Plan the work, work the plan

(a case study based on maintenance practices in the mining industry)

Contents

Abstract

The case study is focused on the operations of XYZ Limited, a heap leach copper mine located in the Atacama desert in Chile. The timeframe is 2012 when copper prices and grade were in decline with both ultimately conspiring to reduce returns to shareholders. A CEO has recently been appointed and given an ambitious target to simultaneously achieve a 15% improvement in production of saleable product (copper cathode), a 20+% reduction in operating costs and a 20% reduction in inventory/investments.

The operation mines copper from a measured resource of 100mt at a head grade of 0.5% copper. The ore to waste ratio is 3:1. Recovery rates are in the order of 75% The process of converting mined ore to copper cathode involves mining the ore and waste from an open pit using a fleet of drill rigs (15) dump trucks (25) and (4) loaders. Overburden is stockpiled for future rehabilitation purposes. In- situ waste is relocated to a sterilised site within the mine and the ore is trucked to a ROM (Run of mine) stockpile located within close proximity of the primary crusher. The ore is progressively crushed using both jaw and cone style crushing equipment and screened to achieve a predefined particle size that facilitates an optimal surface area prior to agglomeration. Agglomeration results in a consist separation of the fragmented particles to facilitate the leaching process. Agglomerated ore is stacked onto existing heap leach pads using mechanical mobile stackers and conveyor belts. The heap leach pads are constructed in a layered formation and then leached via a portable reticulation system which sprays the top of the pad with sulfuric acid. As the acid flows though the heap leach, the acid dissolves the copper and carries it by gravity to the base of the heap leach pad and then to irrigation channels located to the side of the pads where the ‘pregnant’ solution is diverted and eventually directed into accumulation ponds. The pregnant solution is subject to electro winning (EW) and solvent extraction (SX) where the copper in solution is converted (by electrolysis) into copper cathode sheets as an end product. The remaining solution is cleaned and reused in future leaching process. .

The operation produces approximately 100,000t of copper cathode annually

The mine site has been running for approximately 20 years with much of the fixed plant (primary, secondary and tertiary crushing, agglomeration stackers conveyors) infrastructure (buildings, power lines, water pipes , roads etc) and mobile fleet (drill rigs, loaders, dump trucks, light vehicles etc) being subject to regular preventive maintenance. Despite this, the level of breakdown (unscheduled failure) remains high (~50+%) resulting in unexpected and adverse impacts on equipment availability as well as higher than normal cost of repairs (due typically to the need to expediting parts and pay penalty labour/contractor rates to repair higher than normal damage).

The quality and quantity of spare parts holdings is another ongoing problem for the operation. The amount of spares required to be held for maintenance activities is unsubstantiated (according to the CEO) and on the high side with a significant percentage classified as slow moving. Slow moving spares have a greater likelihood of being subject to written off provisions and subsequently sold for scrap value by the store manager. Redundant spares also occurs through equipment being sold or scrapped without including the existing spare parts holding, resulting in a steady but growing accumulation of redundant and worthless parts. This is also exacerbated by the engineering function failing to establish technical standards for the purchase of various types of equipment. This results in a wide variety of manufactured models (for example) of dump trucks, drill rigs, graders, pumps etc all requiring their own specialized parts, tooling and expertise

The method used by finance to account for the operations maintenance costs is another area of concern. Direct maintenance parts and materials when consumed, are charged directly to the cost centre where the equipment belongs. However, indirect maintenance costs such as labour, consulting and overhead (supervision, training etc) are accumulated and allocated on the basis of the % work orders executed in a given area in each month. Consequently, there is no single source of truth in respect to the total cost of maintenance, making it particularly difficult to monitor and therefore manage.

It is widely believed however that annual maintenance expenditure is a least half of the total cost of annual operations ($448m).

1 Introduction and purpose

The purpose of this case study is to provide the reader with a real life situation which can be used to demonstrate proficiency in interpretation, analysis and decision making when answering 'what to change?', 'to what to change to? and 'how to effect that change?'.

This case study will focus on the first question – what to change – it draws on a combination of research and personal experience gained in maintenance management practices in the global mining sector

2 How should a student analyse this case?

This case describes the mining sector in general and maintenance in particular. Much of the data relates to a particular mine site in Chile which produces copper cathode using heap leaching and electro winning technology. The maintenance activities performed are typical of many operating mines worldwide with a high cost and inventory base, a significant proportion of equipment breakdowns and an engrained commitment to preventive maintenance practices. By way of contrast, the highly competitive aviation industry depends on a rigorous cost effective approach to maintenance that not only ensures high equipment availability (in order to generate revenues) but also demonstrates to customers that flying is relatively safe[1]. Many other industries have similarly adopted this approach to maintenance and reaped the financial rewards of such an approach. Mining however, is a particular laggard in this respect as this case study describes.

Students are asked to evaluate the information provided in the case study as well as via their own independent research to complete the objectives and deliverables.

[1] Refer https://www.theguardian.com/commentisfree/2014/jul/24/avoid-air-travel-mh17-math-risk-guide: '' in the wake of the 9/11 air tragedy, huge numbers of Americans switched from flying to driving – for the year following the attack, airline passenger miles fell between 12% and 20% while road use surged.,, Professor Gerd Gigerenzer, a German academic, estimated that the road death toll in the year after 9/11 increased by 1,595 people… compared to.. the latest global airline safety report shows there were 90 commercial airplane accidents in 2013. Only nine involved fatalities – a total of 173 people.

Students should also note that this case study is based on contemplating and answering the three questions posed above in sequence using the Theory of Constraints thinking tools (IO Map, Current Reality tree, Evaporating Cloud). Because the questions need to be answered in sequence, the outcomes of each question is relied upon in the next question. Beware.

The following table summarises the key objectives and deliverables:

Table 1

	The objectives of this project are to:
1	Understand what the relationship between maintenance and the organisation should be vs what is current state
2	Understand what drives the current approach to maintenance practices in mining and why it has persisted
3	Propose and validate a solution (set) that demonstrates real and sustainable outcomes both now and in the future
4	Demonstrate your understanding of how local decisions impact organisational goals
	Deliverables include individual reports/maps/trees which address the following items:
1	A clear and precise articulation of the goal and necessary conditions for Enterprise Asset Management practices at the mine site (IO map)
2	An analysis and validation of the 'as is' state of maintenance in order to identify the root cause (relative to the goal) of current maintenance practices at the mine site (CRT, CLR)
3	Explain why the root cause has persisted and propose a validated solution which will permanently resolve the problem (EC, 5FS)
4	Develop an excel based decision tree which establishes the relationship between maintenance practices and the organisations goal

3 Setting the scene

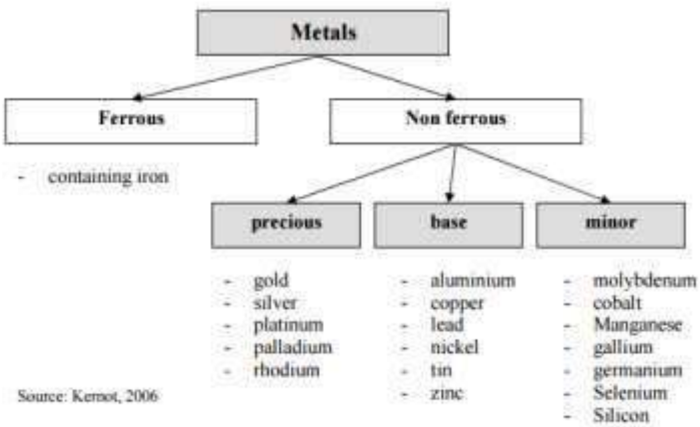
A new CEO has been appointed as a result of both a sudden and sustained decrease in the price of copper. She has been given 3 months to make a significant improvement in the performance of this operation or face the likelihood of closure.

For many minerals, and copper in particular, the London Metal Exchange (refer below) represents a market of last resort (i.e. they can sell everything they produce) The key financial measure the operation uses is Return On Assets (ROA) which can only be improved by increasing profit and/or reducing the underlying asset base

4 Background – metals and mining sector

The metals and mining sector is a global industry involved in the business of locating and extracting metals and minerals wherever they are found to be economically viable[2]. Global reserves[3] of metals and minerals (e.g. coal, iron ore, gold, nickel, copper, gold diamonds) are mined for use in almost all industrial/commercial applications (construction, transport, energy, technology etc). The sector has attracted a significant number of participants both large and small with operating mines located throughout the world on both land (with the current exception of the Polar Regions) and sea. Six of the largest international mining organisations include BHP Billiton, Rio Tinto, China Shenhua Electric, Glencore and Vale[4] . These companies represent the highest revenue producers in the

Figure 1: Classification of Metals



Source: Kernot, 2006

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[2] Economically viable – refers to the evaluation of whether a given ore body will deliver a ROI above a predefined hurdle rate (typically ~>20%) given its location, size, grade and proximity to market. This assessment will be based on key assumptions regarding revenue, capital and operating costs derived from initial development, operating and rehabilitation prior to final closure. The concentration of the ore is a key determinant of financial performance A company with a lower grade of ore will have to process more material, possibly at greater cost in order to obtain a given amount of economically valuable material.

[3] A reserve is the economically minable part of a mineral resource identified initially through drilling, sampling and mapping to identify the containable metal in ore

[4] Refer Appendix 1 for a contemporary list of the top 40 mining companies

industry and have significant influence within the mining sector in terms of supply, employment and even price[5]

The economics of the mining industry, like many industries, is generally subject to cyclical fluctuations driven by both global and regional economic conditions but tends to lag more when compared to other less regulated and capital intensive industries

Specifically, lagging occurs due to the time it takes for investment, evaluation, decision making and regulatory approval. This is the case for both expansions of existing operations as well as developing new sites. The degree of lag is clearly a function of the size and scale of the initiative and the regulatory framework that applies to the country where the development/expansion is to take place. It is therefore in the interests of mining companies to monitor and to a certain extent, forecast changes in future product demand in an effort to maximise opportunities in an expanding market and to take preemptive action in a contracting one.

4.1 Particular characteristics of the mining sector

There are a number of particular characteristics in mining that tend to influence the behaviour of those who manage and invest in this sector. These characteristics are briefly described in the sections that follow.

4.1.1 High initial upfront investment –

The more remote an ore body is located from existing infrastructure (roads, rail, air) and utilities (power, water, housing etc) the higher the initial investment needs to be to provide those same facilities prior to commencing operations.

The reason these costs are considered upfront is because they are often considered to be a prerequisite to investment. To compound the impact, the value of this upfront investment upon closure, is usually zero if there are no opportunities to leverage the remaining utility at other mines within reasonable proximity i.e. When the mine closes any residual value is either zero or nominal.

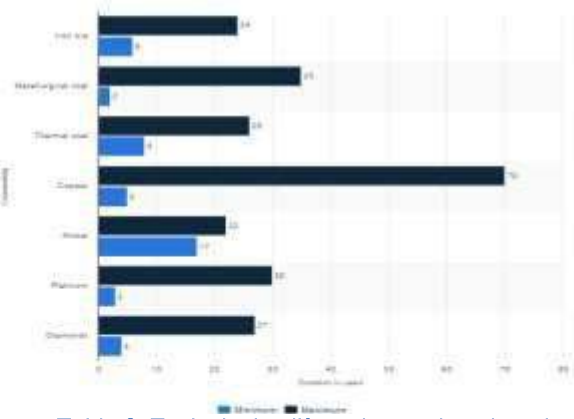

Table 2: Typical mine life estimates by mineral type

[5] This issue is discussed later

4.1.2 Remote locations requiring long life operation

Given the high upfront costs associated with mining, operators recognise the importance of identifying large enough ore bodies with sufficient life of mine7 as a key variable to support the minimum rate of return on investment[8].

4.1.3 High operational fixed to variable cost ratio –

The cost of mining varies greatly based on location, ratio of ore to waste, material hardness, extraction method and equipment type just to name a few variables. Using copper leach mining as an example[9], operating costs typically include the direct costs of maintenance labor, energy, materials, payroll and utilities used directly in the manufacturing processes. Indirect costs include supervision, site administration, facilities management, research, and technical support, corporate overhead, depreciation, insurance, debt interest payments, and taxes. Note that the cost of shutting down and reopening are not included but are generally significant. In order to avoid their occurrence, operations tend to adopt a long term perspective and embed certainty and predictability into their approach by giving preference to permanent employees over temporary contractors and encourage a regular time phased approach to equipment maintenance expenditure, depreciation and amortization charges.

However despite a deep and enduring commitment to cost management, most mining companies do not know their true fixed and variable cost ratio's. This is really a key omission when considering how such information impacts the point at which marginal sales make economic sense, what a mine's minimum volume sales are to break even and how quickly mining operations are able to respond to rapidly changing market conditions. One of the reasons is, surprisingly, a lack of consistency and application of a coherent definition in respect to the categorization of costs. Consequently fixed and variable are often replaced with a less than adequate set of proxies, in/direct, non/cash or capex/opex.

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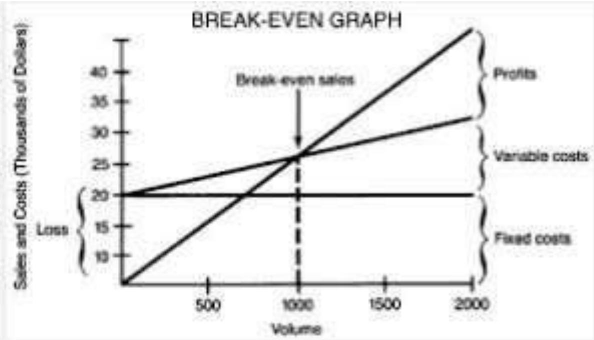
[6] Where the ore body is located close to existing infrastructure (roads, electricity, waters, housing, ports) then the amount of initial capital invested is obviousl21y reduced. However many mines need to make these investments up front

[7] Life of mine refers to an estimate (in years) of the remaining life (in years) before the ore body is depleted assuming the current rate of annual ore extraction e.g if the ore body has 10 million cubic metres of economically recoverable ore and the rate of extraction is currently 1 million tonnes per annum, then the life of mine is calculated to be 10 years

[8] Note that any costs incurred prior to an investment decision would be considered to be sunk costs and therefore should not be included in a ROI calculation

[9] Refer Appendix x for a description of the process of copper extraction using heap leaching



Mining companies do however acknowledge that they do have a high fixed cost base which means that costs remain relatively constant, regardless of the level of output. This would be the case for the majority of the costs for mine services[10] and maintenance, labour and sundry. The primary disadvantage of fixed cost operations is the high break-even point where a mine must generate sufficient sales at whatever price in order to generate sufficient cash to cover the cost of operations[11] Conversely, the primary advantage of a high fixed cost base is the ability to achieve significant economy of scale when market demand is high. i.e. For each incremental sale above break even, the vast majority[12] of revenue hits the bottom line. Over the long term, there are the additional expenses of replenishing the resource, capital replacement and giving the owners and investors a continuing return commensurate with the risk of their investment. costs to be fixed for one producer, but variable for another.

[10] Mine services include the supply of power, air and water(paw) to the site as well as road maintenance, signage etc

[11] Revenue is a function of price x volume and so at low prices volumes need to increase and at high prices, volumes can be moderated accordingly

[12] It could be argued from a TOC perspective that apart from sales commissions and freight, all other costs of production are in fact fixed given the variability in grade means that the relationship between tonnes and finished goods is inconsistent and the relationship between many activities in mining and the finished goods is on a many to one rather than a one to one basis

4.1.4 High capital intensity

One of the main ways of achieving high economies of scale in mining operations is though the development of large scale operations necessarily requiring large scale equipment required to drill, excavate, haul crush, process and transport large quantities of material on a 24/7 basis. Equipment of this type has a high capital investment cost at initial purchase as well as on an ongoing (sustaining capital) replacement

3 processing plant : processing plant: http://www.travelling-australia.info/

2 Drill rig 6 Drill rig ; http://geotechpedia.com

Load and Haul

Hamersley & Robe River Railway

Iron ore train leaving the Brockman 4 mine in June 2012

1 Excavator: http://germany.trendolizer.com/

4.1.5 Price taker's vs price maker's

Because the mining industry participants have historically produced homogeneous products[13] (concentrates, briquettes, lump and fines ores) customers are able to quickly swap one supplier for another. Additionally, the London Metal exchange represents a market of last resort for miners who wish to hedge their risks by selling their product forward at pre agreed prices.[14] Consequently, miners are willing but are not compelled towards product differentiation and as a consequence the LME tends to set a transparent benchmark for price negotiations with customers. Note however, this is not necessarily the case in respect to reliability of supply, quality consistency and the cost of delivery to certain markets (see below).

4.1.6 Self-inflicted volatile economic cycle?

Many of the top 40 mining companies are internationally based and if not, are able to ship bulk material to most places in the world economically. This means that mining companies in one country can be subject to the vagaries of economic cycles in countries other than those within which they operate. Take for example the current (~2016) economic cycle of China (refer Moody's graph) which shows China and Japan at risk of a recession and Australia in economic expansion. This inconsistency is explained by the fact that these two countries accounted for over 70% Australia iron ore exports and therefore it is no surprise that demand (and therefore prices) have weakened for Australia's top export[15]

4 http://www.ironorefacts.com/

However, the global market place is just as likely to provide a buffer to regional economic

[13] It is my view that the issue of product homogeneity is one driven by management mindset rather than industry structure. Consequently, there has and continues to be ample opportunity for individual miners to differentiate their products whilst simultaneously build rapport with customers, but choose not to do so.

14 The London Metal Exchange (LME) was established as a market of last resort for metals that allows buyers and sellers to hedge against future price fluctuations of metals.

15 http://dfat.gov.au/trade/resources/trade-at-a-glance/pages/top-goods-services.aspx

variation and so whilst large demand swings (like we have seen in China between 2013 and 2016) does explain some volatility, it appears that the mining industries high fixed cost base is another contributing factor which drives the industry to chase the price down in order to maintain sufficient cash-flow to cover their high breakeven point

With this background information in mind, we can now turn our attention to maintenance and its more recent strategic equivalent, Enterprise Asset Management (EAM) and their role in helping mining companies to achieve their ultimate purpose.

4.1.7 The difficulty of strategy and maintenance alignment

The issue of aligning maintenance practices with organisational strategy is not necessarily restricted to the mining industry but is definitely relevant to mining.

A review of BHP Billiton's description of its organisational purpose and objectives is found in its charter document[16]. What is noteworthy is that this charter is very clear as to what BHP Billiton's purpose is; to create long term shareholder value. This is an excellent statement of purpose although a little thought provoking as to why the shareholders have to wait for the long term to receive that value. The charter further defines how success will be identified and in doing so introduces a level of ambiguity and inconsistency that impedes rather than assists in guiding decision making. For example, are there potential conflicts between developing valuable supplier relationship with providing superior shareholder returns? or benchmarking the asset portfolio against industry competitors rather than just delivering above average returns regardless of the industry? Finally, when the manager of maintenance reads the charter, is there enough clarity to help guide decision making in the right direction? That guidance doesn't need to be specific but it does need to be consistent and easily reconcilable. e.g. faced with a decision to use a reliable supplier of parts or use a cheaper less reliable alternative, what choices should s/he make?

5 Maintenance in Mining

The truth about all equipment is that they will fail eventually. It's not clear what particular component will fail or when it will fail, but it can be guaranteed with certainty that one day the equipment, will stop working.

The primary activity[17] of maintenance therefore is to preserve or return an item of equipment to its original design capability and sometimes includes a need to

[16] Refer appendix x, and found at http://www.bhpbilliton.com/aboutus/ourcompany/charter
[17] I use the term activity to describe the actions taken. This is different from the purpose and necessary conditions of maintenance.

identify where modifications could be applied where the capability is considered inadequate.

However, when a business decides to maintain equipment, it is making an assumption that the economic benefits of maintenance outweigh the alternative (don't repair, simply replace) For numerous items of equipment this assumption is entirely valid but for others it is not. What is missing is a clear and unambiguous guideline on when and where to repair and when and where to replace. This is in no small way, influenced by the causes of equipment failure[18]

5.1 What causes equipment to fail?

The general perception about why equipment fails and in particular, prior to the 1980's, was that equipment failure was primarily due to wear and tear. Therefore, as the equipment aged, there was a greater chance of failure (and the greater the amount of maintenance required to keep it operational). However, in 1978 Nowlan and Heap published their work[19] based on extensive review of maintenance practices at United Airlines and provided evidence that there are in fact, two broad categories of failure; age based failure and random based failure. This in itself was probably not that surprising as many recognise the random nature of light bulb failure and many other electronic equipment. What was more surprising was the ratio of the different failure types which are described below. These patterns do not depict the failure rate of a single equipment item, but describes the relative failure rates of an entire population of equipment types over time. Some individual units will fail relatively early (infant mortality failures), others will last until wear-out, and some will fail during the relatively long period typically called normal life. Each of these is described as follows:

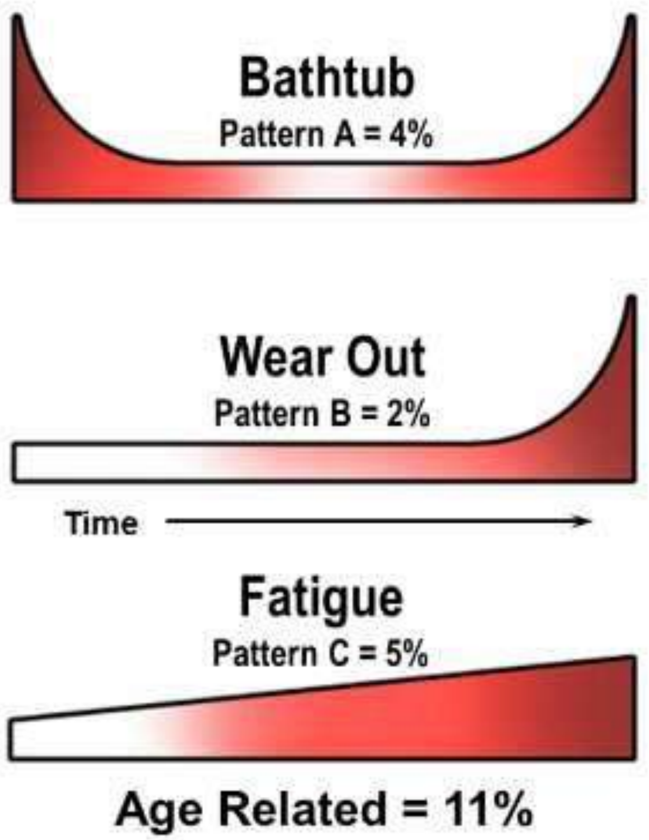
5.1.1 Age based failure patterns

Age based failure patterns include the following subcategories:

a) Bathtub – whether there are higher risks of failure immediately after manufacturing or overhaul (referred to as infant mortality) followed by a constant failure rate and then a pronounced wear out region. An age limit replacement may be an appropriate response

[18] Note that there is a difference between the cause of equipment failure and failure modes. Failure modes are the ways in which something might fail. Examples include a bearing seizing or a cracked casing. Identifying failure modes is only one part of the journey and a requirement to identify both the mode, effect and root cause (FMEA or FMECA)

[19] http://reliabilityweb.com/ee-assets/my-uploads/docs/2010/Reliability_Centered_Maintenance_by_Nowlan_and_Heap.pdf



b) Wear Out – where the equipment will experience a constant rate of failure followed by a pronounced wear out region. Again age limit replacement may be in order

c) Fatigue – a constant and increasing rate of failures but without a pronounced wear-out age. Equipment replacement is not generally justifiable for equipment of this type

These three failure patterns are generally described as age related and represent around 11% of equipment failures which is in stark contrast with the general view that most failures are age related.

5.1.2 Random based failure patterns

Random based failure patterns include the following sub categories

a) Initial break-in period – low initially when new or just after overhaul then a rapid increase followed by a constant level
b) Random - constant probability of failure at all ages
c) Infant Mortality – High initial incidence of equipment failure and constant thereafter

These three failure patterns are generally described as random based and account for 89% of equipment failures. Of particular note is the rate of failures applicable to infant mortality at 68%.

The infant mortality rate bears further scrutiny because of the possibility that it is not the inherent equipment design which is the cause of this type of equipment failure pattern

5.2 T

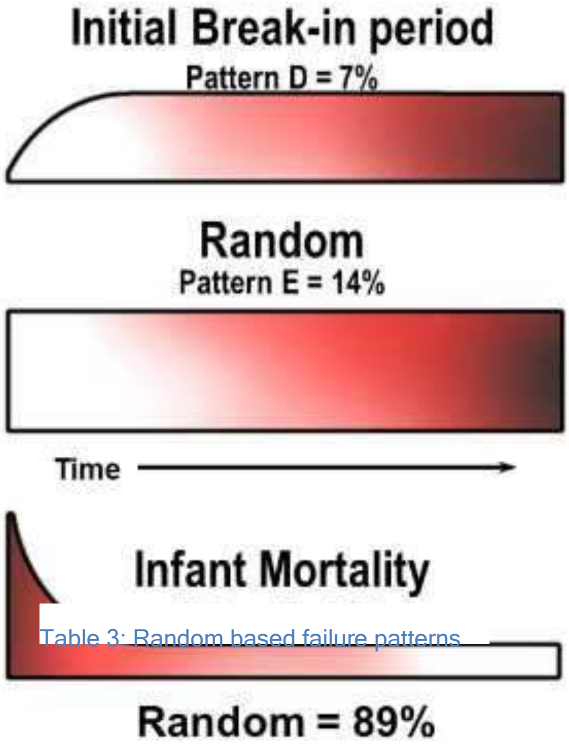


Table 3: Random based failure patterns

Types of maintenance practices

The different approaches to maintenance can generally be described as run to failure (reactive), preventative and predictive.

There are however, variations on the theme which require explanation in order to avoid confusion. These variations include a fourth category 'proactive' which refers primarily to a combination of preventative and predictive practices and for that reason has been left out of the categories as shown. Similarly, the term 'total productive maintenance' is a more recent reference used to describe a holistic approach to overall equipment effectiveness (OEE). OEE involves an assessment of product quality and operational performance (e.g. the impact of worker absence, off spec material, rework etc).

- a more recent strategic approach taken to maintenance that is variously described as enterprise asset management or strategic asset management. EAM describes the lifecycle management of the organisation's physical assets, including design, construction (or purchase) commissioning, operations, maintenance and finally decommissioning or replacement. Note that maintenance is simply a subset of EAM because of the lifecycle view of asset management that EAM provides It should also be noted however that many definitions of EAM include the term 'optimise' without necessarily referring to that object or thing which needs optimisation (is it the equipment, asset, business function or organisation?).

In general each of these approaches either extend beyond the scope of this case study or can be comfortably described as methods used to be more effective in the implementation of run to failure, preventative or predictive maintenance practices

5.2.1 Run-to-failure maintenance

Maintenance carried out following detection of an anomaly and aimed at restoring normal operating conditions. This type of reactive maintenance applies when equipment fails unexpectedly or when a fault is identified through inspection. Typically time is of the essence once an event occurs and as there is general no planning and the cost of correcting the failure/fault is typically much higher (~x2+) than the equivalent cost of a planned maintenance event.

5.2.2 Preventative maintenance

Maintenance carried out at predetermined intervals or according to prescribed criteria. This maintenance type involves preparation of a plan in various forms. These forms include the development of bills of material, parts ordering or issuing, resource type identification, tooling, lifting requirements etc. This type of maintenance is regularly performed on a piece of equipment in order to lessen the likelihood of it failing. Preventative maintenance is performed while the equipment is still functional in order to avoid the consequential impact on operations and costs of a future unexpected failure.

Preventative maintenance, once planned, is then scheduled based on time or usage. e.g. change the engine oil every 6 months or 1,500 hours of operation. Due to a tendency towards risk aversion, justifying organisational positions and creating the illusion of keeping busy, maintenance and engineering personnel also have a tendency to over maintain equipment

The 'plan the work, work the plan' is an important mantra that symbolizes the commitment that many mine sites have to preventive maintenance. This commitment is based on the belief that it is and continues to be the solution to the high levels of breakdowns

5.2.3 Predictive Maintenance-

Maintenance carried out based on equipment performance monitoring which predicts the point of failure and intervenes prior to that failure occurring. The aim is to keep maintenance frequency and duration as low as possible. In a similar vein to preventative maintenance, a detailed work plan is prepared for all equipment failure types.

Predicting failure can be performed by a number of methods but the method/s must be suited to the type of failure mode that is identifiable. Techniques include vibration analysis, oil analysis, thermal imaging, and equipment inspection with the associated equipment, training, data capture & analysis required to monitor and interpret these data sets being in some cases, quite expensive.

The obvious benefits of predictive maintenance include minimising the time the equipment is down for maintenance and a significant reduction in the amount of spare parts and materials consumed (when compared to other forms of maintenance).

Whilst the application of these different types of maintenance methods vary from mine to mine, the general ratio that has applied for the period 1988 – 2005 (17 years) is depicted in the following graph. Unfortunately, there has been no update to this graph since 2008 however based on personal experience gained in a number of operations in Australia and the America's in 2012-13, the graph remains valid

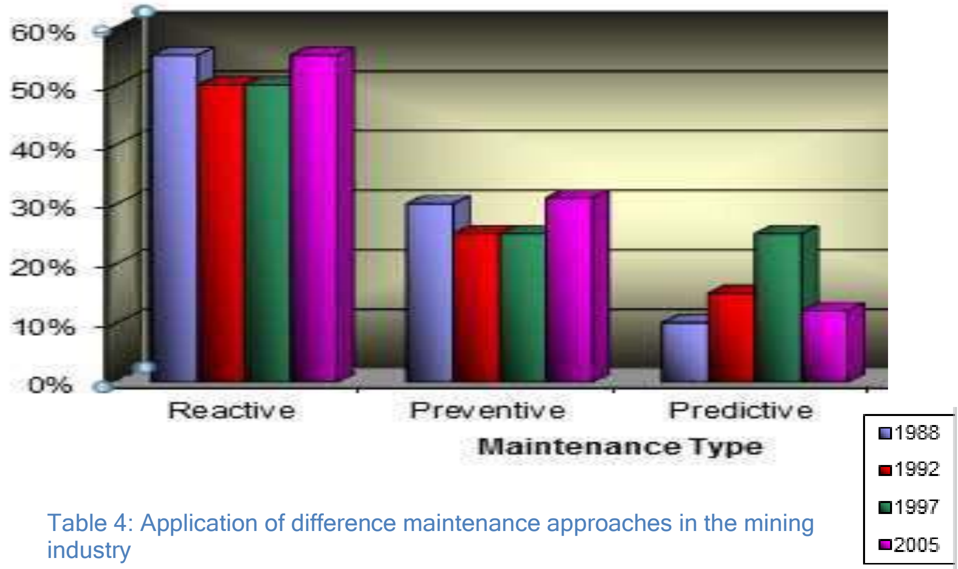


Table 4: Application of difference maintenance approaches in the mining industry

It is clear that the run to failure/reactive approach dominates the maintenance methods.

5.2.4 Planning vs Scheduled maintenance

There are important differences exist between planning and scheduling from a maintenance perspective

Planned maintenance is the process of defining what work needs to be done, how it will be done and the time required to complete the work for a given failure mode and equipment type. The plan is stored electronically and retrieved to help guide the maintenance work when an event of that type occurs. When no such plan exits when a maintenance event occurs, that event is described as unplanned maintenance.

Scheduled maintenance defines when and who will do the job. When a schedule has not been established and a maintenance event occurs, that event is described as unscheduled or breakdown maintenance

Consequently, you can have a maintenance event that is either

Planned and scheduled – A plan exists and a schedule is established in order to execute the planned work

Unplanned and scheduled – No plan exists but maintenance work is scheduled to be performed (relying on the skills and experience of those carrying out the work)

Planned and unscheduled – A plan has been created but an equipment item breaks down unexpectedly where the plan is used to guide the execution of the work

Unplanned and unscheduled - Where no plan exists and an item of equipment fails unexpectedly.

The common use terms used by maintenance personnel is to simply describe work as either planned or unplanned on the assumption that all scheduled work is planned and all unplanned work is unscheduled. This is obviously not necessarily the case.

Based on the common use term of planned and unplanned, many maintenance departments target an arbitrary ratio of 80/20 planned/ unplanned. This is clearly an improvement on their current ratio (~50/50) but it fails to recognise that it is possible to prepare plans for all types of failure modes so that in the event that an unscheduled event occurs, the time to repair is materially reduced.

5.3 Reliability Centered Maintenance (RCM)

Regardless of the type of maintenance used on different equipment types, it should be apparent that the choice should be heavily influenced by the equipment failure pattern, the purpose for which it is being used and the consequences when failure occurs.

Reliability-centered maintenance is a an approach to maintenance designed to establish a safe minimum level of maintenance that matches equipment use and failure patterns with the chosen maintenance method (run to failure, preventative or predictive) at the lowest cost

The RCM process is defined by a series of sequential questions as outlined below:

1. What is the item supposed to do and what are its’ associated performance standards?

2. In what ways can it fail to provide the required functions?

3. What are the events that cause each failure?

4. What happens when each failure occurs?

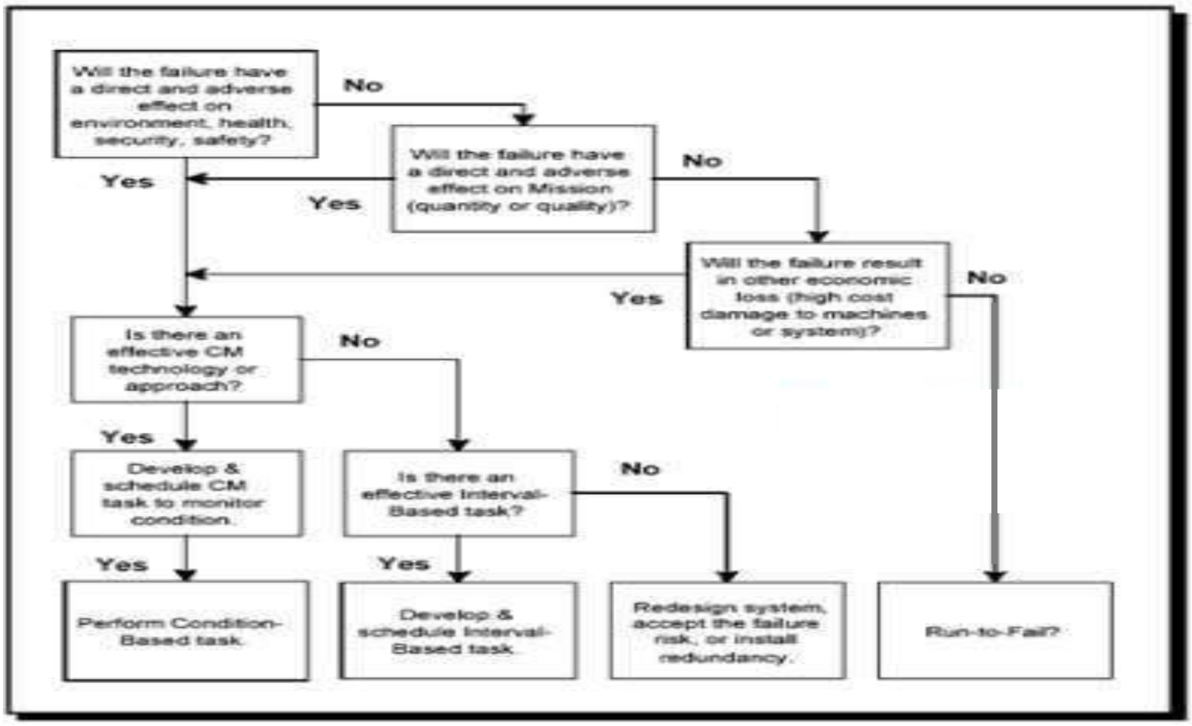
5. In what way does each failure matter?

6. What systematic task can be performed proactively to prevent, or to diminish to a satisfactory degree, the consequences of the failure?

7. What must be done if a suitable preventive task cannot be found?

The final result of an RCM program is the identification, development and implementation of a specific maintenance strategy for each of the assets/equipment items within an operation.

.A summarised version of the RCM approach is described in the following RCM decision tree



5: RCM decision tree
(https://www.wbdg.org/resources/rcm.php)

5.4 The importance of maintenance

Despite its reputation it is hard to identify a function that has equal or greater breadth and depth of influence over the financial performance of a mining operation than maintenance. Its main influences can be summarised as follows:

5.4.1 Throughput

Large scale operations require large scale mining equipment to economically extract the minerals from ore. Therefore the logic that prevails is that all equipment require more uptime in order to enable the higher production targets. Effective maintenance occurs when the amount of time that each item of equipment is available to carry out its intended purpose is maximised

5.4.2 Cost

Due to the nature of how finance treats direct and indirect maintenance costs, it is often difficult to determine the real total cost of maintenance as a % of total operating expenditure. When the effort is applied however, it soon becomes apparent that maintenance can represent between 35-65% of total annual operating costs. For example, in this case study example, a total annual operating expenditure (opex) of $448m pa, could represent between $155m to nearly $300m of maintenance expenditure.

5.4.3 Capital investment

The type of equipment used in mining is both large scale and expensive. For example replacing just one dump truck in a fleet (~25 units) could cost between US$2- 5m and a front end loader U$1-3m. Consequently, most operations are keen to extract as much value as possible from their existing capital equipment and by doing so, defer the significant cost of replacement which directly hits the denominator (investments in plant and equipment) and causes downward pressure on the Return on Asset (ROA) metric

5.4.4 Licence to operate

All mining operations are subject to both formal and informal obligations to perform within acceptable parameters. Example of these obligations include initial and ongoing regulatory compliance of personnel safety & health, federal, state and municipal laws, environmental protection, industrial relations, community engagement, indigenous employment and heritage area protection. Many of these obligations impact on the maintenance function in the following ways;

- Routine and regular maintenance on all statutory equipment
- Preparation of a full risk assessment and use of job safety analysis prior to conducting all maintenance activities
- Use of specific personal protective equipment when conducting high risk maintenance (eg. Pressure vessels)
- Limiting the amount of CO_2 emissions generated to within specific limits
- Allocating sufficient budget to offer local apprenticeships and employment

5.5 The current state

The following summarises the current state of mining operations as they were in 2012 prior to any consulting work being undertaken.

Maintenance was recognised as a significant cost component of the mine site’s annual operating expenditure but there was no quantification of that fact. This was due to the costs being systematically hidden by finance charging production cost centre’s directly with the cost of materials and parts but allocating labour and supervision costs via a simplistic (% time, % work orders) allocation.

Consequently there was no single source of truth in respect to the total cost of maintenance.

However, not knowing the true and total cost of maintenance did not matter when it came to the commitment to reducing costs and in particular in maintenance where management could not fully explain or justify a coherent argument for what types of parts, materials and resources were more important than others. Across many metrics they were below the required performance standard[20] and were unable to demonstrate strong evidence of continuous improvement

There was also a fixation on data integrity within the maintenance function that could by any standard be considered, overwhelming There were numerous concurrent projects involved with either establishing or refining equipment breakdown structures, bills of material, work orders, 1,7,14,21,30 day work plans and or 3, 6,12 and 24 month plans. In many instances the initiatives were based on false assumptions. For example:

- That the equipment in their SAP/R3 aligned with what was installed - physical inspections often revealed that the equipment has been swapped out or significantly modified making many plans redundant
- Far too much detail and insufficient time allocated to many work plans - it was often not clear what the full extent of the maintenance effort was until the equipment had been inspected and or dismantled. This has a flow on effect in respect to knowing what parts to hold or order.
- That the OEM recommended maintenance regime was appropriate for all new equipment purchases - there was no testing of whether the OEM's recommended maintenance regime was fit for purpose. The overriding decision to accept the OEM's maintenance regime was to preserve the warranty[21] entitlement and the perceived resale value without regard for the needs of the business.
- That the plans required no feedback loop -equipment failures often occurred repeatedly on the same equipment without an independent root cause analysis been undertaken

[20] Refer appendices for a benchmark performance standard for maintenance in mining. Note the breadth, level of detail and in some instances the arbitrary nature of these standards which was a contributing factor to why maintenance tended towards inertia rather than action

[21] There are two types of warranty entitlement – statutory and manufacturers. Statutory refers to the legal obligation of a manufacturer to sell goods and services that are fit for purpose. Where that isn't the case the manufacturer is obliged to either replace or make good the equipment. The timeframe for statutory maintenance is usually non-specific but subject to the level of investment and reasonable expectations. Manufacturer warranty is a warranty entitlement that is based on a fixed duration and a set of stringent conditions (e.g. evidence based, only use OEM genuine parts, conduct preventative program at the scheduled times and only use qualified personnel) There is often confusion about when statutory warranty finishes and when manufacture warranty starts and the possibility of overlap and therefore unnecessary cost

Maintenance managers also resisted the opportunity to move to a predictive maintenance approach because

There was a history of failing to keep the computerized maintenance management system (CMMS) up to date with both master and transactional maintenance information. Adopting predictive maintenance would only add to this issue.

Predictive maintenance (PdM) was seen as a separate activity from the normal maintenance performed by the operation. There was no integration of the roles or the information allowing current practices to be modified based on the information gained.

Often PdM data arrived too late with the equipment already failing before the data was collated and presented

Constant complaints from supervisors and teams that inspecting equipment for signs of failure was a boring and repetitive activity when compared to the personal experience and satisfaction gained from overhaul or repairs

The high up front cost of purchasing, training, capturing, analysis and reconciling inspection information was seen as prohibitive

Inertia associated with resisting change that requires a move from a known (run to failure, preventive) to an unknown (predictive) methodology

Continuous pressure from finance to either spend or lose maintenance budgets in the current year or face the risk of an arbitrary cut in future years

Unsuspecting Engineer's proposing and trialing equipment improvements to OEM's without considering the commercial nature of the intellectual property rights

An absence of any robust replace/repair strategy that recognises the inherent failure pattern of different equipment types

The absence of any clear strategy to both contest and find a viable alternative to the mandatory preventive maintenance regime imposed by industry regulators on certain statutory and classified mining equipment

The absence of any methodological approach to when to repair and when to replace resulting in

Over or premature investment in replacement equipment

Unnecessarily high maintenance costs resulting from equipment remaining in service beyond their economic value

Where poor asset management strategy development and practice results in

Incorrect, incomplete, excess and redundant spare parts holdings

Inadequate HR recruitment and training process to properly assess and resolve current and future gaps between current and required maintenance skills

Material mismatching between the planned vs actual time when major maintenance activities will be performed resulting in significant cost variances

Modifications to existing equipment performance and capacity without regard for engineering standards, approval and logging

Increasing frequency of licence to operate breaches resulting from poor timing, execution and reporting of statutory maintenance obligations

Increasing instances of safety incidences resulting from an absence of updated work procedures or trained personnel

6 Systems Thinking Overview

For the purpose of this case study, a system is a set of activities working together towards a common purpose. There are a number of relevant characteristics of systems that are relevant. They include

Systems can be natural or human-made (designed). Based on the abovementioned definition, all systems have a purpose but it may not necessarily be obvious and/or change over time. In respect to human made systems, the system's purpose is defined by the owner of that system and it is that purpose that defines both the output and the types of activities that need to be included in that system in order to achieve the system's purpose.

Systems can be made up of a hierarchy of sub systems, sub, sub systems, processes and activities all of which are components of the larger system.

All components have capabilities, capacities and outputs ('needs) which enable them to perform independently. However as member of a system hierarchy, those activities must subordinate their 'needs' to the requirements of the global system.

A system typically produces an outcome that is different and greater than the sum of the parts

A mining operation is a sub system and maintenance is a sub-sub system made up of many activities within the mining sub system

Thinking systemically in broad terms involves recognising that systems have certain behaviours that influence their performance. These behaviours are largely a consequence of the linkages and interdependencies between the systems components. These linkages and interdependencies are often viewed as complex but from a systems view, it becomes evident that the system behaviour is driven by one or very few components

In contrast, non-systems (traditional?) thinking tends to address complexity by breaking down the system down into smaller and smaller parts in order to analyse and address each component individually. The key assumption underlying this approach is that improvements at the component level can be added together with other component improvements to generate an aggregate benefit to the system as a whole

6.1 Overview of the Theory of Constraints

Theory of constraints is a systems thinking philosophy developed initially for business but expanded to consider all human made systems.

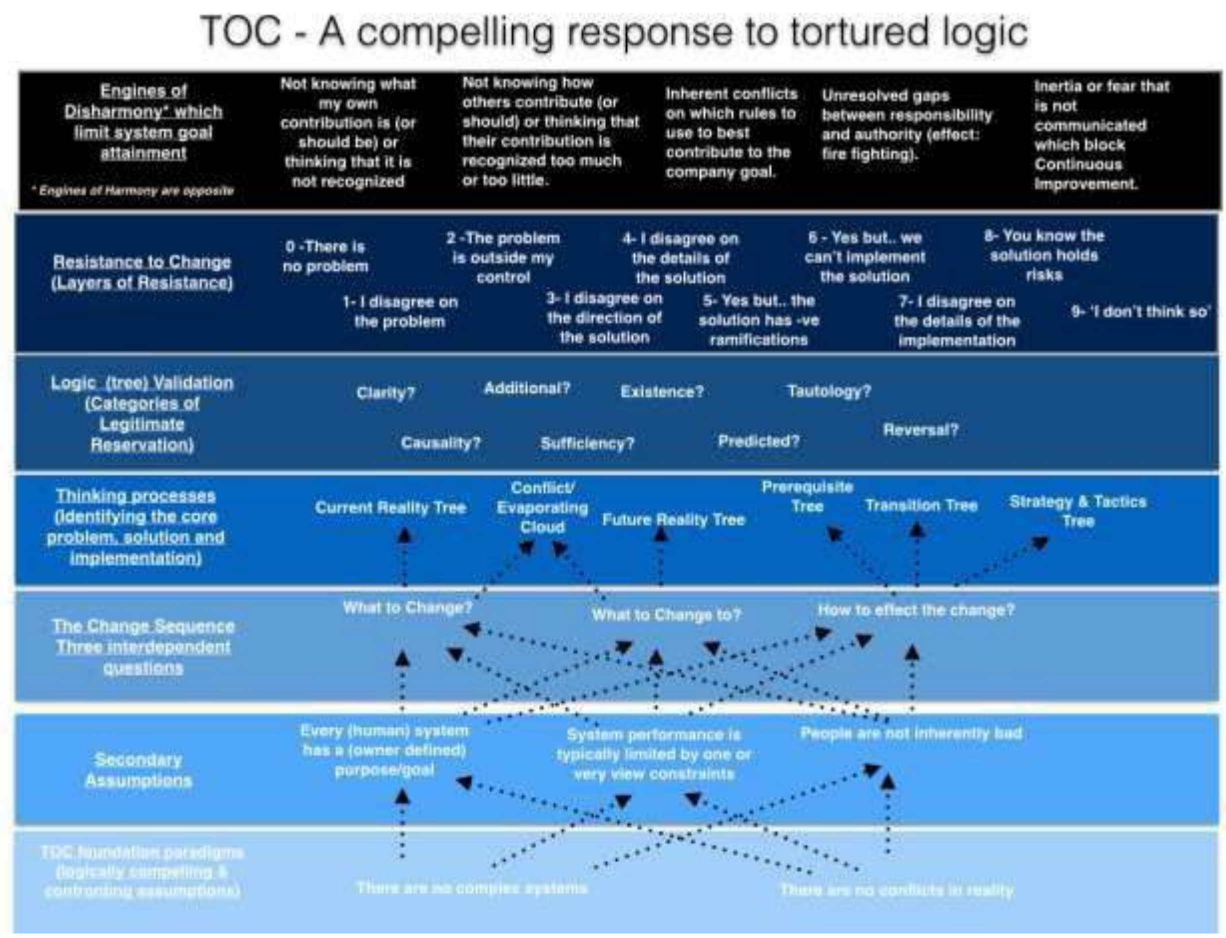
ToC is predicated on a number of key concepts from which its methods and practices flow. These concepts are summarised as follows:

Concept	Traditional Non systems approach	TOC systems approach
Constraints	Managers accept that there are many constraints in their business but many are outside of their control and are caused by others	Constraints are either part of your span of control or you have the ability to influence others where necessary
Complexity	Break the system down into smaller and smaller components until you can identify and resolve the component at that lowest level	Recognise that all activities in a system are interdependent and that there is typically one or very few points of leverage that once identified represent the point of focus

Conflicts	One side must lose in order for the other side to win or a compromise must be established that neither party is fully satisfied with	Win/win is not only possible, but must be achieved for any sustainable solution to survive
Uncertainty	Identify all the variables and identify a method to optimise based on a localised objective	Find a good enough solution and develop a feedback mechanism to adopt continuous improvement practices
Bad Behaviour	Get rid of people who are either inherently incompetent or intentionally disruptive	People are good; identify and test the assumptions that make you believe otherwise

6.1.1 TOC body of knowledge

There is much to the TOC body of knowledge and there are many references on the topic that explain both the theory and its application. The following image provides an abridged version of its broad approach. The image should be read from the bottom up



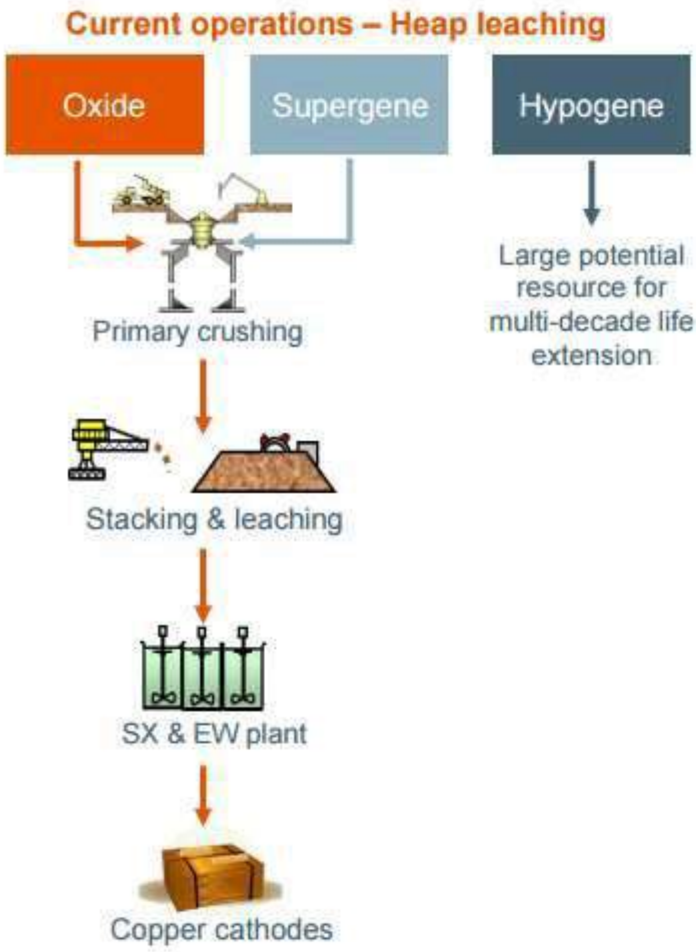
(Students: Note that much of what you need to understand in respect to TOC can be found via the internet, online book stores and the references included in this case study. Some explanation of the key concepts will also be provided during the semester)

7 Appendices

7.1 Brief description of Heap Leach Copper operations

1. Mining -

The mine is an open pit operation utilizing vertical benches (defined by the mine plan) that allows for the extraction of ore and waste at different levels in the mine. The cut-off grade that distinguishes between economic ore and waste is 0.20%. ie. The amount of copper in a tonne of ore needs to be at least 1/5 of 1% of that tonne in order for it to be economic to extract. Material that does not meet this specification is defined as waste. Drilling, sampling and laboratory analysis using pre-defined methods are used to establish what parts of the mine hold ore vs waste. Once the delineation occurs, the bench is drilled in a pattern that recognises a number of factors including rock hardness, ore type, depth, explosive type and target fragment size. The mine is generally evacuated and the charge (explosive) is detonated causing the rock to fragment. Loaders and trucks are then bought in to transport the waste component to waste stockpiles and ore to the next step in the process primary crushing



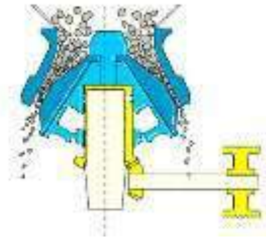
Primary Crushing

Primary crushing is actually the first of 3 stages (secondary and tertiary) used to progressively reduce the size of the rock with the objective of exposing enough surface area to enable efficient leaching of the contained copper. Primary crushing involves loading the mined ore into a hopper (funnel) at the top of the crusher where a set of mechanical jaws, crush the ore to a maximum size. Subsequent secondary and tertiary crushing using a series of conveyors, screens an mechanical equipment continues to refine the fragment to the required size.

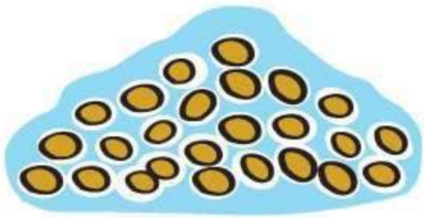
Primary (jaw) crusher

Agglomeration –

Agglomeration is the process of taking the crushed ore fines and clustering them into a uniform shape. This shaping enhances the percolation of the acid through the ore thereby maximizing the copper recovery rate



secondary and tertiary cone crusher

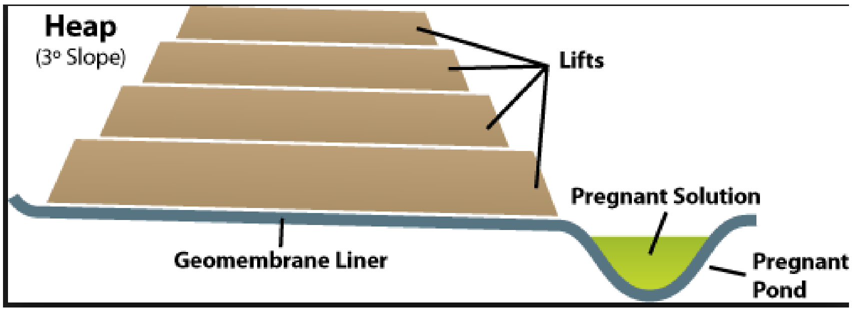


Stacking –

Stacking involves lifting the stockpile of agglomerated ore and placing (heaping) it onto a giant pre-prepared pads (areas of land) which have had plastic lines layed in preparation for the heap leach process

Heap leaching –

Leaching refers to the process of reticulating the top of a heap leach with sulfuric acid in sufficient quantity to allow the acid to flow through the heap leach pad dissolving and therefore separating the copper from the ore and transporting it to the bottom of the leach pad. When the acid/copper solution reaches the bottom of the heap leach, it gravity feeds into channels located on the side of the heap leach and is eventually accumulated into (pregnant) ponds ready for further processing



Electro-winning (EW) /Solvent extraction-(SX)

The pregnant solution is moved into a series of baths where electrolysis is applied to cause the copper from the solution to be attracted to the cathode in the bath (steel sheets) where the copper accumulates in sufficient volume to form sheets of copper on both sides of the cathode. These sheets of copper are the final product and are routinely removed washed and stacked in preparation for transport to customers

Solvent extraction is the process of cleansing the solution so that the sulfuric acid can be reused in leaching process

7.2 Glossary of terms

Bankable feasibility study is a comprehensive forward analysis of a project's economics to be used by financial institutions to assess the credit-worthiness for project financing. The feasibility part is guided by a set of assumptions, a strategy, development conditions and a planned outcome. The outcome is uncertain and targets and objectives may not be achievable. The bankable part relates to the basis and condition for a future financial agreement to collateralize mining assets for a project loan, to set a premium and a repayment schedule, with appropriate risk/reward factors. Then a lender would accept or not accept a feasibility study prepared by the borrower or the borrower' consultants as the basis for financing the project

Mineral Reserve – is the economically mineable part of a measured or indicated mineral resource demonstrated by at least a preliminary feasibility study. This study must include adequate information on mining, processing, metallurgical, economic and other relevant factors that demonstrate (as at the time of reporting) that economic extraction can be justified. A mineral reserve includes diluting materials and allowances for losses that may occur when the material is mined

Ore – is a mixture of valuable minerals and gangue minerals from which at least one of the minerals can be extracted economically. An ore body is a natural concentration of valuable material amenable to economic extraction

Open Pit Mining – is a method of extracting rock or minerals from the earth by their removal from an open pit or burrow. Mining companies choose this way to get rocks and minerals out of the ground because it is the easiest and cheapest way to do it. Open pit mining is only used if the rocks or minerals are close to the surface of the land or if a normal tunnel-type mine isn't possible. Underground mining is carried out when the rocks, minerals or gemstones are located at a distance far beneath the ground to be extracted with surface mining.

Ripios – Spanish word for waste

7.3 Top 40 mining companies

10. Top 40 companies analysed

Name	Country (**)	OECD(O)/ BRICS(B)	Year-end	2014 Ranking	2013 Ranking
BHP Billiton Plc/BHP Billiton Limited	UK/Australia	O	30-Jun	1	1
Rio Tinto plc/Rio Tinto Limited	UK/Australia	O	31-Dec	2	2
China Shenhua Energy Company Limited	China/Hong Kong	B	31-Dec	3	5
Glencore plc	UK	O	31-Dec	4	4
Vale S.A.	Brazil	B	31-Dec	5	3
Coal India Limited	India	B	31-Mar	6	8
Potash Corp. of Saskatchewan, Inc.	Canada	O	31-Dec	7	9
Anglo American plc	UK	O	31-Dec	8	7
Freeport-McMoRan Copper & Gold Inc.	United States	O	31-Dec	9	6
Grupo México S.A.B. de CV	Mexico	O	31-Dec	10	11
MMC Norilsk Nickel	Russia	B	31-Dec	11	10
The Mosaic Company	United States	O	31-Dec	12	13
Goldcorp Inc.	Canada	O	31-Dec	13	14
China Coal Energy Company Limited	China/Hong Kong	B	31-Dec	14	23
Barrick Gold Corporation	Canada	O	31-Dec	15	12
Antofagasta plc	UK	O	31-Dec	16	18
Zijin Mining Group Co. Ltd	China/Hong Kong	B	31-Dec	17	32
Inner Mongolia Yitai Coal Company Limited	China/Hong Kong	B	31-Dec	18	25
Saudi Arabian Mining Company (Ma'aden)	Saudi Arabia	B	31-Dec	19	28
Newmont Mining Corporation	United States	O	31-Dec	20	19
NMDC Limited	India	B	31-Mar	21	24
Polyus Gold International Limited	UK	O	31-Dec	22	21
First Quantum Minerals Limited	Canada	O	31-Dec	23	20
Jiangxi Copper Company Limited	China/Hong Kong	B	31-Dec	24	31
Sumitomo Metal Mining Company	Japan	O	31-Mar	25	33
Yanzhou Coal Mining Company Limited	China/Hong Kong	B	31-Dec	26	34
Teck Resources Limited	Canada	O	31-Dec	27	16
Consol Energy Incorporated	United States	O	31-Dec	28	26
Industrias Penoles S.A.B. de CV	Mexico	O	31-Dec	29	22
ALROSA	Russia	B	31-Dec	30	29
Fortescue Metals Group Limited	Australia	O	30-Jun	31	15
Newcrest Mining Limited	Australia	O	30-Jun	32	37
Cameco Corporation	Canada	O	31-Dec	33	27
Randgold Resources	UK	O	31-Dec	34	35
KGHM Polska Miedz Spolka Akcyjna	Poland	B	31-Dec	35	30
Uralkali	Russia	B	31-Dec	36	17
Agnico-Eagle Mines Ltd. ***	Canada	O	31-Dec	37	38
Zhongjin Gold Corp., Ltd. ***	China	B	31-Dec	38	39
Shandong Gold Mining Co., Ltd. ***	China	B	31-Dec	39	40
China Northern Rare Earth (Group) High-Tech Co., Ltd *	China	B	31-Dec	40	36

http://www.pwc.com/ca/en/industries/mining/publications/mine-2015.html

(*) 2014 [illegible]
(**) Refe[illegible]
(***) Refers to companies which were not included in the 2013 analysis

7.4 Mine site- equipment list

Mine equipment (220ktpd)

- Mine trucks 25 , Front End Loaders (FEL) 3

Plant facilities (51ktpd)

Plant N° 1 facilities

- Dry area
  - Primary crusher (1)
  - Secondary crusher (1)
  - Tertiary crusher (3)
- Agglomeration
  - Agglomeration drum (4)
- Stacking and ripios reclaim
  - 17 mobile conveyor belt (Stacking)
  - Ripios reclaim with trucks

Plant N° 2 facilities

- Dry area
  - Primary crusher (1)
  - Secondary crusher (1)
  - Tertiary crusher (2)
- Agglomeration
  - Agglomeration drum (3)
- Stacking and ripios reclaim
  - 24 mobile conveyor belt (Stacking)
  - Ripios reclaim with trucks

SXEW (130ktpa)

- 130ktpa cathode capacity

7.5 Production and maintenance statistics

	Equipment statistics by function							
	rate per day	drill & bla•t	Loading & Trucking	Cru•hing & Grinding	Agglomoration	Stacking	Heap leaching	Electro-winning
working hours /day		24	24	24	24	24	24	24
Design capacity	t/hr	33,100	25,000	7,200	6,800	4,400	6,700	15
availability	%	0.9	0.9	0.9	0.8	0.7	0.9	0.9
productive utilisation	%	60%	80%	70%	60%	100%	50%	95%
productive utilisation	t/hr	17,874	18,000	4,536	3,264	3,080	3,015	13
required sprint capacity	t/hr	?	?	?	?		?	?
daily production	t/d	428,976	432,000	108,864	78,336	73,920	72,360	308
annual production	t/pa	156,576,240	157,680,000	39,735,360	28,592,640	26,980,800	26,411,400	112,347
Assumptions								
Copper production								
Waste to ore ratio		1.3						
Head grade	% contained cu	0.5						
Recovery rate	% of Cu	0.75						
actual cu recovery rate	%of Cu	0.375						
Maintenance activity								
Run-to-failure		40%	55%	40%	45%	55%	40%	30%
Preventative		45%	35%	45%	40%	35%	45%	55%
Predictive		15%	10%	15%	15%	10%	15%	15%
Total		100%	100%	100%	100%	100%	100%	100%

7.6 Maintenance performance standard

Best Practices Maintenance Benchmarks	
Category	Benchmark
Yearly Maintenance Cost:	
Total Maintenance Cost/Total Manufacturing Cost	< 10-15°/o
maintenance Cost/Replacement Asset Value of the Plant and Equipment	< 3%
Hourly Maintenance Workers as a % of Total	15%
Planned Maintenance:	
Planned Maintenance/Total Maintenance	> 85%
Planned & Scheduled Maintenance as a % of hours worked	≤s-95%
Unplanned Down Time	.....Q%o
Reactive Maintenance	< 15%
Run to Fail (Emergency + Non-Emergency)	< 10%
Maintenance Overtime:	
Maintenance Overtime/Total Company Overtime	<5%
Monthly Maintenance Rework:	
Work Orders Reworked/Total Work Orders	......Q%o
Inventory Turns:	
Turns Ration of Spare Parts	> 2-3
Training:	
For at least 90% of workers, hours/year	> SO hours/year
Spending on Worker Training {% of payroll)	,..,4°/o
Safety Performance:	
OSHA Recordable Injuries per 200,000 labor hours	< 2
Housekeeping	'''96°/o
Monthly Maintenance Strategies:	
Preventive 1aintenance: Total Hours PM/Total Maintenance Hours Available	20%
Predictive Maintenance: Total Hours PdM/Total 1aintenance Hours Available	so%
Planned Reactive Maintenance: Total Hours PRM/Total Maintenance Hours Available	20%
Reactive Emergency: Total REM/Total Maintenance Hours Available	'''2°/o
Reactive Non-Emergency: Total RNEM/Total Maintenance Hours Available	'''8°/o
Plant Availability:	
Available Time/ Maximum Avalable Time	> 97°/o
Contractors:	
Contractors Cost/Total Maintenance Cost	35-64%o

7.1 Recommended References

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