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A new approach to the efficiency concept in South African industry

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Abstract

This millennium is marked by a new trend: efficiency. In the actual economical environment, business sustainability requires high-efficiency technological processes. The efficiency concept has to be present at all levels of industrial activities. However, as common practice, the efficiency concept is still regarded equivalent to 'energy efficiency' as mentioned in the Intergovernmental Panel on Climate Change (IPCC 1996), and specifically re-defined by the Federal Energy Management Plan (Department of Energy Federal Register 1994.

By analysing specific industrial processes, the authors have defined a global concept of efficiency presenting results of sound research in this field, with reference to electric motors and drives. Typical examples supporting the theoretical background reveal general impacts on the South African economy by implementing this new concept:

- *Technical and economical performance improvement and competitiveness of South African companies to international standards;*
- *Defusing an incipient energy crisis in the sector;*
- *Improving environmental conditions (less emanations of carbon dioxide at the power plants); and*
- *Creating new job opportunities in the sector.*

The global concept of efficiency proposed in this paper can be further developed in assessing efficiency of various processes, thus improving companies' corporate energy policy.

Keywords: efficiency concept, South African industry, application engineering, energy efficient policies

Introduction

South Africa's real growth rate in value-added manufacturing in the mining industry was 1.4% for the period between 1997 and 2002. This figure compares poorly to the average rate of 3.9% for developing countries, and the average of 5.8% for transitional economies (Department of Trade and Industry 2002). The Department of Trade and Industry reveals in 2004 that employment in the industry was falling at an average of 8.4% a year.

'The declining share of manufacturing is perhaps the best evidence that the business-economics environment for manufacturing is poor versus the competitors', says Roger Baxter, Chief Economist of the Chamber of Mines in an interview with *Mining Weekly* (2006). A potential hindrance in the beneficiation wheel is the declining contribution to the GDP in South Africa.

One of the explanations can be the misunderstanding of the global efficiency concept (GEC). To date, there are not any specific references on this subject. Focusing on South Africa, a short discussion is necessary. The new monetary policy promoted by the South African Reserve Bank compounded with an energy and materials crisis in the world has had a huge impact on industrial processes.

The targets prescribed by the South African Department of Minerals and Energy (DME) in the last years (Department of Minerals and Energy 1998 & 2005) indicate that new efficiency concepts are now breaking the old rules that dictate, 'as long the initial price (investment) is cheap, it is good enough'. However, the South African market industry is still divided into two distinct tiers:

- Discerning product market, and
- Non-discerning product market.

The 'non-discerning market' is price driven and the initial cost is usually the chief driver of the purchasing decision. This market is not specification driven and its focus is not, at least, on the Total Cost of Ownership (TCO). The 'discerning market' has made great strides in raising the bar in terms of product specifications. The modern technical terms are frequently mentioned in purchasing specifications. This market secures business sustainability and international competitiveness.

A new approach towards the global efficiency concept (GEC)

Countless inspectors, engineers, accountants and clerks are monitoring industrial processes at different levels. Billions of rands are annually spent on investments, maintenance, monitoring, and repair activities and electricity costs related to industrial processes and applications. However, down time production costs are still present, requiring a new global concept of efficiency to be included at all horizontal and vertical levels (technical, economical, financial, etc).

The global approach towards the efficiency concept is rejecting excessive profit taken from a specific business. The global efficiency concept must incorporate the following:

- A study of the process (application engineering);
- Mathematical modelling by using multidisciplinary techniques (including statistic-probabilistic methods in estimating reliability);
- An energy efficiency policy (currently standardised in some countries);
- Estimations of the total cost of ownership (TCO);
- Planning, prediction and process efficiency control based on the 'critical path method';
- Co-operation of unions and employees with management;
- Indigenous participation (Research & Development, products, software, etc).

As a common characteristic, it was found that in most of the industrial applications, improved efficiency has been initially obtained by increasing the process speed. However, the rule of maximizing process productivity 'Π' by increasing the process speed 'v' must always be applied in conjunction with adequate technical support.

That means in the process rated domain:

- The process productivity 'Π' can be approximated as proportional to the process speed[1] 'v';
- The global efficiency of the application (process) is a function of the various costs and adopted policies.

Figure 1 shows that these costs are grouped under global Total Cost of Ownership (TCO) structure as a component of the global efficiency concept (GEC):

- Initial price (investment) (IP);
- Electric energy costs (EEC);
- Maintenance and monitoring costs (MC);
- Repair and replacement costs (RC);
- Logistic costs (LC);
- Direct and Indirect costs (DIC);
- Downtime production costs (DPC).

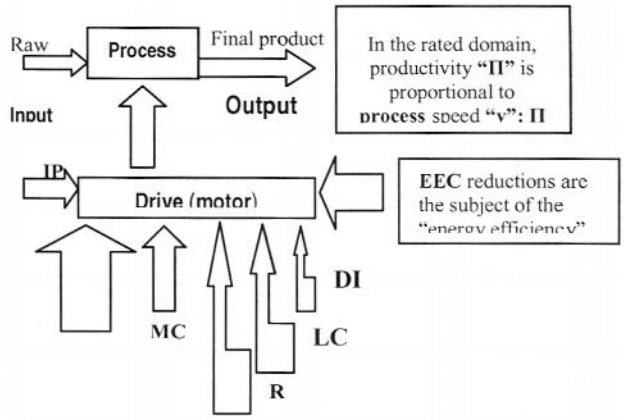


Figure 1: TCO structure of an application (drive) used for a particular mining process

The role of application engineering towards GEC

Essentials of application engineering

Engineering is nothing more than planning based on knowledge instead of guesswork. In this sense, everyone in design, service, maintenance and technical sales, work as his (or her) own engineer every day. Using application-engineering principles, one must do a study of the industrial processes.

Let us consider a motor driving a load. LOAD represents all the numerical values of the electrical and mechanical quantities that signify the demand to be made at a given instant on a motor by an application. Proper application of electrical motors does take some fundamental knowledge requiring a strong technical background.

When selecting a motor for specific application, five essentials of what is called application engineering must be taken into consideration as shown in Figure 2.

- Matching the motor to the load is the most important – and the most complex - of the five areas to be considered.
- Matching the power supply conditions is related to the motor protection from the system, but also to the motor's influence on the incoming power and electrical distribution.
- Matching the motor to its environment means the motor must not be destroyed by its surroundings. Conversely, it must not in turn inflict damages.
- Matching the reliability indicators enables the end-user in planning the maintenance, repair activities, and minimizing downtime production

costs (DPC) (see also Figure 1).
- Matching conditions of business sustainability ensures stability of the 'discerning product market' as defined in Section 2.

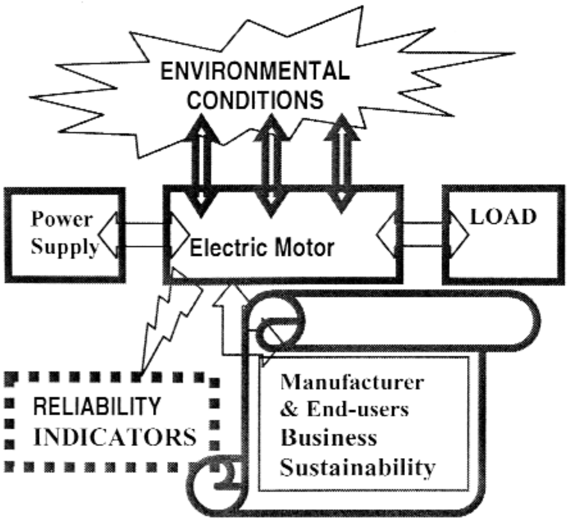


Figure 2: Essentials of application engineering required when designing an electric motor for a drive

Case study: Contradicting essentials of application engineering

Overseas-designed continuous miners (CM) have been imported in South Africa for the coal mining industry. For various reasons, their declared rated performance of 40 000 tons of coal cut/month has been totally outrun in South Africa (currently production figures are ranging between 80 000 and 1200 000 tons of coal/month). The main reasons for the increased production are shown below:

- South African coal is much softer (allowing for CM a higher speed of the cutting process);
- A higher speed process tempted the user to increase productivity with all related economic advantages ($\Pi = f(v)$, see also Figure 1 and Note 1);
- Higher productivity enabled attractive export opportunities at an exceptional competitive price (Euro 40…50/ton of coal).

However, after a while, it becomes obvious that some overseas-designed motor powering these CMs were not satisfying the harsh South African requirements.

- Higher volume of cutting coal brought the motors into overload conditions with accelerated degradation (ageing) and higher failure rates (essential one);
- Heavy working conditions (frequent DOL stop/starting and re-closures, prolonged stall conditions, heavy overload conditions, etc);
- Machinery was forced to withstand specific South African power supply conditions as: unbalanced or out of standard voltages, dips, sags, transients, frequency and voltages variation, etc (essential two);
- Various other harsh conditions such as dirty cooling water, by-passed thermal protections, unplanned production and maintenance activities, lack of co-operation between unions and employer, etc (essential three).

The effects of the South African harsh conditions as failures of CMs' equipments are shown in Photos 1 and 2.

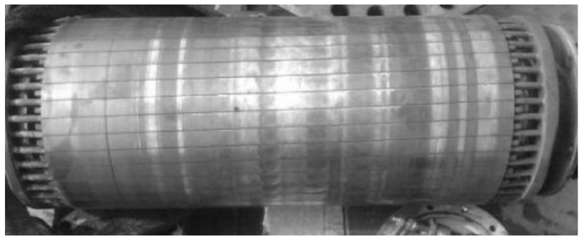


Photo 1: A 315 kW rotor subject to heavy thermal stress

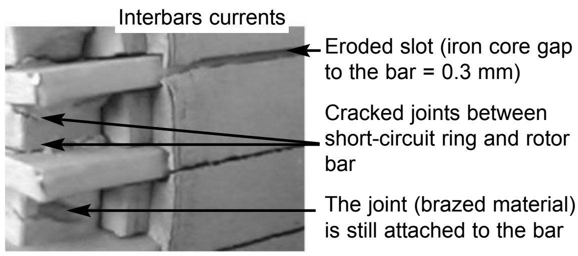


Photo 2: Cracked 220mm 2 joints of a 200 kW rotor

Table 1: Financial losses generated by the failure of a 200 kW cutter motor (Euro)

Item	*Cost*	*Financial loss*
DPC, hour rate	125 t x 40 E = 5000 E	
DPC loss@ 18h	5000 E/h x 18 h	90 000 E
Penalties 10%	500 E/h x 18 h	9 000 E
New motor	74 000 E	
New rotor	10 000 E	10 000 E
Av. cost repair	Max 60 % of new	40 000 E
Total losses		149 000 E

The machinery failure rate increased beyond expectation with obvious consequences: high financial losses (essential five), as presented in Table 1. According to statistical data processed over the years, the following information is available for a 200 kW cutter motor:

- Stoppage time duration = 18 hours (6 hours logistics + 12 hours replacing and commissioning of the motor);

- Average production rate/hour is estimated as 90 000 tons/month: 720 hours/month = 125 tons/hour;
- In the DPC (downtime production costs) all other costs are included.

Conclusion: By contradicting the five essentials of application engineering, the business shall be exposed to heavy financial losses. In this specific case, losses generated per motor failure raised to a double price of a new motor. In South Africa, the amount of losses is subject to the currency exchange rate.

Estimation of the reliability indicators as part of GEC

Fault tree method

Multidisciplinary techniques as statistic-probabilistic methods in estimating reliability and thermodynamics calculations must be co-related as a part of the global efficiency concept (GEC). Mathematical modelling using a 'fault tree method' in assessing a process or designing a financially competitive product with improved technical performances is currently used in various fields.

Fault tree analysis is a method of combining various components failure rates, first proposed by HA Watson to analyse the Minuteman Launch Control System (Schweitzer 1997). Refined over the years, the method models system failure of interest is called Top Event (TE) i.e. equipment failure. The fault tree breaks down TE into lower-level events (LLE).

Logic gates show the relationship between LLE and TE. Mathematical model is based on Boolean algebra. The 'OR' gate showed in Figure 3 (a) expresses the idea that ANY of several component failures can cause an output event, here, TE = equipment or process failure. The output event failure rate λ_o function of LLE failure rates λ_i can be calculated as:

$$\lambda_o = \Sigma \ \lambda_i \quad \text{[1/hours] units} \qquad (1)$$

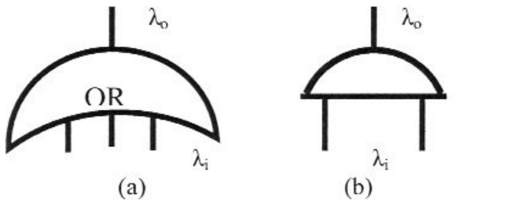


Figure 3: Gate 'OR' and gate 'AND' description

The 'AND' gate showed in Figure 3 (b) expresses the idea that both (or all) components must fail in order to produce the output event. The output event failure rate λ_o function of LLE failure rates λ_i can be calculated as:

$$\lambda_o = \Pi \ \lambda_i \ \text{[1/hours] units} \qquad (2)$$

Case study: Fault tree of an electric motor (EM)

A basic fault tree for specific type of electric motors is shown in Figure 4. Top event (TE) is considered to be failure of an electric motor (EM). LLE is considered as bearing, windings, rotor failures, and environmental conditions. Any of them can produce TE. The failure rate is expressed in 10^{-6} 1/hour.

Table 2 shows the estimated failure rates from the statistical data on MTBF. These specific types of electric motors are running on an average of 4000 hours/year.

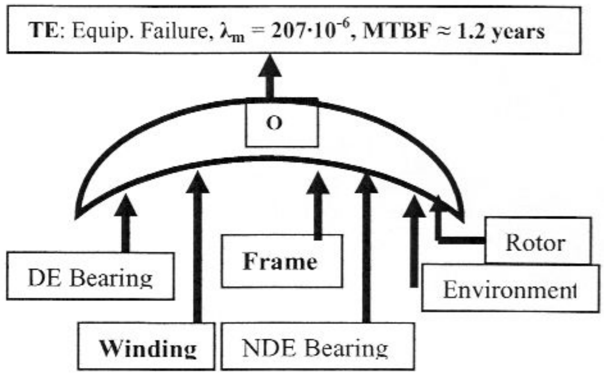


Figure 4: Typical fault tree used for estimation of reliability indicators of an electric motor

Table 2: Basic failure rates used in estimation of failure probability for a specific type of electric motor

EM component	*MTBF (hours)*	*$\lambda_i \times 10^{-6}$ (1/hour)*	*Lifetime Expectancy*
Rotor	23490	42.5	5.3 years
Winding	24360	41.0	5.6 years
Drive bearing	26100	38.31	6 years
Frame	30960	32.3	7.3 years
Non-drive bearing	30450	32.8	7 years
Environment	48550	20.6	11 years
Failure rate of motor		207.51	1.2 years

Evaluation of global efficiency and the process based on fault tree results

The fault tree is the basic point in evaluation of this specific electric motor behaviour in relation to global efficiency of the process (from reliability point of view):

- EM failure is occurring beyond the warranty period, i.e. 1.2 years (ensuring business sustainability);
- 'Weak points' of the motor are the rotor, windings and drive bearing. These 'weak points' failures

were found to be mostly due to:
- Thermal stresses: overheating, poor heat transfer, cooling, non co-ordination of heat transfer;
- Maintenance and monitoring activity;
- Specific working conditions of the application (see also paragraph 3.2).

Conclusion: This fault tree method can be applied to any process. This model enables you to analyse global efficiency of the process from a reliability point of view. It is a useful tool in making technical and economical strategic decisions. Used in real time, with automat data acquisition systems, this mathematical model enables easy planning and comprehensive predictions based on simulations.

The role of energy efficient policies towards GEC

Energy efficiency policies

Numerous international conferences stressed that energy efficiency improvements in various industrial processes, residential appliances, heating equipment, lighting, etc play a key role in assuring a sustainable energy future and socio-economic development.

In order to change unsustainable patterns of energy use, developed countries have already enforced specific standards for energy efficient electric motors (EEEM) (NEMA 1988; CEMEP 2000).

Basic characteristics of an energy efficient electric motor (EEEM)

EEEM design is orientated towards a full load losses re-distribution as follows (to give a total of 100%) (Pitis 2004):

- Stator winding loss 35 to 40 %
- Stator core loss 15 to 20 %
- Rotor loss 15 to 20 %
- Friction and windage loss 5 to 10%
- Stray and windage losses 10 to 15%

Besides an optimum balance between specific electrical and magnetic loading, a dedicated EEEM motor design has to incorporate specific features:

- Stator/rotor slot combinations, with specific shape and optimum openings (dedicated slot tooling)
- Copper fabricated rotor, reducing rotor losses
- Double layer mush winding with reduced LMT (length mean turn), reducing copper losses
- Short winding pitch (some slots sharing coils from different phases - causing overlapping between adjacent phase-bands, to the benefit of the air gap flux pattern)

EEEM can also be regarded as highly reliable motors with an increased motor life span an important requirement.

Case study: Savings in using energy efficient products for water pump station

For a new pump station project for a particular gold mine in the Free State, WEIR-Envirotech decided to use nine (9) high efficiency (En.Eff.) products.

According to estimations done on mathematical models it was found that product life span and Mean Time Between failures (MTBF) are superior to the standard (Std.1 and Std.2) products. That means a reduced number of repairs during the entire life of the product.

Taking into consideration South African repairer's activity, after every repair, it was considered a performance degradation of rated values in a range of 1.5% (SABS 1992). Comparative figures are presented in Table 3.

Table 3: Comparative EEC savings per 132 kW pump

Equipment	*Std. 1*	*Std. 2*	*En. eff.*
Rated input power (kW)	145	143.5	139.7
$MTBF_{Motor}$ (months)	7.2	8.6	14.4
Repairs number	11	9	5
Initial efficiency (%)	91.0	92.0	94.6
Effic. After last repair (%)	78.2	79.8	89.0
Average efficiency (%)	84.6	85.9	91.8
Average input power (kW)	156	153.7	143.8
Annually energy savings per pump (MWh)	NIL	13.8	73.2
Financial saving /pump (R)	NIL	2 500	13 180

The motors are continuously running at 6000 hours/year. According to a National Electricity Regulator (NER) Board meeting (February 2006), the electricity price is R 0.15/kWhour with an annual price increase = 5.7% resulting in the average electricity price = R 0.18/kWhour over 7.5 years assessment period.

Conclusion: The mine annual average EEC savings on pump stations are R 119 000.

Estimating total cost of ownership as part of GEC

Setting evaluation criteria

Evaluation criteria based on Total Cost of Ownership (TCO) are only considering the following components (as shown in Figure 1):

- Initial price (IP) as cost of initial investment;
- Electric energy costs (EEC);
- Repair and replacement costs (RC);

Other costs of maintenance and monitoring, downtime production, logistic activities, direct and indirect costs, reactive energy costs, etc have been neglected.

The results:

$$TCO = IP + EEC + RC \quad (3)$$

Year-to-year price increases for IP and RC were neglected. It was considered that their trend evolutions (increments) have the same slope. Electricity price EEC and the assessment period are the same as in Section 5.3.

Case study: Estimations of TCO for an auxiliary underground ventilation system

The estimations (shown in Table 5) have been done on four different types of 45 kW fan motors (Pitis 2006):

- Standard motors fitted in a PAD casing denominated as Std.1, Std.2;
- Energy efficient motors as dedicated motors to the application denominated as EEM1, EEM 2.

The time period for evaluation was 7.5 years. On average, the fan motors are running 8 000 hours/year. The costs were expressed in pu units having the same base reference, i.e. cheapest IP of 45 kW Std.1 PAD motor, with pu = 1.0. The average repair cost is 45% of the motor price (IP).

Conclusion: Motor purchasing was not specification driven but only by initial motor price (IP). the initial price (investment) IP represents only 1.9% - 3.3% of Total Ownership Costs. Buying low cost standard electric motors produced negative impacts on the market and mining industry.

Planning, prediction and process efficiency control

Supposing a repaired motor worked 6 months + 1 day, which means 1 day more than the required warranty period. Would this motor be repaired again? The customer has to be sure that after a repair process the motor will be in a reliable condition, making a profit. The repairer has to be sure that after a repair process the motor will be in operation longer than the warranty period. These two sentences have common ground: the motor has to perform longer than the warranty period, and the time period between failures having acceptable values for both repairer and customer.

At this stage, on the market, this issue has been addressed empirically, depending on repairer expertise and his dedication to his customer. The Global Efficiency Concept requires mathematical support in deciding how many times a motor can be repaired before being scrapped in a non-economical process (known as 'repair policy').

The chief phenomenon decreasing the mean time period between failures (MTBF) is the ageing process occurring with different intensities, mainly in two situations:

- During motor operation
- During repair process of the motor

As a result of the ageing process, motor failures are occurring with increasing values of intensity during and after every repair process. It has been agreed that during the motor repair, the ageing process has higher intensity than the motor operation process and also enhances the ageing process in operation.

Faults distribution during the ageing process has been agreed to be according to Weibull distribution law (EASA 1998; Dakin 1948) The ageing process assessment of the motor components has been based on bibliographic research (EASA 1998) and many years experience in the field.

Figure 6 shows a schematic diagram of a fault intensity motor evolution during the operation and repair process, simulating the maximum of three (3) motor failures. The mathematical model for this present case study is based on this diagram.

Legend:

LIFE 0: Fault intensity evolution for a normal motor

Table 4: Estimations of TCO for a 45 kW motor fan

Motor	*Std. 1*	*Std. 2*	*EEM1*	*EEM2*
IP (pu)	1.00	1.16	1.28	1.52
$MTBF_M$ (months)	7.2	8.6	14.4	17.8
Repairs number	11	9	5	4
Rated motor efficiency (%)	90.0	91.0	94	95.2
Efficiency after last repair (%)	77.38	80.64	88.48	91.0
Average eff. (%)	83.7	85.8	91.2	93.1
Total EEC (pu)	46.45	45.31	42.62	41.75
1 repair cost (pu)	0.45	0.522	0.576	0.684
Total RC (pu)	4.95	4.7	2.88	2.74
IP@3.5 yrs (pu)	1.00	1.16	None	None
Total TCO (pu)	53.4	52.33	46.78	46.0
Annually savings per fan (Rand)	Nil		86 000	96 200

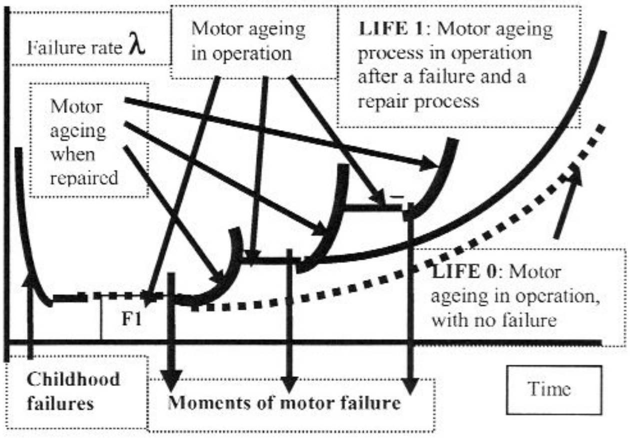


Figure 5: Schematic diagram of failure rates evolution

life without any failure and any repair process; the fault intensity is increasing as a result of the ageing process and failure may occur after a long life-time in operation.

LIFE 1: Fault intensity evolution when one motor failure occurred at the moment F1, followed by a repair process and a new operational process without any failure but a normal ageing process after a shorter life in operation. The mathematical model is based on ageing laws as the Arrhenius chemical rate equation, where windings thermal life being evaluated by (AngloGold 2003):

$$ln\, L = ln\, B + (\phi / kT) \quad (4)$$

where,
L = insulation life time in hours
B = characteristic constant for specific insulation
ϕ = Activation energy in eV
k = Boltzmann constant: 0.8617 exp (–4) in eV/K
T = absolute temperature in K

Experimental measurements have been done and charts drawn are available for different classes of insulation. Motor temperature rise influence on motor life for overloads conditions is:

$$Lx = L100 / 2\, exp\, ((Tc - Tx)/ HIC) \quad (5)$$

where,
Lx = percent lifetime at x% load
$L100$ = the percentage lifetime at rated load
Tc = total allowable temperature for insulation class °C
Tx = the hot-spot temperature for insulation class °C
HIC = halving internal index designating the increase in degrees Celsius for a corresponding 50% reduction in time-to-end point applicable to insulation systems (Arrhenius chart).

For example, the approximate effect of motor loading on motor life, based on 20 000 h, the service factor = 1,0 for H class insulation expected life is 2.3 years @ 100 % load, dropping to 0.2 years life time @ 110 % load. Based on this mathematic model supplied by the data acquisition system of a field service, the process can be controlled and monitored by:

- Planning of the number of repair activities;
- Predicting the equipments failure; and
- Monitoring the equipment capability to perform in a certain range of parameters (overall parameters being considered the motor efficiency, temperature rise on the winding and other components).

An example of a global efficiency evaluation of a specific process

Setting the problem

The gold mining industry experiences a new challenge with activities moving to ultra deep levels (UDL) in excess of 2800 - 3000 m depth. Dust and gases dilution and heat removal (when walls temperature is reaching 65°C), preventing unsafe environmental climate in a high air density condition, on the one hand, while increasing ventilation costs may reflect in business sustainability on the other. Axial fans are used for auxiliary underground ventilation. A typical schematic diagram of such an axial fan is shown in Figure 7.

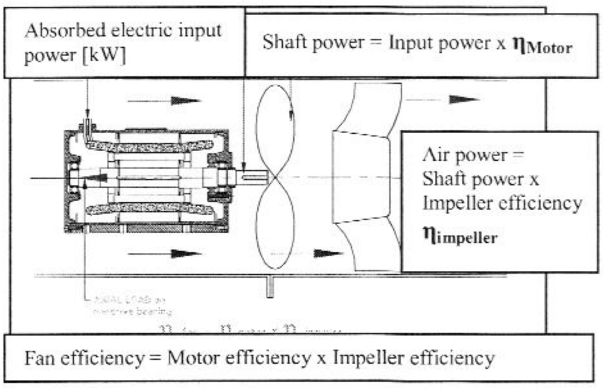


Figure 6: Schematic diagram of an axial fan

In Western Deep levels – Carletonville area, North West Province, a particular gold mine experienced higher values of production costs in the last four years.

In this mine the existent fan deep levels - FDL type fans working below levels of 2 800 m and fitted with standard 45 kW PAD motors have been replaced after a working period of only 4 hours - 2 weeks.

Upon investigations, it was found that 45 kW standard motors powering a FDL fan type perform very high failure rates (as shown in Photo 3).

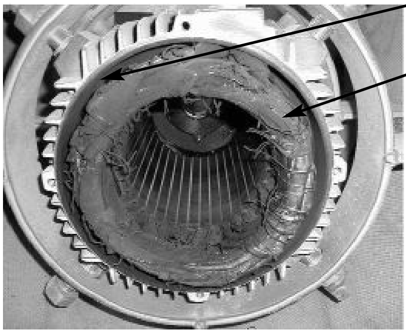


Photo 3: A standard 45 kW PAD motor was burnt out after 4 hours working at 3 100m depth conditions

Studying the process – essentials of application engineering

In UDL conditions, air density values are far bigger than standard conditions i.e. $\rho_{air} = 1.2$ kg/m^3.

Air density measurements performed at 3 220m in a specific day (as shown in Figure 8) revealed air density variations far beyond the value of 1.4 kg/m^3:

- Case A: $\rho_{air} = 1.45$ kg/m^3 for 7.5 hours
- Case B: $\rho_{air} > 1.48$ kg/m^3 for 4 hours.

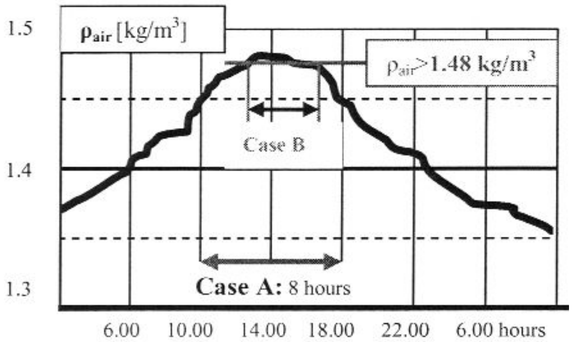


Figure 7: Air density variation at UDL = 3220 mm (Pitis 2006)

This air density variation was due to the type of air circulation (extracted from the surface or re-circulated)**.** As a result, the air mass moved by the fan will increase in direct proportion. The fan air power may increase in a range of 120 - 130% comparing to standard conditions.

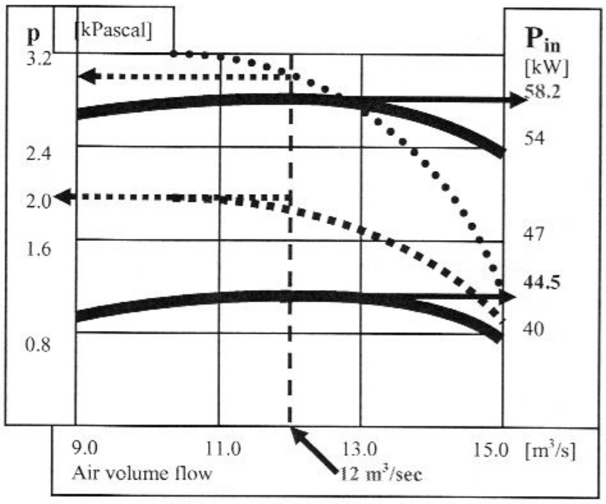
Therefore, standard motors are working in overload conditions and are exposed to winding and rotor failures (as shown in Table 6).

Measurements have been done on four different types of 45 kW fan motors**:**

- Standard motors fitted in a PAD casing denominated as Std.1, Std.2;
- Energy efficient motors as dedicated motors to the application denominated as EEM1, EEM 2.

Comparing EEEM to standard motors did the evaluation. The evaluation was based on case B: ρair = 1.48 kg/m^3.

Because the fan and impeller geometrical dimensions are unchanged, at UDL (AngloGold 2003), the fan performances will be modified according to red line graphs shown in Figure 9.



Air pressure 'p' vs. air volume flow (dot lines)
Absorbed electric power: Pin (solid lines)
Standard $\rho_{air} = 1.2$ kg/m^3 (bottom horizontal)
UDL $\rho_{air} = 1.48$ kg/m^3 (top horizontal)

Figure 8: Fan characteristics

The fan air power at UDL will become:

$$P_{UDL.air} = \text{Air flow x } [\rho_{airUDL}/\ \rho_{air}] \text{ x } p_0$$
$$P_{UDL.air} = 12 \text{ x } [1.48/1.2] \text{ x } 2.0 = 29.6 \text{ kW}$$

Considering an average impeller efficiency of 60%, the average required motor shaft power is:

Shaft power P = 49.35 kW > 45 kW!

Table 5: Evaluation of EEEM at ultra deep levels

Motor	Std. 1	Std. 2	EEM1	EEM2
Motor efficiency	90 %	91 %	94 %	95.2%
Consumed input				
Power (kW)	54.83	54.2	52.5	51.0
Rated Temp. Rise	105°C	105°C	80°C	72°C
Actual Temp. Rise	126°C	126°C	96°C	87°C
Motor condition	Burnt out		Good	Excel.

Conclusion: Standard motors are not able to perform at ultra deep levels. Considering quadratic law variation of the motor, T_{mot}, temperature rise (Say 1995) for a standard 'F' class winding temperature rise being $T_{ST.W} = 105°C$ results:

$$T_{mot} = T_{ST.W} \text{ x } ((49.35)/45)^2 = 126°C \qquad (6)$$

Therefore, the motor temperature rise will increase beyond the insulation's thermal capability (or rating). The process re-evaluation is based on reliability indicators (by using a mathematic model). Reliability indicators enable a more realistic process evaluation (as presented in paragraph 4.1 and Table 7). The motors are running 8 700 hours/year.

Table 6: Basic failure rates used in estimation of failure rate probability for standard 45 kW PAD motor (Std 1)

Component	*MTBF (hours)*	*λ_i x 10^{-6} (1/hour)*	*Lifetime expectancy*
Winding	23490	42.5	2.6 years
Drive bearing	26100	38.3	3.0 years
Rotor	26100	38.3	3.0 years
Non-drive bearing	30450	32.8	3.5 years
Environment	24270	41.2	2.7 years
Total for motor	5178	**193.1**	0.59 years

Further investigations revealed that only dedicated EEM 45 kW PAD motors are able to sustain the harsh working and environmental conditions at UDL. Taking into consideration South African repairers activity, after every repair, it was considered a performance degradation of rated values in a range of 1.5% (SABS 1992).

As a result of the motor efficiency degradation, the motor losses are increasing in direct proportion. To sustain the load requirements the motor will absorb more power, estimated in a range of 57.7 - 58.1 kW (as shown in Table 8).

Motor temperature rise T_{mot} variation function of the motor losses increase (Say 1995) for a standard 'F' class winding temperature rise being $T_{ST.W}$ = 105°C and is:

$$T_{mot}=T_{ST.W}X((9.75\ldots8.36)/(5.48\ldots4.85)) =177°C..180°C$$

Estimating electric energy costs (EEC)

The electricity price and assessment period are the same as in paragraph 5.3. A new generation of energy efficient fans has to replace the 'standard' existing equipment at ultra deep levels. An energy efficient electric motor fitted in a 45 kW fan generates an estimated annual savings of R12 500 on an electricity bill.

For a 24 hour process, energy efficient motors pay for themselves in a very short time, after which they will save on electricity bill costs many times their difference in purchase cost.

Estimation of total cost of ownership (TCO)

The estimations are presented in Table 5. In this particular mine, there are 33 FDL units out of 75 FDL units working at UDL > 2 650 m.

Conclusion: Economical implications of introducing EEEM 45 kW fan motors in ultra deep levels for a particular gold mine, resulted in R0.5 m annual savings, equivalent to 10.5 kilograms of gold at production cost.

Planning, prediction and process efficiency control

Reliability indicators and performance degradation estimations reveal that after 3.5 years (running the standard motors) produce unusual high losses and must be discarded. A maintenance plan will enforce periodical stoppage and inspection.

It was also decided that the equipment should be sent for refurbishment after 1.2 years continuous running. Mechanics and environmentalists will inspect and monitor periodically the motors and fans. As a result, statistical data regarding the air quantity delivered by fans becomes available. Typical average figures are shown in Table 9.

Table 7: Comparative features of the 45 kW fan motors after 7.5 years running (end of assessment period)

Motor	*Std. 1*	*Std. 2*	*EEM1*	*EEM2*
Shaft Power (kW)	49.35	49.35	49.35	49.35
Cos φ	0.846	0.894	0.925	0.935
Initial Temp. Rise	105°C	105°C	80°C	72°C
Initial Effic. (%)	90.0	91.0	94.0	95.2
Efficiency after the last repair (%)	77.38	80.64	88.48	91.0
Actual Temp Rise	180°C	177°C	90°C	79°C
Input power (kW)	58.15	57.7	55.3	53.0
Annually saved energy kWhour	None	18800	58400	69600
Initial $MTBF_{Motor}$	7.2 m	8.6 m	14.4 m	17.8 m
Last $MTBF_{Motor}$	5.3 m	6.8 m	12.8 m	16.2 m
Mot. Degradation	74%	79%	89%	91%

Table 8: Air quantity delivered annually by a 45 kW type fan at different air densities

No.	*Description of Impeller type and air density*	*Tons of ventilated air annually delivered by 45 kW fan*
1.	'1.2 impeller' @ 1.2 kg/m^3 air density ('F' fan)	454 118
2.	'1.2 impeller' @ 1.4 kg/m3 air density ('FDL' fan)	**529 805** (Using energy efficient motor)

Table 9: Estimations of FEI for auxiliary ventilation 'F' type fans in different scenarios

No.	*Fans @ various air densities driven by standard and energy efficient 45 kW motors*	*FEI (Rand/ton of ventilated air)*
1.	'1.2 impeller' @ 1.2 kg/m^3 air density driven by a standard motor	0.158
2.	'1.2 impeller' @ 1.2 kg/m^3 air density driven by energy efficient motor	0.121
3.	'1.2 impeller' @ 1.4 kg/m^3 air density driven by a standard motor	Burned out
4.	'1.2 impeller' @ 1.4 kg/m^3 air density driven by energy efficient motor	0.125
6.	'1.2 impeller' @ 1.32 kg/m^3 air density driven by a standard motor	0.253

Table 10: FEI values (specific energy costs per ton of ventilated air) measured in a specific ultra deep level

Fan no. (45 kW)	*Motor type*	*Absorbed power (kW)*	*Air volume flow (m^3/sec)*	*FEI (R/ton of air)*
1. FDL 165	Energy efficient	48.33	14.50	0.181
2. FDL 082	Standardmodified	52.44	10.64	0.268
3. FDL 149	Standard, 2 hours	53.76	9.78	0.298

Considering electric energy costs EEC and ventilated air quantities delivered, the process efficiency control can be dynamically monitored by using a specific estimator (as shown in Table 10) denominated as Fan Efficiency Indicator (FEI) (19):

FEI = EEC / Air quantity (Rand / ton of ventilated air)

Conclusions based on validation activities

An FEI estimator is a useful indicator in assessing fan efficiency:

- It incorporates ventilation process specific costs in the production cost of the final product;
- Monitors permanently the global efficiency of the fans population and/ or individuals.
- A global FEI estimator per shaft (for a specific mine level) can be produced as a global efficiency indicator of the process, part of company corporate energy policy.

During the validation process, various measurements have been performed on 'FDL' type fans at ultra deep level shafts with average air density = 1.42 kg/m^3 (as shown in Table 11). As a result of these activities, the following conclusions are available:

- Regardless, the shaft level energy efficient motors offer a boost and a global solution for auxiliary ventilation systems (high efficiency and reliability at any level of the mining shaft without motor or ventilation system frames alteration).
- The FEI estimator is an expression of the global efficiency concept applied to a specific process.
- Auxiliary fans fitted with energy efficient electric motors driving '1.2 impellers' are characterised by low and approximately constant FEI values, regardless of the environmental working conditions.
- High performance fans (impellers equipped with energy efficient motors) pay for themselves in a very short time (calculated pay-back period for energy efficient motor is 0.8 - 1.1 years) after which they will continue to pile up savings worth many times their purchase cost as long as they remain in service, having by design, a higher reliability.

The novel method of improving squirrel cage induction motor performances by using MCFR

Setting the problem

In the South African industrial environment, about 20 to 25% of the repaired squirrel cage motors need motor replacement. Old motors with cast aluminium rotors are scrapped, especially when manufacturers cease the production of rotors.

As an example, for more than a decade, a specific motor used in the coal-mining industry was a challenge for repairers, manufacturers and mines. Because of a dramatic productivity increase in the South African mining industry (200% - 300% of rated values of the equipment), the rotor and motor reliability and performance have been dramatically reduced. The equipment non-performances were enhanced by characteristic harsh mining conditions.

As a result, a reputable mining house recorded multimillion Rand annual losses as a result of specifically imported aluminium rotor failures. All attempts in replacing this specific rotor failed, the manufacturers not able to match the required performances. Since 2004, the problem was solved when a new set of motors (shown in Photo 4) was fitted with patented Mixed Conductivity Fabricated Rotors (MCFR) (Pitis 2005) and is running successfully.

Photo 4: Gathering arm (spinner) motor fitted with MCFR, after 1.8 years working underground

Studying the process (essentials of application engineering) and the costs evolution

The process study was presented in Section 3.2. Based on statistical data collected from various technical and economical activities, it was found that specific cost indicators are a function of the process speed, as shown in Figure 10 (abbreviations are according to Figure 1).

As presented in Section 3.2, the overseas-designed motor was not able to comply with harsh South African mining conditions, contravening its essentials of application engineering as presented in Section 3. Based on financial and technical information, estimations of the costs variation laws function of the process speed are presented in Table 11.

Table 11: Costs estimations function of process speed

Item	*Estimation function of process speed* ***'v'***	*Costs (Euro/ton)*
Mining licence	Constant	
IP	Constant	
DIC	~ (1/v)	
LC	~ (1/v)	
MC	~ (0.1…0.25) (v)	
EEC	~ (v)	
Production cost	@ Rated process speed	~ 10…13
Predicted production cost*	@ Double speed of the process	~ 7…9
RC	~ $(v)^2$	
DPC	~ (3…5) (v)	
Real cost**		~ 14…17
Selling price***		~ 15…18

* Neglecting repair and replacement costs due to accelerated ageing of the equipment (RC) and downtime production costs (DPC)
** Influenced by RC and DPC (after statistical results collected over 3 years)
***Including profit margin

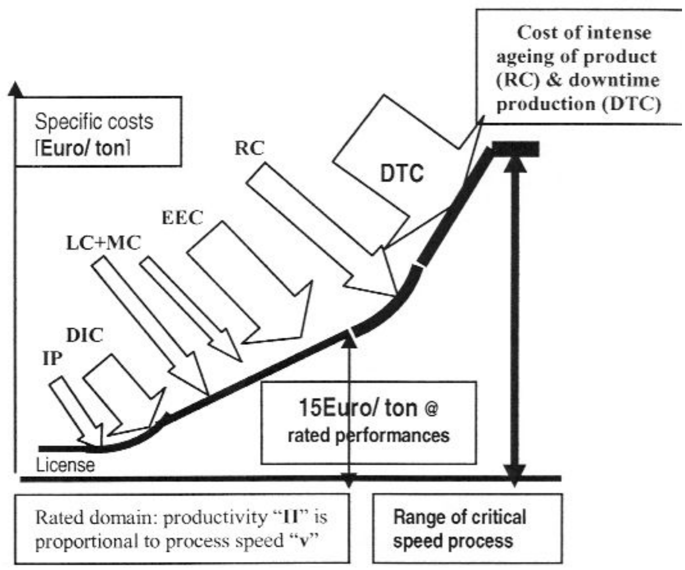


Figure 9: Specific costs evolution function of the process speed for a specific mining process

Estimations of financial losses (TCO)

Estimations on financial losses (as shown in Table 12) have been done on a specific gathering arm 36 kW motor, powering continuous miners.

Table 12: Financial losses due to unplanned motor stoppages

Item	*Cost rate (Rand)*	*Magnitude loss (Rand)*	*Financial*
Down time production	35 000 per hour	7–9 hours*	280 000
New motor	65 000		
Average motor repair cost	45 000	0.7 of new	45 000**
New rotor cost***	26 000	120 units/year	
Motor repairer warranty costs	20 000	R20 000	
Repairer losses		10 000	10 000
Financial loss			355 000

* According to customer planning, the following activities (with time duration) take place:
Spare motor availability = 3 to 5 hours
Replacing motor and commissioning = 4 hours
** Including rotor replacement @ success rate of 50%
*** Imported cast aluminium rotor price was R 26 000

Assessing reliability indicators

Based on statistic results, reliability indicators have been assessed in a mathematic model by using the 'fault tree method 'as presented in Section 4.1. The assessment indicated that rotors are the 'weak point' of the motor producing unplanned stoppages and heavy financial losses. Predicted events were done for a 15 year period for an overseas designed aluminium rotor and MCFR patent (as shown in Table 13).

Table 13: Predicted events on a 36 kW spinner motor

Item	*Aluminium rotor*	*MCFR*
Number of motor failures	13	7
Rotor replacements number	8	None
Down-time production total	104 hours	56 hours
Rotor life span (months)	14…18	Est. 200
Motor MTBF (months)	13 (unplanned)	24 (est.)
Motor cost	R55 000	R60 000
Rotor cost	R26 000	R20 000
Motor repair cost	R45 000	R25 000
Av. production loss cost/hour	R35 000	R35 000

In this situation of the aluminium rotor, it becomes obvious that the unplanned motor failure occurred before the planned replacement. Proving its extended life span, MCFR enables the end-user to repair the products based on a solid maintenance plan.

Requirements for a new rotor type (MCFR)

Based on the facts presented above, a new rotor model was created (as presented in Table 14).

Table 14: Conditions of a new rotor model (MCFR)

Existing conditions Aluminium rotors	*New proposals Fabricated rotors*
Imported product	Locally manufactured
High price & fluctuation	Indigenous components
Monopoly of the big organisations, price control	Medium-sized organisations able to manufacture rotor
Investments for cast process machinery are required	No special investments processes required
Special quality assurance system required	Normal quality assurance system
Needs a load test of every motor to prove rotor quality	Test only for prototype No hidden defects
Need high quantities to become economically viable	Can be produced in any quantities, custom made
Special training and expertise of the personnel	Normal expertise required
Inconsistent performances	Performances stability
Has 'weak points'	Homogenous reliability
Life time 1.25 to 2 years	Minimum 10 years
Non-reparable, high TCO	Cheap repair possibilities

Basic performances of a spinner motor fitted with MCFR

The MCFR assessment has been done during validation and verification activities. The results enabled performances comparison against other rotors existing on the market (as shown in Table 14).

Conclusions

The proposed global efficiency concept is based on a new approach of efficiency in the equipment processes, regarded as a complex project. Process efficiency can be dynamically monitored by using:

- Specific global efficiency indicators;
- A mathematical model of process efficiency; and
- An automatic data acquisition system.

This will result in 'real time' strategic, technical and economical decisions. As a product of R&D indigene activity, MCFR was designed as a need of improving efficiency of a specific mining process. MCFR represents one of multiple possibilities in approaching the global efficiency concept.

Various case studies and examples were presented as guidance in support of the proposed glob-

Table 14: Performances comparison of MCFR versus other rotors existent on the market

Parameter	*MCFR*	*W. Europe aluminium rotor*	*East Europe aluminium rotor*	*RSA manuf. copper rotor*	*RSA Double cage rotor*
Motor efficiency	90 %	87 %	88 %	89 %	89 %
Winding temp. rise 3 h. (°C)	75… …85	100… …115	90... …105	85... …90	100… …105
Rotor T rise 3 h. (°C)	155	265	240	200	220
DOL starts in row	8	1	2	4	3
Rotor life (years)	20	1…			
…1.5	1…2	5 …8	6…7		
Motor life (years)	15 years	1.5…2 years	3 to 4 years	5…8 years	6…8 years

al efficiency concept. The technical presentation was proven by economical effects. These examples can be extended to various other processes.

Notes

1. A process rated speed domain can be slightly extended (increasing productivity) without new investment or a re-capitalization process being necessary. However, a consistent increase of productivity is always conditioned by a sound study of the process (application).
2. In a gold mine, there are 70 fan units, on average, equipped with 45 kW PAD motors.
3. At UDL, standard ambient 40°C does not apply.

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