slip events (Nm x 10^6)	10.0	80.0	0.6	10.0	0.4	2.0	0.4	5.0
		0.2	Maximum inferred magnitude of slip events on features	3.4	4.0	2.6	3.4	2.5	2.9	2.5	3.2
		Objectives 4: Off reef stability effectiveness									
	0.1	0.2	Footwall stress relaxation index (s) along tunnel paths	0	0	0.2	0.5	0.1	0.4	0.1	0.4
		0.2	Footwall stress orientation index (o) along tunnel paths	0	0	0.1	0.5	0.1	0.4	0.1	0.4
		0.1	Range of influence of RCF variability (m) along tunnels	0		149		57		98	
		0.3	RCF variographic index ($D = \gamma(d)_{min}$) along tunnels	0.1		0.3		0.7		1.6	
		0.2	Likelihood orepass failure caused mining sequence	Lower		Higher		Moderate		High	

k_i = partial objectives weights; w_i = attribute weights

Several reflectors representing major stratigraphic breaks were mapped. Faults with throws greater than 18 m clearly offset the reflectors and could easily be mapped, while faults with throws less than 6 m cannot be detected. The orebody considered is 24 square kilometres in extent, ranging from 3800 m to 5000 m below surface, with an average dip of 23° (Figure 1). This model orebody with a total mineral resource area of 19.7 x 106 m2 was named 'poneleng', a Setswana word meaning 'discover me' or 'explore me'. A reef thickness of 1.5 m was assumed, typical of the Ventersdorp Contact Reef horizon.

Certain operational assumptions were made and applied consistently. Firstly access to the ultra-deep reserves is through an existing main-shaft and a newly sunk sub-shaft system, the latter infrastructure requiring new capital investment. The position for the sub-shaft infrastructure was assumed to be common for all tested alternatives. The shaft intersects reef at a depth of 3500 m below surface. The full sub-shaft column ranges from a depth of between 3500 m to 5020 m below surface.

The alternatives

Four mine layout alternatives are proposed to extract Iponeleng reserves (Figure 2). A detailed description of these mining methods is given by Vieira *et al.*[5] and is not repeated here, although the following characteristics should be noted:

- The longwall layout with strike pillars (LSP) advocates a breast advance sequence
- The sequential grid mining layout (SGM) advocates single-side breast mining in cyclic raise-availability periods. Pillars are orientated along the dip-direction
- The sequential down-dip mining (SDD) advocates down-dip extraction. Pillars are also orientated along the dip-direction
- Closely-spaced dip pillar mining (CSDP) advocating breast mining with an overall up-dip direction and with dip-orientated stability pillars.

Scenarios studied

A minimum production target to mine at least 45 000 m2 of gold-bearing conglomerates per month was set, in view of preliminary economic considerations. The four conceptual mine designs were applied to arrive at an extraction path of the Iponeleng orebody and then subjected to exhaustive evaluation with respect to: efficiency and cost of providing ventilation and refrigeration; efficiency and cost of transporting men, material and rock; the degree to which rock engineering criteria, such the energy release rates, average pillar stress, excess shear stress and stresses in footwall excavations, were met; and the financial viability of each alternative, using a comparative cost model.

Mill tonnage profiles were calculated based on a pre-defined ore-account scheme of each layout and the respective production profiles from CADSmine scheduling models (Figure 3). The impact of three mining scenarios was investigated for each alternative, namely:

- *Scenario 1*—The base case considered full extraction of reserves, whereby the entire lease ground had reef at a constant grade
- *Scenario 2*—Specific mining rules, (e.g. rates of stope advance, development, equipping delays, etc.) applied to Scenario 1 evaluation, were optimized to produce more realistic extraction models. A constant grade was still applied throughout, though
- *Scenario 3*—A *kriged* grid of variable grade was applied to all Scenario 2 models, to test the impact of grade variability.

These studies enabled the determination of the range of variability of certain attributes.

The fundamental objective

The decision maker (mine management) needs to determine which layout design is most appropriate to safely and economically extract the Iponeleng reserves. Upon consulting the relevant experts it is determined that in order to attain the main objective a number of secondary objectives need to be met in parallel. Debate on the best way to structure the decision problem suggested that the objectives hierarchy in Figure 4 would characterize with the decision problem with sufficient confidence.

Specialist studies results

LOM production output

Numerous scheduling iterations in CADSmine yielded the best possible attainable production profiles over the life-of-mine (LOM) (see Figure 5). It emerged from a production

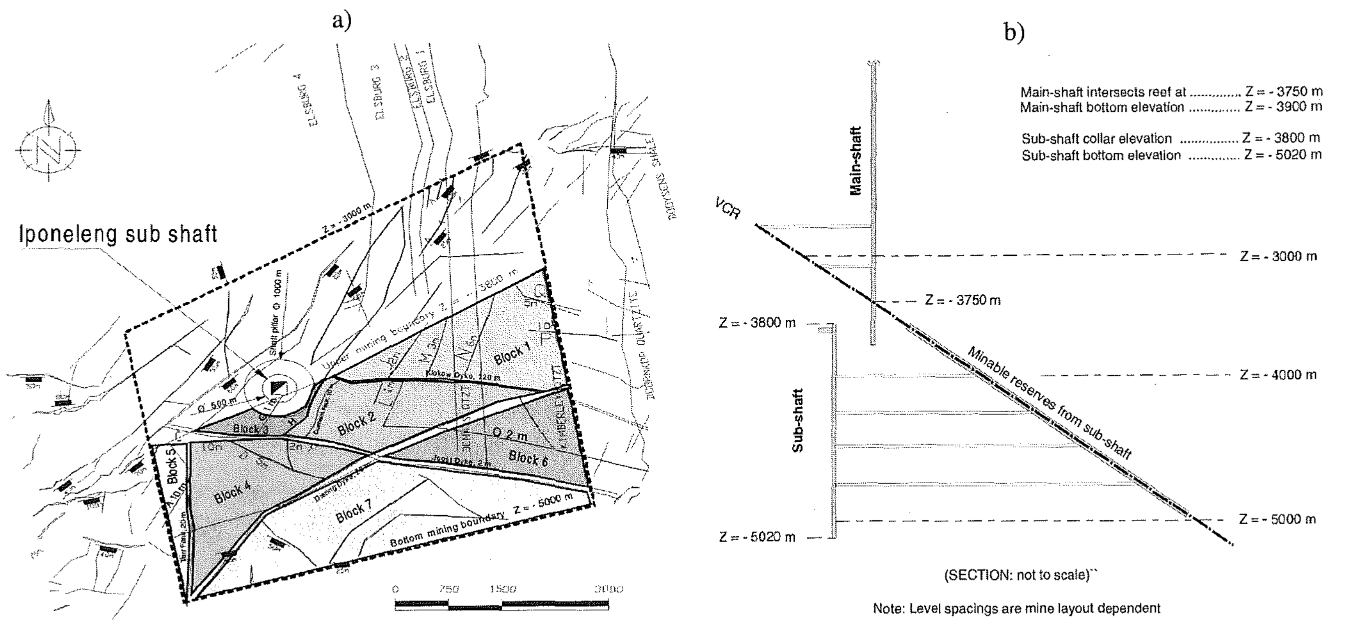


Figure 1. Iponeleng Mine geological model with identified mining blocks (a) and vertical limits of the mineable reserves (b)

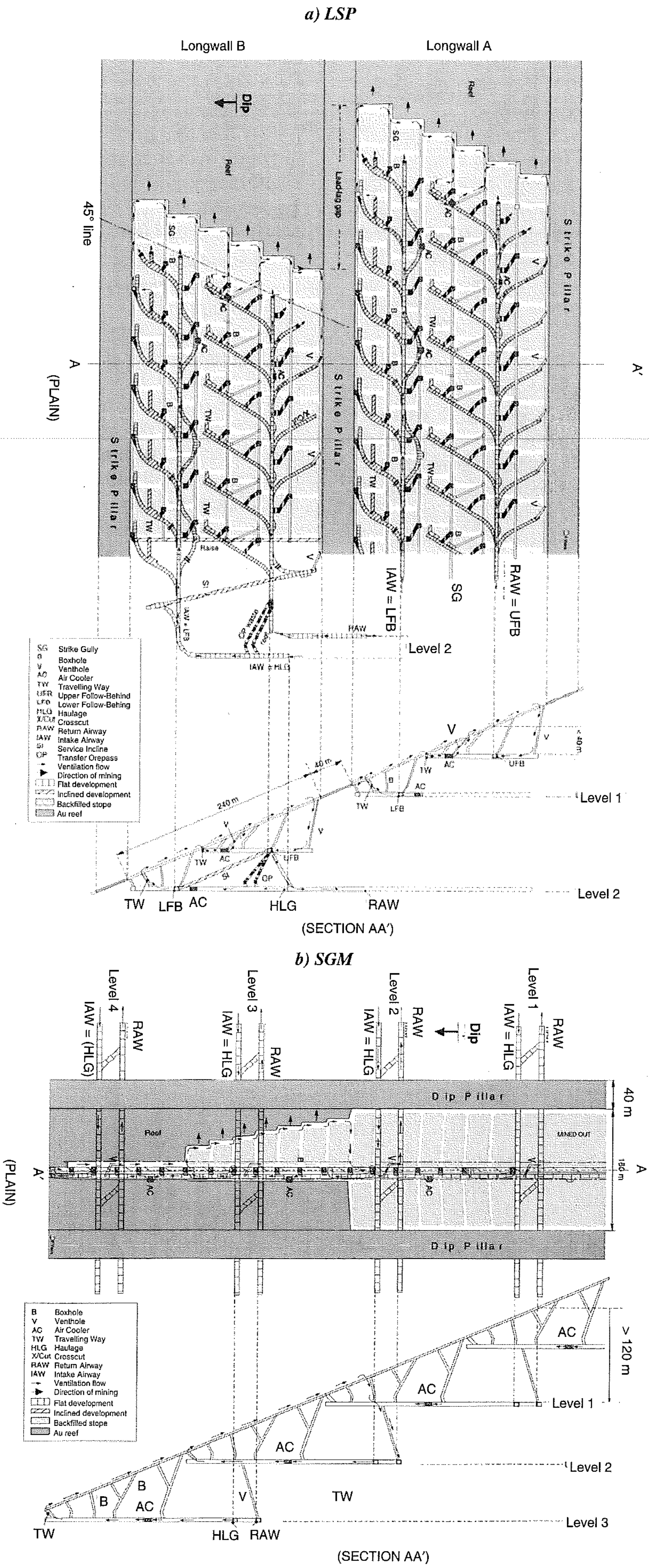
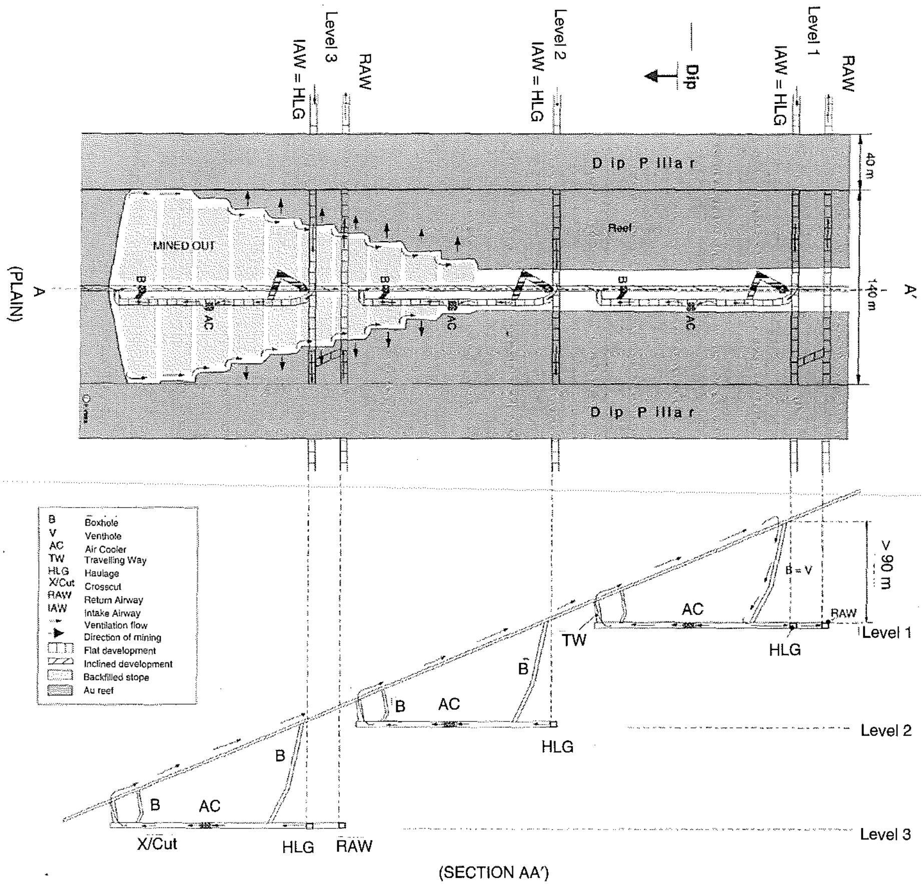


Figure 2. Micro concepts of mining layout for ultra-deep narrow, tabular deposits

c) CSDP



d) SDD

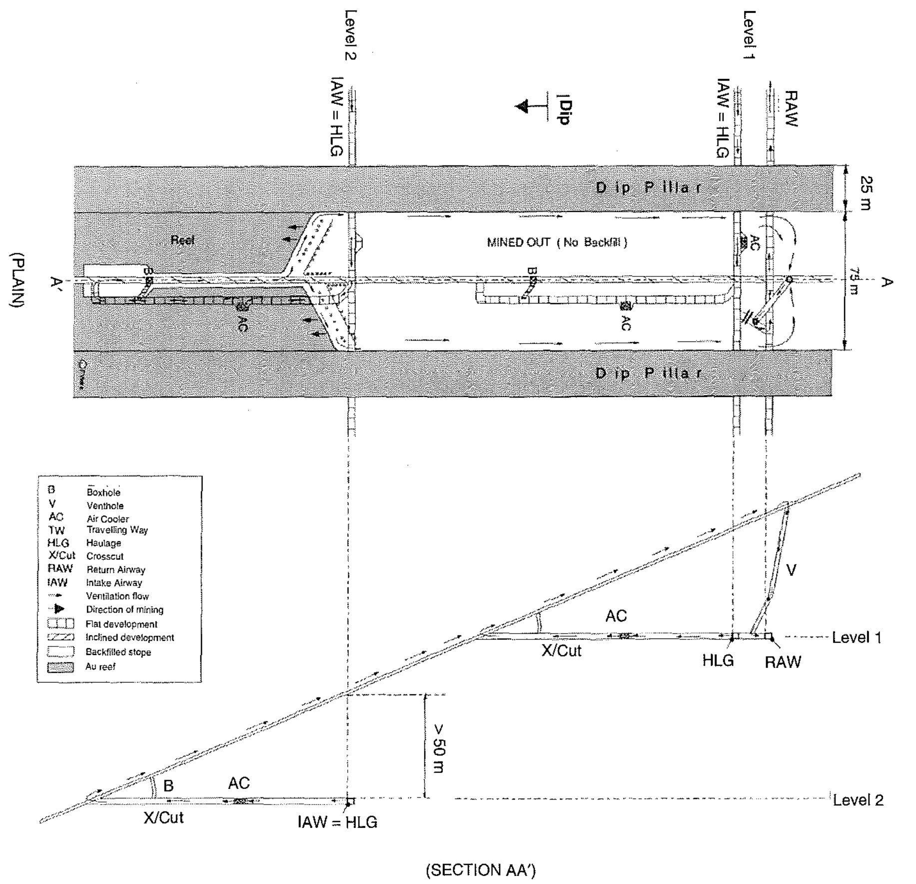
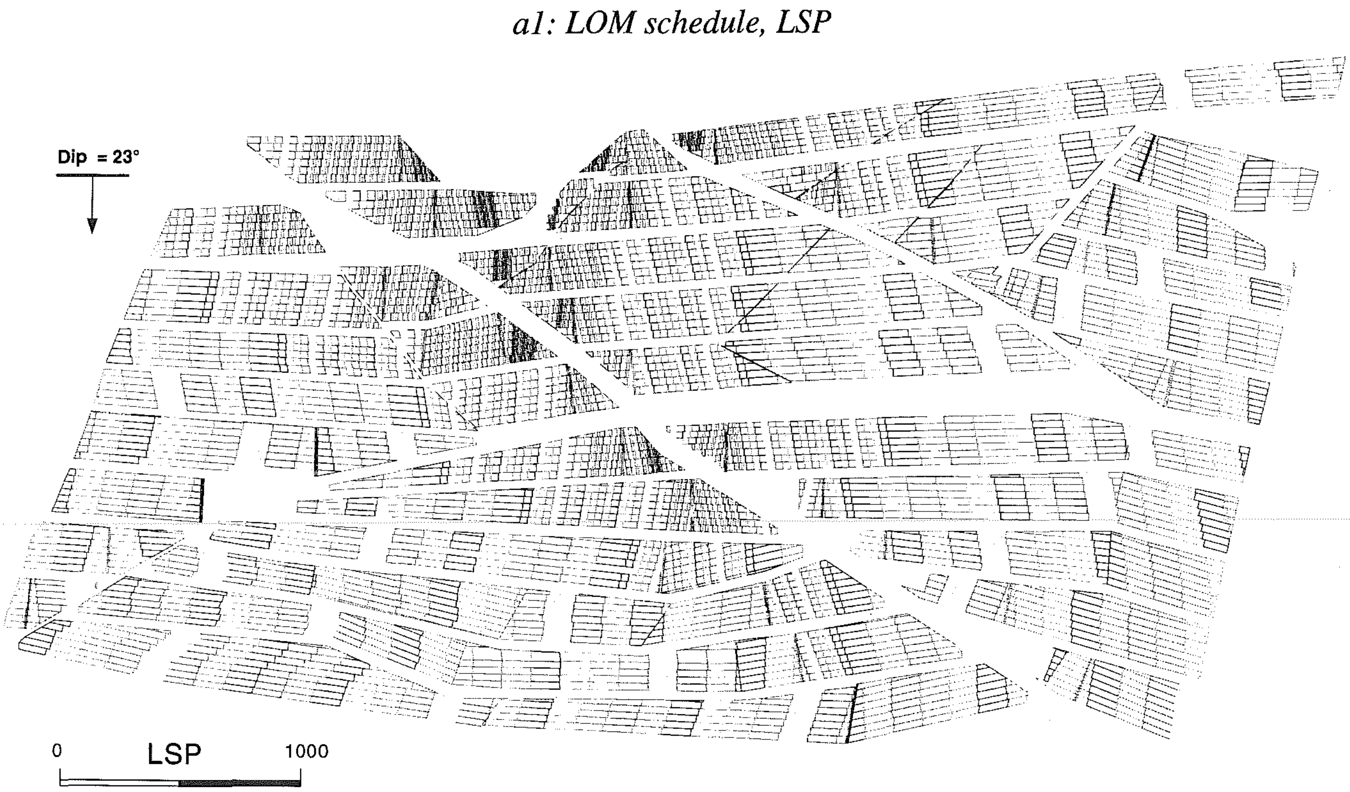


Figure 2. Micro concepts of mining layout for ultra-deep narrow, tabular deposits (continued)



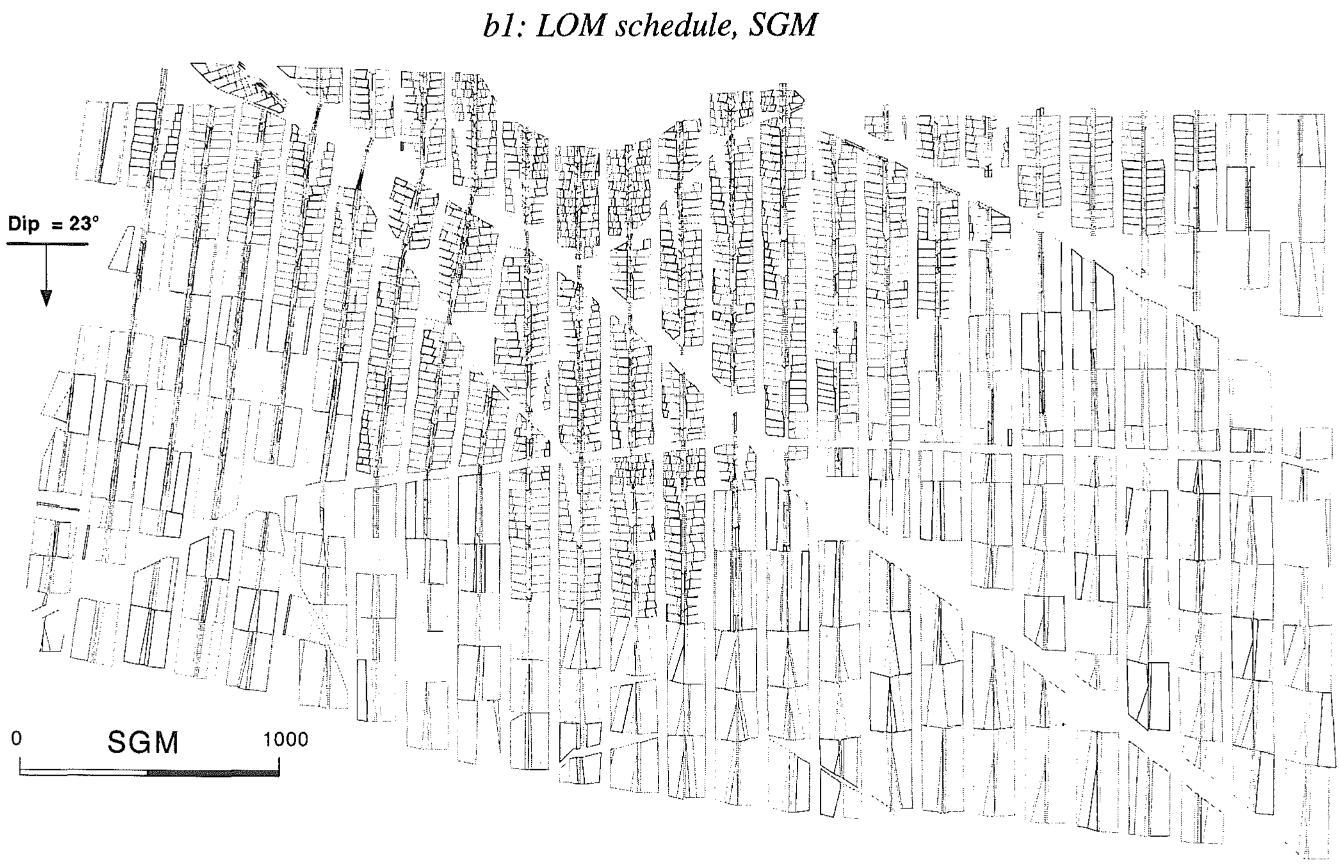
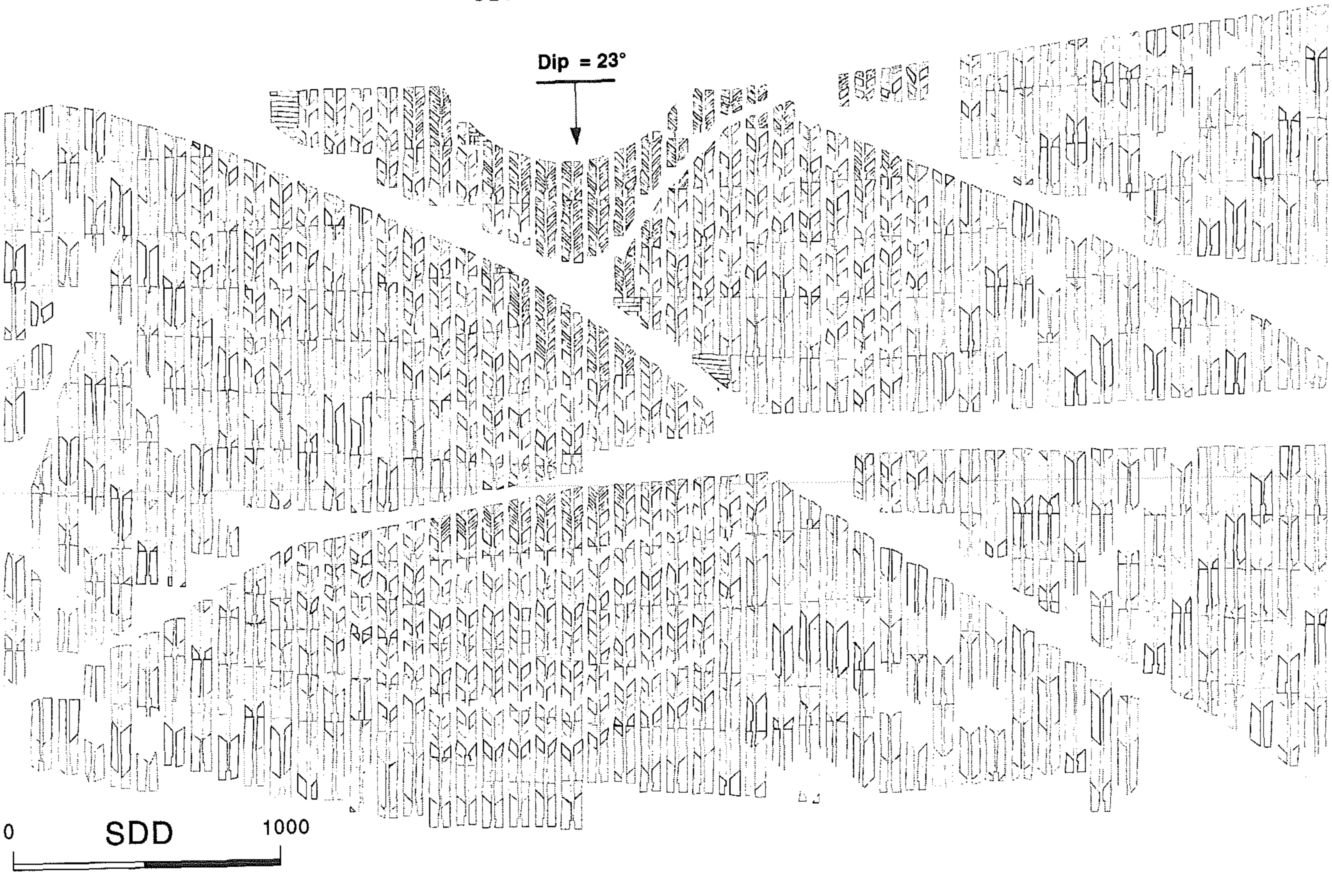


Figure 3. LOM scheduling outcome: Face outlines over the life-of-mine of the LSP, SGM, SDD and CSDP extractions of the Iponeleng orebody, respectively, modelled in CADSmine

c1: LOM schedule, SDD



d1: LOM schedule, CSDP

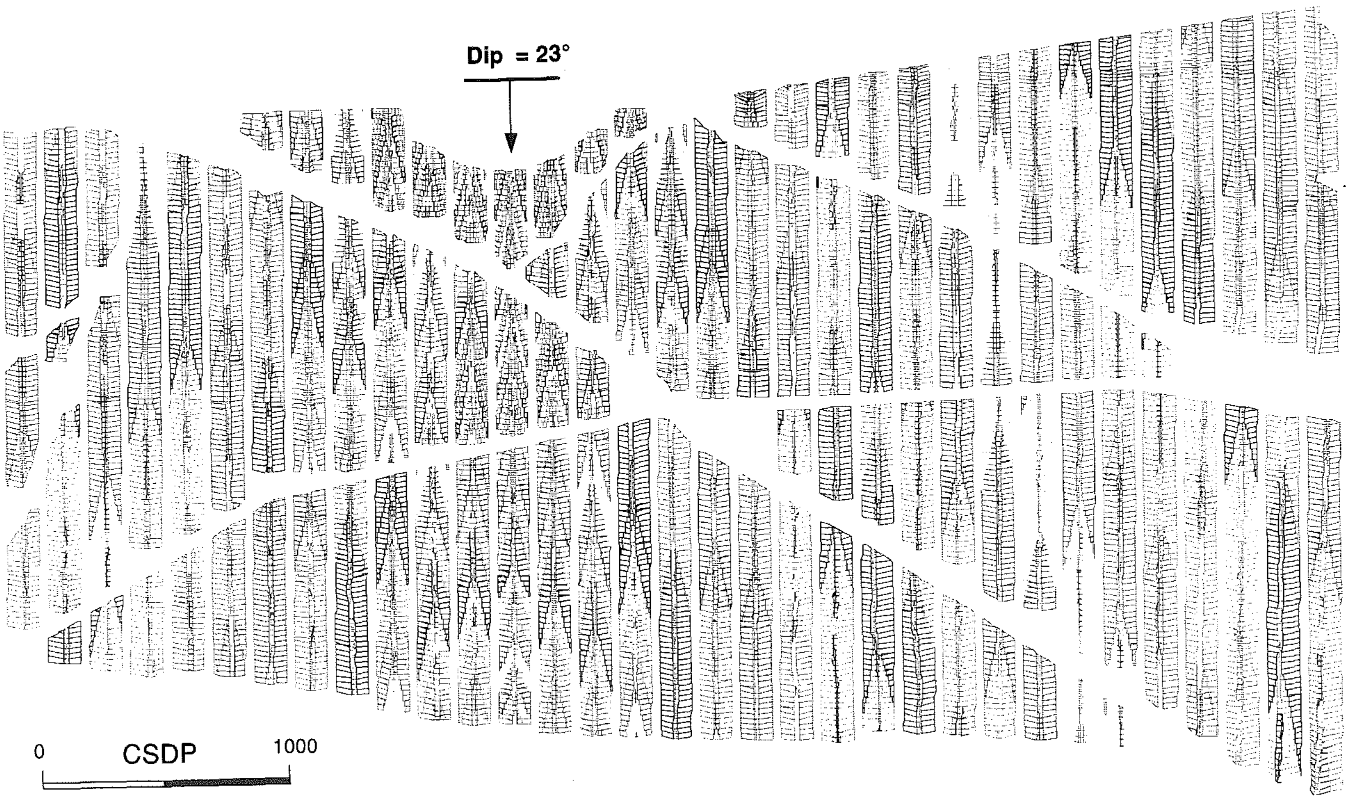


Figure 3. LOM scheduling outcome: Face outlines over the life-of-mine of the LSP, SGM, SDD and CSDP extractions of the Iponeleng orebody, respectively, modelled in CADSmine (continued)

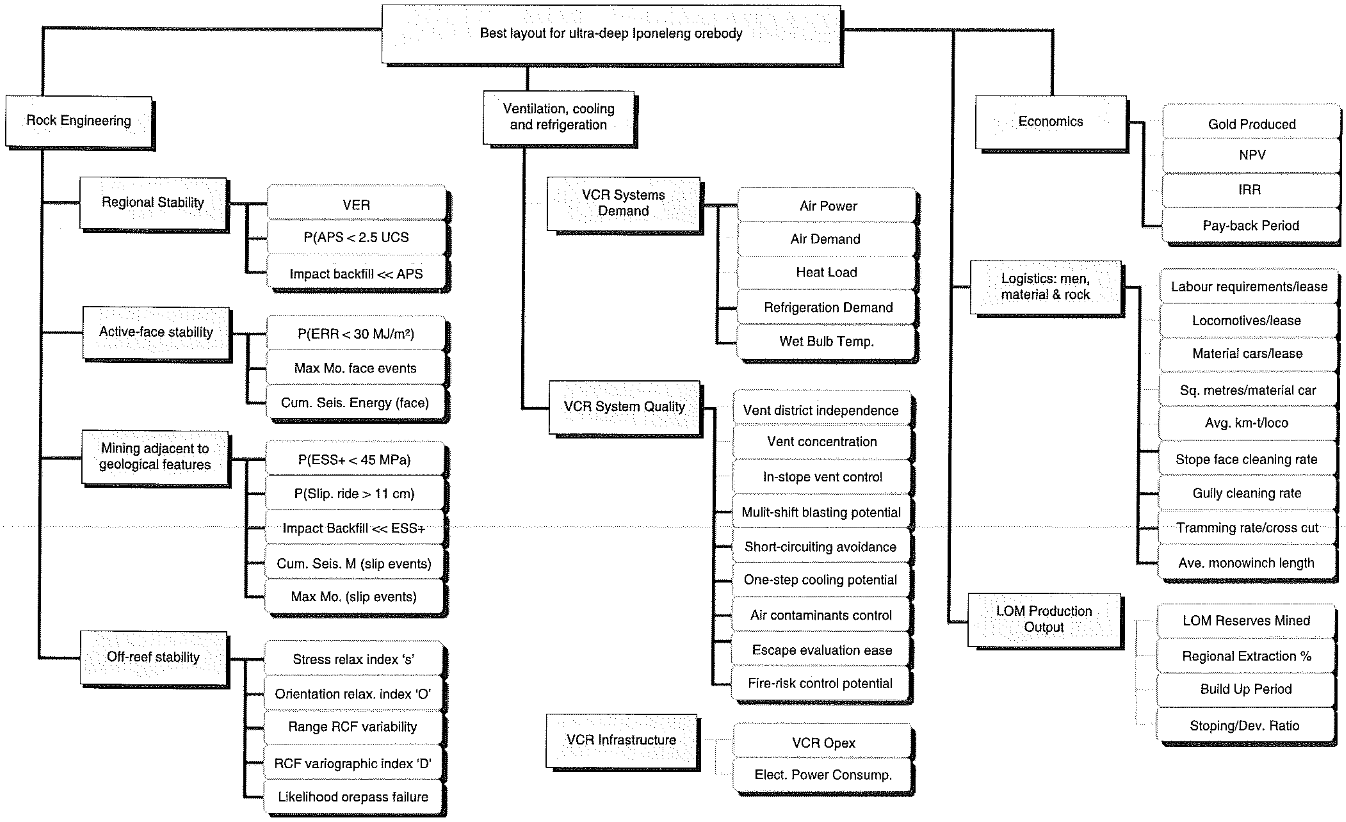


Figure 4. Fundamental-objectives hierarchy with sub-objectives and related attributes

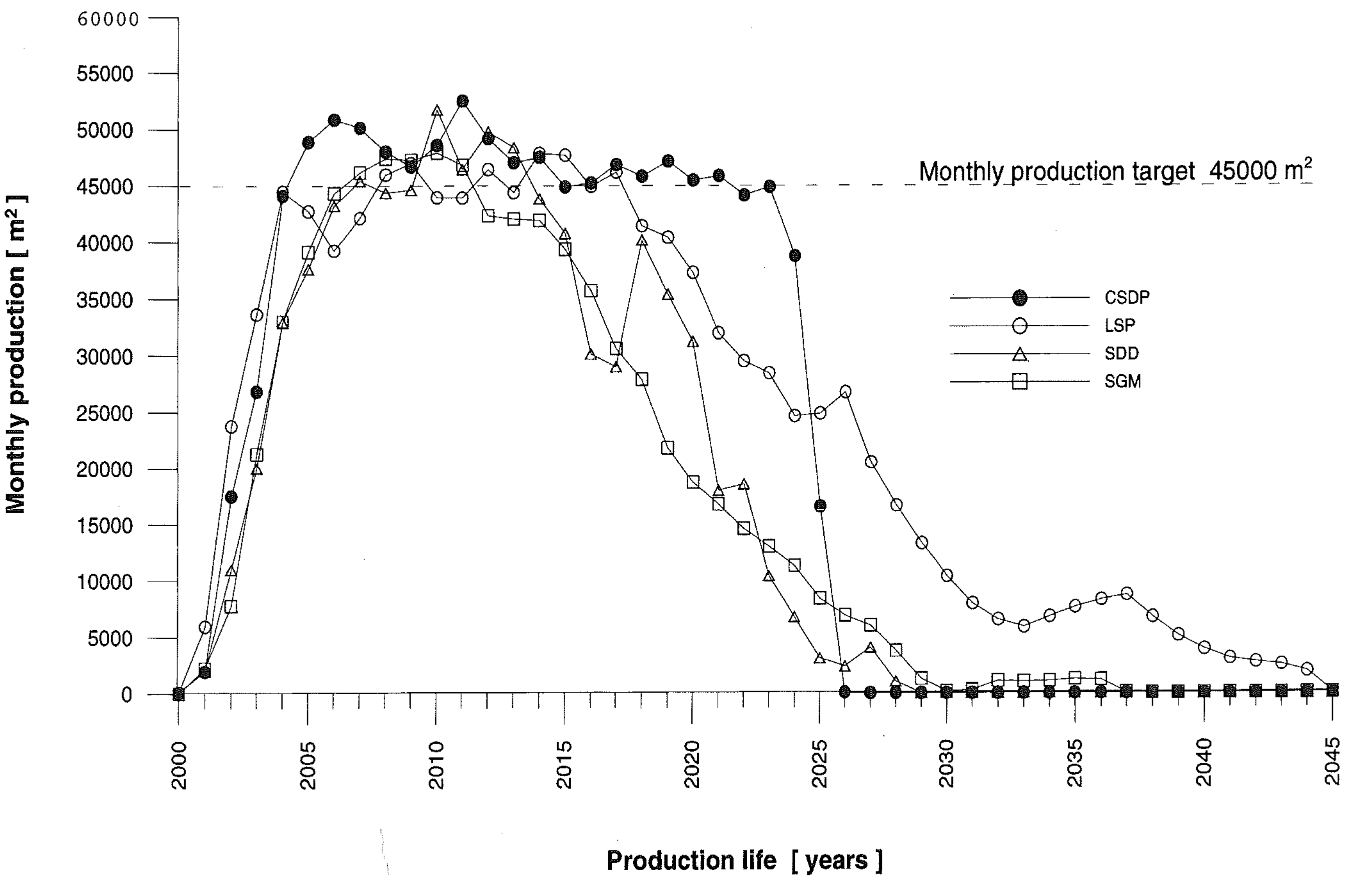


Figure 5. Optimal production profiles for the four mining alternatives after numerous optimisation iterations

outcome viewpoint that the CSDP showed the best profile in terms of the extent of full-production (23 years) and tail-off period (roughly 1 year). The LSP and CSDP alternatives denoted the same build-up period of 5 years. The LSP had the next longest production period of 16 years and the longest tail-off period of 22 years with an overall production life of 42 years. The SGM had the longest build-up period of 8 years; the build-up for SDD was 5 years. The square metres and tons milled over the life of the mine were compared for all scenarios studied. The LSP layout consistently had the highest production in all scenarios. The CSDP layout denoted the second highest mill tonnage production. With respect to gold produced over the life-of-mine period, the LSP produced the most gold, followed by CSDP.

Initial scenario studies considered mining at a constant grade throughout the orebody. Under these circumstances, the CSDP alternative produced, overall, a similar amount of gold (730 tons) to that of LSP (745 tons) but in a shorter period of 28 years (compared to 42 years for LSP). Also, the square metres mined were very similar for LSP and CSDP at approximately 13.2 million m^2 compared to the 9.9 million m^2 and 9.,4 million m^2 for SGM and SDD, respectively.

Rock engineering

It was determined that the worst performer in terms of the ERR risk measure was the LSP alternative. Pillars in the longwall layout are subject to higher values of APS. For the depth range considered, some pillars are likely to fail in terms of the criterion APS < 2.5 x UCS. The layout SDD guarantees the lowest APS values, owing to the fact that this layout offers the lowest areal extraction (between 67 and 60 per cent). It was shown that the SDD concept also offers the best chance of a low incremental ERR ahead of active faces. SDD gives the highest probability of a low face ERR (i.e. P(ERR<30 MJ/m^2) = 0.85). For SGM, likelihood is 0.62 that incremental face ERR is below the threshold value of 30 MJ/m^2. Next best is LSP with P(ERR<30 MJ/m^2) = 0.56. The last is CSDP, with a probability of only 0.49.

It was inferred that stopes adjacent to geological features in an LSP layout benefit the most (26%) when backfill is applied in terms of a reduction in the propensity for damaging seismicity due to slip-type phenomena. The SGM and CSDP alternatives draw similar benefits (18% and 16%, respectively); whereas the SDD alternative benefits vary marginally (5% only) from the introduction of backfill. When mining along one particular geological feature, the CSDP alternative shows the greatest incidence of high ESS values (ESS > 45 MPa) when no backfill was applied, whereas the LSP showed the lowest. Results indicate, for example, that the LSP alternative offers the highest risk for slip-type events to occur in all analysed geological features. This is demonstrated by the highest values of cumulative seismic moment and maximum event magnitude on selected features. The CSDP alternative offers the second worst potential of high seismic risk from shear slip along two of the analysed features. Clearly, the SDD alternative appears to impart the best control of shear slip along discontinuities, thus denoting the lowest seismic risk for related seismicity.

The LSP mining alternative is likely to induce magnitude 4.0 events along any of the active discontinuities if the current geometry and layout sequence are adopted. By comparison, the maximum event magnitude triggered by the influence of an CSDP type extraction can be as high as 3.6. The SGM extraction alternative may trigger a maximum magnitude event of 3.4 in adjacent geological features, whereas SDD will trigger a maximum 2.,9 magnitude event. When seismic risk is measured by seismic moment and seismic energy, the LSP layout denotes the greatest reduction in the total seismic moment and total seismic energy for the area mined when backfill is applied. Volumetric Energy Release (VER) and Local Energy Release Density (LERD) were also adopted as estimators of seismic hazard. Despite the lack of backfill, SDD has greater loading system stiffness, hence yields lower LERD. SGM has the second lowest local energy density, followed by CSDP and then LSP. SGM has the lowest extraction area, thus scoring most favourably in terms of Cumulative Moment Release followed by SDD (unfilled), CSDP and LSP.

It was determined that the RCF variance in LSP footwall strata is more regular than in the other three layouts. The rate of this increase of RCF variability in LSP strata is lower for small distances apart than in other layouts. For example, in LSP footwall strata a RCF variance equal to one occurs between points in the rock mass that, on average, are only 140 m apart. By contrast, the same level of RCF variance in SGM and SDD footwall strata occurs between points in the rock mass that are 14 and 20 m apart, respectively. The CSDP layout has the greatest negative impact of design characteristics on tunnel conditions. Out of the three grid-type mine design alternatives, the SDD layout shows the lowest variance of RCF values beyond which the design constraints of the layout no longer impact on footwall rock conditions. It was determined that certain orepasses of LSP layouts will be subjected to field stresses that exceed strength criteria. Single-side SGM extractions were also determined to be unsustainable for ultra-depth, as far as the stability of footwall excavations is concerned. SDD layouts with a down-dip advance sequence will at some stage cause unsustainable stress concentrations near stope entrances orepasses. This is in spite of the area around the orepass been previously wide-ledged over a span of 20 m. Walls of travellingways nearer to stope entrances and sidewalls of 'No. one' orepasses in CSDP layouts would also fail during early stoping. The attributes that characterize the rock engineering systems performance for the four alternatives are presented in Table VIII.

Ventilation, cooling and refrigeration

The SGM and LSP layouts were designed with extensive dedicated intake and return airway systems. This arrangement enhanced the SGM layout while it seemed to serve little purpose for the LSP layout. The concentrated nature of mining presented by the CSDP layout resulted in a number of positive spin-offs resulting in positive quantitative comparisons. The SDD layout seems to be penalized unduly by restricting the rate of face advance to 15 m per month. This results in having to ventilate a large number of stoping units, with relatively high air quantities per unit. The resultant large air volume requirements penalize this layout in terms of both capital and operational ventilation and cooling requirements. Similarly the SDD layout is less feasible as a large number of stoping units have to be ventilated, with relatively high air quantities per unit, and once again penalizing the infrastructure in terms of both capital and operational ventilation and cooling requirements. In all layouts, the capital cost of fans is considerably less than the operational air power costs over the life of the mine, even with 30 per cent recirculation.

The variation in the heat load characteristics of the different layouts ranges from approximately 100 MW to 130 MW or approximately 78 MW to 95 MW. In all cases, the restructuring of the mining scheduling to serve a more limited extent of the orebody has resulted in a sensible decrease in the levels encountered. Due to the inherent usage of large air quantities, the SDD layout is exposed to the largest heat load. The CSDP layout being the most 'concentrated' is exposed to the lowest. Once more, the design of the SDD layout can be modified to ameliorate this aspect to some extent through the use of serial ventilation networks. The attributes that characterize the VCR system performance for the four alternatives are presented in Table IV and Table V.

Financial evaluation

The financial appraisal was made based on specified criteria, namely: the Payback Period (PBP), the Internal Rate of Return (IRR), and the Net Present Value (NPV). NPV is the most suitable criterion for the assessment, of financial risk. Mine managers indicate that PBP and IRR are also good measures of certain projects viability, thus these parameters have been considered. The financial analysis was carried out based on four cash flow models developed for each of the layouts. Each cash flow model integrated the following components; the *extraction schedule* for the specific mining alternative; the *revenue* produced from tons milled (inferred from the scheduled production); the assumed *capital expenditure*, and the assumed *working cost* required to mill the output production (the latter two were synthetically generated using MinEcon).

Grade was identified as the first critical parameter controlling feasibility of the mine layout designs. The application of variable grade to the layouts shortened the overall production life and reduced NPVs with the exception of CSDP, which had the highest NPV at R286 million. The LSP was the only other layout, which achieved a positive NPV (R41 million) with an IRR of 10.17%. Both SGM and SDD returned lower NPVs than when grade was assumed constant. The main reasons for this were the shorter production life and the low grade mined during the build-up period, especially in the case of SGM. Also, the high-grade areas were mined towards the end of the life-of-mine. The benefits of improved grade control on the NPV and IRR, when compared to a base case, were noted. For example, the NPV for SGM improved from—R272 million to—R10 million and for the SDD, went from—R23 million to R293 million when grade control was modelled. The SDD moved from third position to second position in terms of the NPV rating in all the scenarios. SGM achieved a positive NPV of R63 million (-R191 million) and moved into third place, displacing the LSP layout, when grade controls were considered in the models. A sensitivity analysis on grade, working costs and capital showed that the LSP alternative was slightly more sensitive to grade and working costs than the other layouts.

The financial analysis showed that, in terms of the NPV attribute, the CSDP performed the best overall. With respect to the other three layouts (LSP, SGM and SDD), although the NPV values varied considerably (from -R310 to R495 million), the range of the IRR variation was less than 3 per cent (from 9.18 per cent to 12.0 per cent). One shortcoming of the SGM layout is the lengthy build-up period (i.e. the longest extraction sequences of all layouts). If full production could commence within a year of any of the other layouts, the SGM would show an NPV only marginally lower than CSDP (e.g. R495 million compared to R534 million).

Framework to select the optimal mine design alternative

Utility function

From the above, it can be established that the selection of a mining alternative depends on judging several objectives using relevant attributes (see Figure 4). Ranking the feasible alternative requires a scale for quantifying the degree of preference (or compliance to criteria) among the attributes. Well-established scales of measure exist for some of the attributes but not for others. The problem of value measurement is complicated further when the consequences in the decision matrix require the evaluation of a combination of attributes (multi-attributes). In order to establish a uniform scale for measuring the overall value of an alternative, the concept of *utility* can be used. Utility theory provides a framework whereby values may be measured, combined and compared consistently with respect to a decision maker. Utility theory is used as a decision-making process to facilitate the evaluation of *probabilistic alternatives*. Utility-based decision methods assign single values, the expected utility, to each probability outcome. Expected utilities are compared and the biggest expected utility yields the preferred alternative.

A decision maker whose preferences satisfy the axioms of orderability, transitivity, continuity, substitutability, monotonicity and decomposability[1] may have his preferences encoded in specific utility functions. A utility function quantifies the order of preferences. Mathematically, the function represents a mapping of the degree of preferences into the real line, thus permitting preferences to be expressed numerically. A utility function might be specified in terms of a graph, given as a table or as a mathematical expression.

In order to compute the expected utility, each possible outcome in the probability distribution of a given measure (attribute level) needs to be converted to a utility value. These utility values are numbers that express the preference of the decision maker for various alternatives. Since the decision maker in the current study (i.e. mine management) is assumed to be risk averse, sub-optimal engineering and mine design attributes are assigned lower utilities.

In the case of risk management, utility values could be assigned to each possible outcome of a loss distribution, and would then be weighted by multiplying them by the probabilities of occurrence of the associated outcomes. The expected utility for the distribution is obtained by the summation of the weighted utility values. In considering the optimal layout for ultra-depth, weighted objective decision analysis based on a decision matrix of the type shown in Table I was considered. Relative weights were assigned to the various objectives and attributes, based on expert knowledge regarding their relevance levels.

The decision analysis methodology applied in the current study includes the listing of feasible alternatives a_i and the assignment of probabilities p_{ij} to available attributes x_i (Table I). Some of these probabilities were determined from numerical modelling. Models that assessed rock mass response as a result of mining were used for the rock engineering assessment. Models that simulated ventilation and cooling loads were used to determine VCR systems requirements. Other models were applied for logistic and financial evaluations. Where applicable, attribute levels were estimated subjectively, based on the decision maker's expert knowledge and judgement. The overall relative utility of each alternative can be computed as in equation [1], when probabilities are assigned. When a distribution of a particular attribute was determined, Monte Carlo simulations of 10 000 iterations were carried out to generate the most likely value of p_{ij} (e.g. Figure 7). In general, attribute functions are applied in order to 'reduce' to the same scale, attributes with different units.

$$U_i = \sum_j p_{ij} w_j \quad [1]$$

Additive utility model

The selection of an optimal mine layout is a mining engineering design and planning decision problem that involves conflicting interests of various disciplines. Decision analysis with multiple objectives requires a determination of multiple-attribute utility functions instead of a single utility function. The multi-attribute function evaluates the *joint utility* value of several measures of effectiveness, toward fulfilling the various objectives. The decision problem discussed in this paper is of the type that requires the resolution of several objectives versus a number of feasible alternative mining engineering designs (LSP, SGM, SDD, CSDP). The relative merits of importance of the various objectives (rock engineering, ventilation and cooling, logistics and economics) are different, and the likelihoods of different alternatives achieving a stated objective are, also, intrinsically different. Weighting factors are assigned to differentiate the relative importances.

The easiest way of dealing with conflicting objectives is by creating an *additive* preference model in which utility scores for each objective are calculated, then added and weighted appropriately, according to the relative importance of the various objectives. The additive utility function is composed of two different kinds of elements, scores on individual attribute scales and weights for the corresponding objectives. Additive models work well when attributes are 'preferentially independent'. The latter status has been assumed for all attributes in the current study. It is possible to create a decision model defined by *multiplicative* preferences that would model attribute interactions. The multiplicative utility would require an additional scaling constant, however.

The additive utility function works as follows. Consider that there are individual utility functions $U_1(x_1)$, …, $U_m(x_m)$ for m different attributes x_1 through to x_m (Table I). Assume that each utility function is assigned values 0 and 1 to worst and best levels, respectively, on any particular objective and attribute. The additive utility function is essentially a weighted average of the different utility functions in the decision model. The utility of an outcome that has levels $x_1,\ldots, x_m$ on m objectives is calculated as in Equation [2], where $k_1,\ldots, k_m$ are positive weights, adding up to 1.

$$\begin{aligned} U(x_1,\ldots,x_m) &= k_1U_1(x_1) + \ldots k_mU_m(x_m) \\ &= \sum_{i=1}^{m} k_iU_i(x_i) \end{aligned} \quad [2]$$

This utility function is consistent with attribute scores, in that each utility function U_i in Equation [2] defines an attribute scale. Ultimately, the optimal alternative is the one that has the maximum relative utility. The absolute numerical value of U_i is not important, though; the relative value is sufficient for the selection of the optimal alternative.

Structuring the decision model

How should we proceed with structuring a decision analysis involving multiple objectives measured by multiple attributes? The starting point is to create a fundamental-objectives hierarchy (e.g. Figure 4), which characterizes the decision problem. The following criteria[2] was applied when defining the fundamental objectives in this study.

- The set of objectives represented by the fundamental-objectives hierarchy should be complete; i.e. it should include all relevant aspects of the mine design decision problem.
- The set of objectives should be as small as possible. Too many objectives can be cumbersome and hard to grasp. The objectives hierarchy should represent objectives that are important to mine management (the decision maker). Furthermore, each objective should differentiate the available alternative. An objective is irrelevant if the mine layout alternatives are equivalent with regards to that particular objective
- The set of fundamental objectives should not be redundant, i.e. the same objective should not be repeated in the hierarchy and the objectives should not be closely related (dependent).

The fundamental objectives represent the reasons why the decision maker (mine management) cares about the decision on which layout is most suitable, and more importantly, how the available alternatives should be evaluated. Too often mine design decisions are based on wrong attributes and measurements because inadequate thought is given to the fundamental objectives in the first place, or certain measurements have different objectives from those of the decision maker. How much detail is included in the fundamental-objectives hierarchy is a matter of choice and the principle of *requisite model* comes into play. A decision 'model can be considered *requisite* when only no new intuitions emerge about the problem'[4]; i.e. when it contains the essential decision elements to solve the problem; including knowledge of the degree of uncertainty and dependency preferences. In the current decision analysis, decision software was used to structure the decision situation involving multiple-objectives.

The fundamental-objectives hierarchy starts at the top with an overall objective ('Best layout for ultra-deep Iponeleng orebody'), and lower level objectives in the hierarchy describe important aspects of the more general objective. Each objective is measured on the same utility scale, hence they can be compared. Attributes for each objective are then identified and their respective scales specified. Some of the related attributes have natural attribute scales (e.g. m^2/m, Rm, °C, kW); others have not but can be described qualitatively, using an attribute scale that characterizes the objective most adequately.

Each alternative is identified in a consequence matrix for each of the objectives (e.g. Table III, Table IV, Table VI, Table VII, Table VII). This matrix is used to determine all partial and overall utilities, having taken regard of the appropriate attribution of weights. Weighting factors, k_i and w_i are entered to define interactions between active members of the decision (objectives and attributes). Various methods exist to assess weights for objectives and

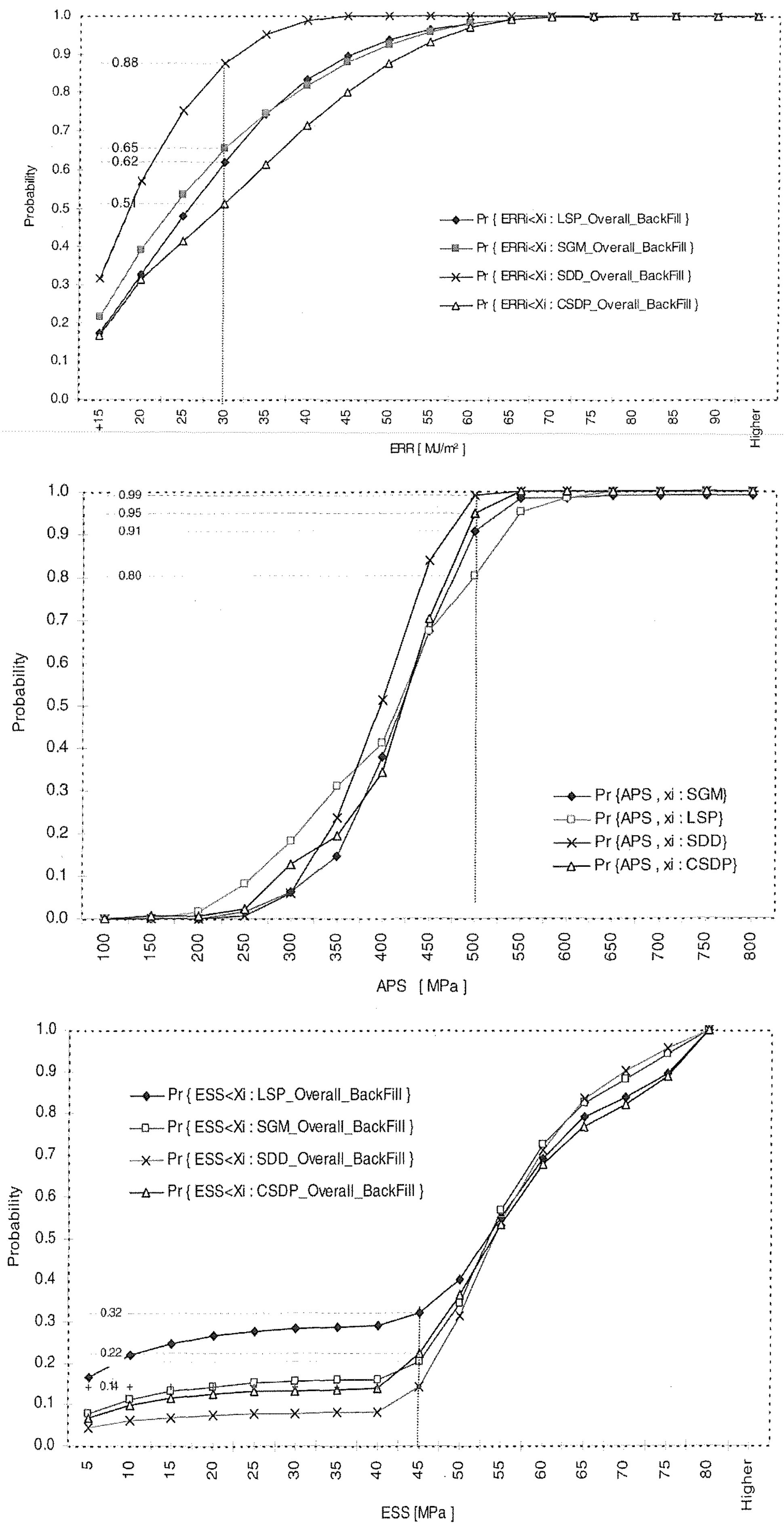


Figure 6. ERRi and APS estimation over the LOM

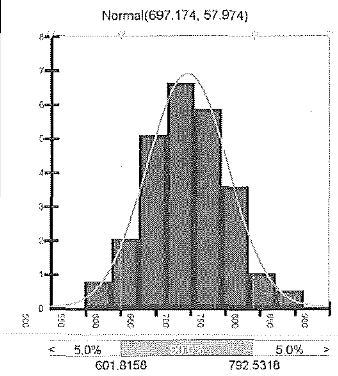
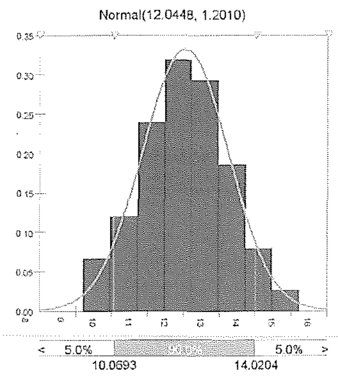
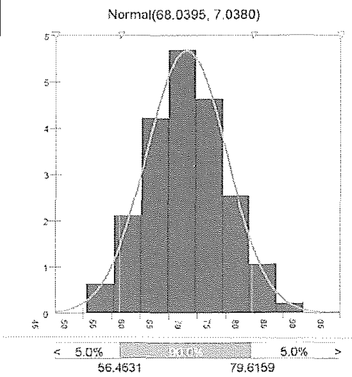
Attribute	Gold Produced (t)	Reserves mined (km^2)	Extraction ratio (%)
Alternative			
LSP			

Figure 7. Variability of three attributes. These distributions applied during Monte Carlo simulations

attributes (e.g. 'order of importance', 'ratios' 'tradeoffs', etc.) but a discussion on these is not relevant here. Ultimately, mining alternatives are ranked in terms of the preferences of the decision maker, considering his set of pre-defined criteria for *selecting* the optimal layout. In summary, the proposed methodology involves the following steps:

- Identify the available alternatives of the decision, a_i
- Define the fundamental objective and *requisite* secondary objectives, where applicable, O_i
- Define attributes that can measure the degree of compliance to defined objectives, x_i
- Do specialized studies to determine attribute levels (using modelling, back analysis, observation)
- Create a decision matrix of *levels* of attributes (deterministic or stochastic, p_{ij}), for each alternative
- Set preferences including the *pass* criteria for all attributes
- Set interdependency rules of value functions for each attribute (trade-off rules)
- Define interactions between objectives and between attributes (weights), w_i and k_i
- Determine utilities for all attributes, secondary objectives and overall fundamental objective
- Rank alternatives and choose the one that best conforms with pre-defined *selection criteria*

Ranking the alternatives: utility results

Mining alternatives are ranked in terms of the preferences of the decision maker, considering his set of pre-defined criteria for *selecting* the optimal layout. Figure 8, Figure 9 and Figure 10 show the results of the utility-base decision model adopted. It can be seen that CSDP is the alternative that, overall, meets most closely the preferences set by the decision maker (maximum utility is 0.71). Second-best is the SDD alternative, denoting an overall utility of 0.45, followed by LSP and lastly CSDP. Figure 8 shows the relative utility counts, with respect to the *secondary objectives*. In many instances the CSDP alternative did not perform well and was actually the last preferred alternative (e.g. with regard to 'Rock engineering', 'Active face stability', 'Off-reef stability' and 'VCR systems quality'). Various weighting factors, k_i and w_i, which specified the relative interactions between active members of the decision (objectives and attributes) were instrumental in identifying CSDP as the preferable alternative. Indeed, a greater relevance was placed on the economic objective than, for example, on the rock engineering one. Normally, if a constraint can be engineered around, then its relevance should be less significant.

Conclusions

A mine designer needs to ensure that mining takes place as safely and profitably as possible, thereby reducing the risk of deep-level mining to both the underground worker and the investor. Invariably, mine designers have numerous options to consider, each of which presents advantages and disadvantages. Often the mine designer has to consider that a solution must be investigated from a multidisciplinary approach, and measured by numerous attributes. The easy way out must be to narrow the problem down and offer solutions on a one-discipline dimension only. This is unacceptable as all mining engineering problems involve multidisciplinary solutions, measured by multi objectives, which are described by multiple-attributes. Faced with this decision scenario, the utility-based framework proposed is a powerful tool that will assist mine management in making rational decisions, which meet specified attribute criteria and achieve maximum compliance with set preferences.

Acknowledgements

The sponsors of the DEEPMINE Programme are thanked for granting permission to publish this paper.

Glossary of terms

- *MINSIM* stands for 'Mining Simulation' stress-analysis software[6]. This is a 3D elastic boundary element program based on displacement discontinuity technique, suited to modelling stress and displacement on and around tabular excavations. MINSIM 2000 is the most recent version of MINSIM. It comprises four separate applications with distinct functionalities,

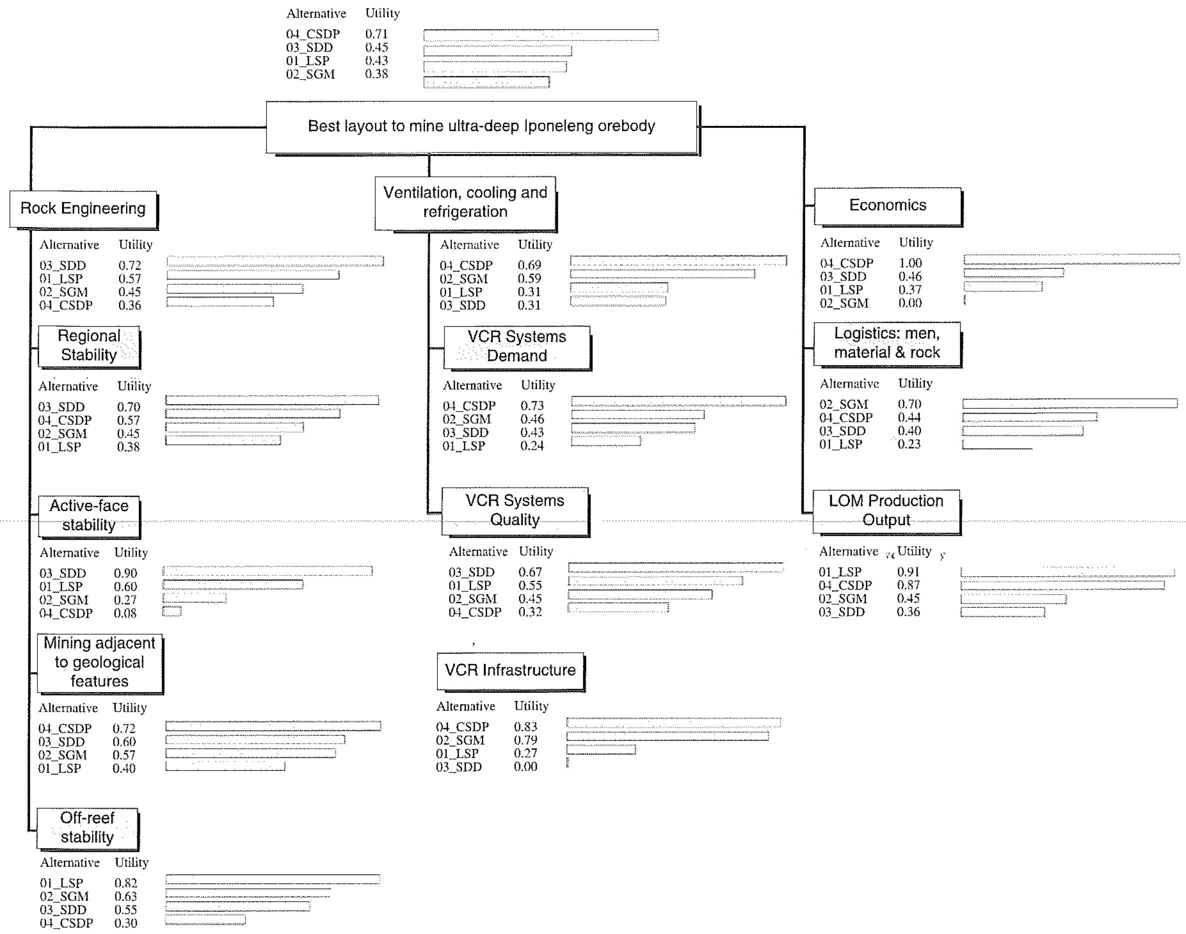


Figure 8. Fundamental-objectives hierarchy with utility results

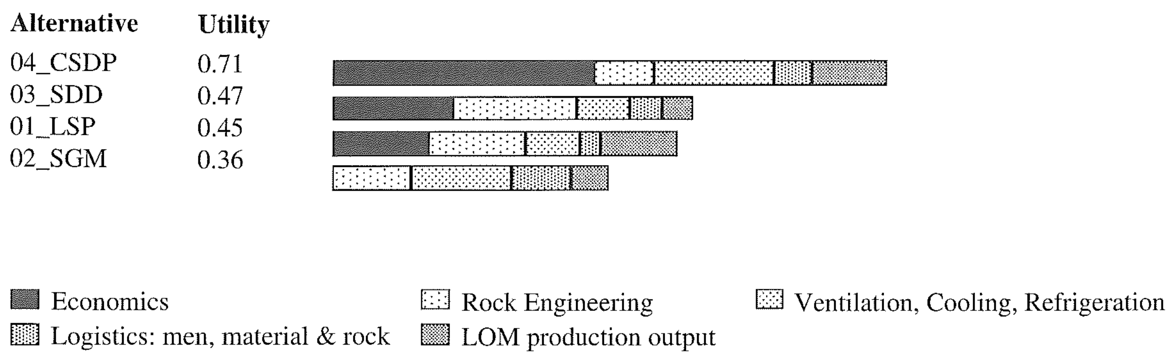


Figure 9. Stacked-bar utility results, denoting relative contribution of secondary objectives to the overall ranking

namely: MinPlan, MinPrep, MinSolve; MinPost (CSIR).

- *MINF* is a boundary element solver for mining of parallel reefs. It is used to analyse complex mining layouts. MINF generates synthetic seismic catalogues that have been shown to be similar, in several ways, to observed seismicity[7]. When calibrated against historical seismicity, MINF can be used to estimate the future seismicity and incidence of strong ground motion for different mining scenarios. MINF is file-compatible with MinSim2000. Its past and on-going development (2002) is supported by SIMRAC.
- *MAP3D* is a boundary element program, based on Indirect Boundary Element Method[8]. It is a comprehensive 3D rock stability analysis package, used to construct models and analyse and then display displacements, strains, stresses and strength factors. Zones of different moduli may be entered.
- *VUMA-network* → Software that allows for simulation of ventilation flows, temperatures, gas concentrations, humidity and dust throughout a mine network. It calculates heat flows, dust and gas loads, etc. Cooling strategies, contaminant dilution and ventilation tactics can be analysed using VUMA models. Overall energy

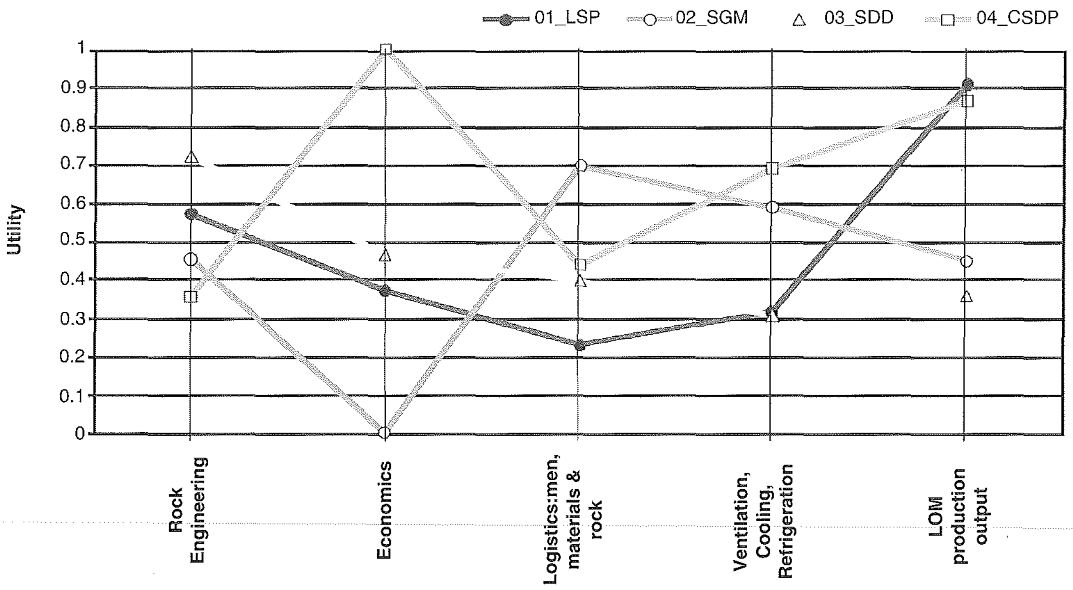


Figure 10. Utility results: ranking results profiles

requirements, including fans, air coolers and scrubber or filter needs, can be determined. The code is used to assess a variety of underground mining methods for narrow reefs, massive orebodies and colliery layouts with different levels of mechanization.

- *MinEcon*. A financial analysis routine developed to operate in an EXCEL® platform, which generates comparative mining-cost models based on pre-established working cost profiles of specific mining operations.

References

1. ANG, ALFREDO HUA-SING, and TANG, WILSON H. *Probability concepts in engineering planning and design. Vol. II. Decision, Risk, And Reliability*. John Wiley & Sons. Inc. USA. 1984.
2. CLEMEN, R.T. *Making hard decisions. An Introduction to Decision Analysis*. 2nd Ed. Duxbury press. Wadsworth Publ. Co. 1995.
3. GIBSON, M.A.S., JOLLEY, S.J., and BARNICOAT, A.C. Interpretation of the Western Ultra Deep Levels 3-D Seismic Survey. *South African Geophysical Association 6th Biennial Conference and Exhibition* (28th September- 1st October. 1999).
4. PHILIPS, L.D. Requisite decision modelling. *Journal of the Operational Research Society*., 33, 1982. pp. 303–312.
5. VIEIRA, F.M.C.C., DIERING, D.H., and DURRHEIM, R.J. Methods to Mine the Ultra-Deep Tabular Gold-Bearing Reefs of the Witwatersrand Basin, South Africa. In *Techniques in Underground Mining* by R.L. Bullock and W. Hustrulid (editors). 2000
6. CSIR, 2000. MINSIM 2000 stress analysis software suite. Comprising: MinPlan, MinPrep, MinSolve; MinPost. CSIR Mining Technology. Johannesburg. South Africa.
7. SPOTTISWOODE, S.M. Keynote address: Synthetic seismicity mimics observed seismicity in deep tabular mines. *5th Intl Symposium on Rockbursts and Seismicity in mines*, S. A. Inst. Min. Metall., 2001. pp. 371–378.
8. WILES, T.D. MAP3D SV program. WWW.MAP3D. com. 2000.
9. MARX, W.M., BIFFI, M., VON GLEHN, F.H., and BLUHM, S.J. VUMA (Ventilation of Underground Mine Atmospheres)- A mine ventilation and cooling network simulation tool, *7th International Mine Ventilation Congress*, Krakow, Poland, September 2001. pp. 24–27
10. CSIR, 1997. MinEcon EXCEL® routine. Mining Technology: Mining Systems Programme.