The product material supply chain starts with stage 1 in manufacturing. In Life Cycle Analysis (LCA) or in an SLCA (streamlined LCA) this is premanufacture. Ideally the first stage starts with recycled material, however most material comes from mining, and will do so for the foreseeable future. The first stage has five elements: material, energy, solids, liquid and gas. Important considerations are water use (liquids), emissions (toxicity and carbon) and energy consumption. This paper considers energy use in mining extraction, in particular energy consumption by equipment such as LHD’s (Load-Haul-Dump machinery) and by HVAC systems.

1. Introduction

This paper considers energy use in mining extraction. It is intended as information that can be used by practitioners of LCA and SLCA when assessing premanufacture energy use.

1.1. The Reason for this paper

Materials are an important mainstay of all manufacturing. The supply chain for materials includes either mined material or recycled material, however most material used by production-manufacturing engineers, is supplied by mining at the beginning of the material supply chain. For sustainability, as defined in CIRPedia [1], the ideal material supply chain uses 100% recycled materials. The definition used for environment in this paper can be found in reference [2].

Production Engineers, know very little about mining engineering and extraction, which has an effect upon product assessment when conducting a Life Cycle Assessment (LCA). LCA is method commonly used to judge environmental impacts. It has its origins with SETAC [3]. Part of the SETAC definition for LCA includes, “the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use/de-use/maintenance; recycling; and final disposal”. Current practice in conducting an LCA is that if material comes from a mined instead of recycled source, usually a very low rating is given for that part of the product assessment. There is no recognition or awareness by the LCA practitioner of best & worst practices in mining [4].

A caveat to mining is that although ore extraction and petroleum appear to be similar, this is only superficial [5]. They are both commodities, but have different customers and uses. They are priced and marketed differently. Therefore petroleum exploration and extraction is not included in this paper.

This paper is part of an ongoing review of mining practices in relation to production engineering. The intent is to create awareness of good and bad mining practices and how this impacts manufacturing and product assessment.

1.2. Product Demand, Complexity, Sustainability and LCA

First we will set the scene for product life cycle. The demand for products has both increased and changed since the industrial revolution. Since the industrial revolution there has been an increased ability to mass produce more complex...
products, including: more sophisticated materials, higher production rates, shorter times to market and lower market prices [6]. Increasing volumes of materials have been needed to meet customer demands. Traditionally this has been done by mining, although recycling has been around since ancient times [4], and although recycling is a now a major goal, it cannot provide the amount of material needed for future products. In the latter part of the 20th century, concern about consumption and damage to the environment became a concern [5, 7, 8, 9]. This included: resources, material use, the energy used to make and use products, the energy needed to transport products to market, the toxic elements produced in making products, including waste gases, fluids and solids. Product Life Cycle Assessment looks at the effects upon the physical environment, with one tool being LCA, Life Cycle Assessment (LCA) [10]. The Life Cycle of a product consists of stages beginning with extraction of raw materials, then design, processing, manufacturing, packaging, distribution, use, re-use, recycling and, ultimately, waste disposal.

With respect to the mining industry, Brundtland [11] noted that mineral resource renewability is not an option, and that the rate of use should not be greater than the capacity to regenerate. For non-renewable resources, such as minerals, the rate of use should not exceed the capacity to find new sources, acceptable substitutes, or recycling. Sustainable development implies that industries such as mining should use land with care. Mining must not endanger the environment [2]. Lists of concerns have evolved since the early days of environmental work. These depend upon who is addressing the question, yet the lists are all very similar. They are included because they come into play in the assessment of mining in product manufacture. Top environmental concerns (1998) [4]: 1) Global climate change; 2) Ozone layer; 3) Biodiversity loss; 4) Changed human organism; 5) Water; 6) Soil depletion; 7) Acid dispersion; 8) Poor land use; 9) Smog; 10) Aesthetic degradation; 11) Fossil fuel depletion. Top environmental concerns (2014) [12]: 1) Population; 2) Climate change; 3) Biodiversity loss; 4) Phosphorus-nitrogen cycles; 5) Water; 6) Ocean acidification; 7) Pollution; 8) Ozone layer; 9) Over fishing; 10) Deforestation.

A simplified SLCA (Streamlined Life Cycle Analysis) [4] can be used to illustrate how the different stages of a product are involved in its Life Cycle. Figure 3 illustrates an SLCA product matrix. Stage 1 in figure 1, is euphemistically called premanufacture (mining). Row 1 includes assessment of environmental stressors: material, energy, solids effluents, liquid effluents, gas effluents. Inherent in this are water use and toxicity. Cell 1,2, energy use in mining, is addressed in this paper. In environmental assessments, the cells in row 1, are usually given low ratings, without specific reasons. Part of the SETAC [3] definition of LCA is the inclusion of “the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use/deuse/maintenance; recycling; and final disposal”.

In this paper the energy needed for extraction and processing in mining is considered, and is directly related to cell 1,2 in the matrix shown in figure 1.

2. The Mining Industry

Although mining occurs everywhere, established mining countries that control the mining scene, and mining techniques, are: Australia, Canada, Chile, South Africa and USA [13]. In Australia, mining was responsible for 7% of Australia's GDP in 2011, and in 2014 the Australian minerals industry directly employed over ≈244,700 people. One third of the world’s bauxite supply (2014) comes from Australia. Canada is one of the largest mining communities globally (≈400,000 people) where 66% of the world’s public mining companies are listed on Canadian Exchanges, with 70% of the equity capital raised globally for mining companies being on these exchanges [14]. Canadian financed companies hold ≈1,400 metal mining properties from Mexico to Argentina [15]. Mining is the largest employer in Chile, with copper mines providing over 30% of the world's mine production, the largest globally [16]. Between 2006 and 2012, the mining industry accounted for 15.7 percent of Chile’s gross domestic product and 64 percent of the country’s exports [17]. In the USA, from 2003 to 2013, mining accounted for ≈2.5% GDP in 2009, but in a state by state analysis this is: ≈30% (Wyoming), ≈25% (Alaska), ≈13% (West Virginia), ≈5% (ND), ≈10% (Oklahoma), ≈9% (Texas) [18]. In South Africa 150,000 people are employed in gold mining alone.

2.1 Major Types of Mining

The two major types of mining are surface (mainly open pit and strip) and underground [19]. Underground is more complicated, requiring special techniques to get safely to an ore body.

In many cases a mine will start out as an open pit and later develop into an underground mine [20, 21]. It is easier to open a pit mine and if the ore is rich enough, to continue with underground mining. In rare cases an open pit mine will operate along with an underground mine, as in the case of the Bjorkdal mine [22]. According to one source there were 2500 major mines operating in 2014 with 52% being open pit, 43% underground and 5% as other [23]. The type of mining will dictate the equipment needed, including auxiliary systems. Both pumping and HVAC are needed in underground mining, whereas HVAC is unnecessary in open pit mining. Both open pit and underground mining need water pumps.

2.2 Environmental Stressors

Environmental stressors in mining are typically divided into two broad categories: solid and gaseous residues. This is illustrated in Table 1.

<table>
<thead>
<tr>
<th>Life Stage</th>
<th>Materials</th>
<th>Energy Use</th>
<th>Solid Residues</th>
<th>Liquid Residues</th>
<th>Gaseous Residues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1, Premanufacture</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>Stage 2, Manufacture</td>
<td>2.1</td>
<td>2.2</td>
<td>2.3</td>
<td>2.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Stage 3, Delivery</td>
<td>3.1</td>
<td>3.2</td>
<td>3.3</td>
<td>3.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Stage 4, Use</td>
<td>4.1</td>
<td>4.2</td>
<td>4.3</td>
<td>4.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Stage 5, Disposal/EDL</td>
<td>5.1</td>
<td>5.2</td>
<td>5.3</td>
<td>5.4</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Figure 1. Example of an SLCA product matrix [4].

2.3 The Value Chain

Figure 2 illustrates the mining and materials industry value chain.
Regardless of a mine being open pit or underground, the sequence of events in producing metals occurs as shown in figure 2. This paper is concerned with extraction.

The foregoing can be broken down into activities shown in figures 3 and 4. Open pit and underground mining are shown in figure 4, including where energy is consumed, points E to K [27]. Point A, in figure 4, is open pit mining. Drilling and blasting are the first steps in both open pit and underground mining. Differences in equipment occur this stage. In open pit, drilling equipment and blasting is the same as in quarries but done at a much larger scale. Equipment used in underground drilling and transportation is much more sophisticated. Locating drill holes is also much more precise in underground mining.

3. Open Pit Mining

Open pit mines (figure 3) account for 70% of the ore bearing rock mined globally (11.5 billion tonnes). Hence underground mines account for 5.1 billion tonnes per year of ore bearing rock [28]. The total ore bearing and waste rock removed yearly from open pit mines is ≈ 67.3 billion tonnes. The aesthetic impact of open pit mining is greater than underground mines, one of the concerns listed earlier [4, 13]. Visual impact may well be one of the reasons mining is viewed negatively. Hence remediation efforts become important [29].

4. Underground Mining

Underground mining occurs out of sight and does have the visual impact that an open pit mine does. Generally underground ore bodies are one of three types: 1) vein type, 2) massive or 3) tabular [16]. They may be narrow and irregular, large and irregular, or tabular: flat and gently dipping, or they may be a combination of the foregoing. Room-and-pillar mining is one technique often used to extract ore, hence this is described [16].

4.1 Types of Underground Mining

Often a mine starts as an open pit, but eventually the geology of the ore, leads to underground mining. To be able to get to an ore body and excavate underground, a subset of twelve major underground mining methods has developed: 1) Classic room-and-pillar, 2) post room-and-pillar, 3) step room-and-pillar, 4) vein, 5) shrinkage stoping, 6) sublevel open stoping, 7) longhole stoping, 8) vertical crater retreat (VCR), 9) cut-and-fill stoping, 10) longwall, 11) sublevel, 12) block caving. Each is used for a specific circumstance and usually depends upon the orientation of the ore vein. In the case of underground mining, equipment is often transferable for use in the different types of mining [16, 25].

Room and pillar (classic, post, step) includes three types: classic room and pillar (smooth floors), post room-and-pillar (inclined ore bodies at 20 to 50 degrees with large vertical heights), step room-and-pillar. See figure 5. In all three types of mining, equipment specific to underground mining is common, including: Jumbo drills, LHD’s (Load-haul-dump articulated vehicles. See table 1. This is a composite of information provided by manufacturers.

LHD’s (load-haul-dump; a combination, articulated scoop and truck) are common in modern mines. They are used in more than 75% of underground mines, globally. LHD power is usually a function of the load. Examples are shown in table 1. As with any vehicle, LHD options vary with each manufacturer, of which there are three major ones, globally: AtlasCopco (Scooptram), Sandvik (automine) and Caterpillar (Minegem). Each manufacturer offers an optional remote guidance system, shown in brackets. These systems are still undergoing research because not all remote control problems have been solved [31]. If higher rock removal rates are needed and it is financially viable, a specially designed underground conveyor system can be installed. In one example a mine used two 355kW (476HP) motors to operate a conveyor line [32].

5. Underground Mining Ventilation

HVAC (Heating, Ventilation & Air Conditioning) is one of the most critical operations in an underground mine [34, 16]. Ventilation is required: to clear toxic fumes due to blasting,
remove exhaust fumes from diesel equipment, remove
dangerous gases that come from the rock mass (strata), and
keep deep mines cool for workers. Standards exist to control
mine air. For example, “employers must provide and maintain
a mechanical ventilation system that will provide a partial
pressure of oxygen of more than 18 kilopascals to dilute and
remove contaminants from underground workplaces” [35].
This includes the requirement that there be at least 0.06 cubic
meters per second for each kilowatt of power of
diesel-powered equipment operating underground in the workplace.

Mines can use 15-20 tonnes of air per tonne of ore. Typically,
large-scale mines require large volumes of ventilating air (from 350,000 to 500,000 cfm). Requirements for five Nevada mines are shown in table 2. In table 3 it can be seen that underground mine ventilation contributes to 25% of underground mine energy consumption [35].

Table 1. A composite of mining equipment with power capabilities.

<table>
<thead>
<tr>
<th>Trucks</th>
<th>LHD</th>
<th>Drills</th>
<th>Raiseborer</th>
<th>Crushers (rod mill)</th>
</tr>
</thead>
<tbody>
<tr>
<td>304kW (408HP)</td>
<td>123kW (165HP)</td>
<td>169kW (227HP)</td>
<td>55kW (72HP)</td>
<td>432kW (579HP)</td>
</tr>
<tr>
<td>439kW (589HP)</td>
<td>175kW (235HP)</td>
<td>310kW (416HP)</td>
<td>120kW (161HP)</td>
<td>650kW (871HP)</td>
</tr>
<tr>
<td>600kW (805HP)</td>
<td>305kW (409HP)</td>
<td>kW (670 HP)</td>
<td>175kW (235HP)</td>
<td>720kW (956HP)</td>
</tr>
</tbody>
</table>

Table 2. Mine ventilation in Nevada underground mines 2011 [34].

<table>
<thead>
<tr>
<th>Mine</th>
<th>cfm x10^6</th>
<th>for HP</th>
<th>cfm</th>
<th>m³/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.3</td>
<td>booster, 2000 x2</td>
<td>11040</td>
<td>309</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>intake 250 x2, exhaust 250 x3 + 125</td>
<td>10400</td>
<td>290</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td>exhaust, 250 x3 in series</td>
<td>10400</td>
<td>290</td>
</tr>
</tbody>
</table>

Table 3. Mine needs for a proposed underground mine [34].

<table>
<thead>
<tr>
<th>Equipment</th>
<th>HP</th>
<th>kW</th>
<th>cfm</th>
<th>m³/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>jumbo</td>
<td>92</td>
<td>69</td>
<td>11,040</td>
<td>309</td>
</tr>
<tr>
<td>jumbo</td>
<td>139</td>
<td>104</td>
<td>16,680</td>
<td>467</td>
</tr>
<tr>
<td>truck</td>
<td>80</td>
<td>60</td>
<td>9,600</td>
<td>269</td>
</tr>
<tr>
<td>forklift</td>
<td>116</td>
<td>87</td>
<td>13920</td>
<td>390</td>
</tr>
<tr>
<td>forklift</td>
<td>116</td>
<td>87</td>
<td>13920</td>
<td>390</td>
</tr>
<tr>
<td>loader</td>
<td>250</td>
<td>187</td>
<td>30000</td>
<td>840</td>
</tr>
<tr>
<td>tester</td>
<td>250</td>
<td>187</td>
<td>30000</td>
<td>840</td>
</tr>
<tr>
<td>haul truck</td>
<td>409</td>
<td>305</td>
<td>49080</td>
<td>1374</td>
</tr>
<tr>
<td>haul truck</td>
<td>410</td>
<td>306</td>
<td>49200</td>
<td>1378</td>
</tr>
<tr>
<td>haul truck</td>
<td>411</td>
<td>307</td>
<td>49320</td>
<td>1381</td>
</tr>
<tr>
<td>truck</td>
<td>149</td>
<td>111</td>
<td>17880</td>
<td>501</td>
</tr>
<tr>
<td>truck</td>
<td>117</td>
<td>87</td>
<td>14040</td>
<td>393</td>
</tr>
<tr>
<td>boltter</td>
<td>154</td>
<td>115</td>
<td>18480</td>
<td>517</td>
</tr>
<tr>
<td>boltter</td>
<td>155</td>
<td>116</td>
<td>18600</td>
<td>521</td>
</tr>
<tr>
<td>Other diesel equip</td>
<td>200</td>
<td>149</td>
<td>24000</td>
<td>672</td>
</tr>
<tr>
<td>Total</td>
<td>3048</td>
<td>2274</td>
<td>365760</td>
<td>10241</td>
</tr>
</tbody>
</table>
Energy Use in Mining

This section surveys energy use in established mining countries [13].

In Chile the mining industry consumes 38% of all electricity produced [38]. The average mine consumes 25MW/h per tonne of material processed [39]. In northern Chile, in 2014, 90 percent of the electricity generated was consumed by the mining industry. Solar energy can provide most electrical energy needs, hence in June 2012, the country’s first industrial solar power plant (one MW) was started. It will supply electricity to an open pit mine, reducing carbon emissions by 1,680 tonnes [39]. For reference, Chile had 18 gigawatts (GW) of installed electric capacity as of 2011. One-third is attributable to hydroelectric plants. Wind capacity has grown to an estimated 190 megawatts (MW) as of 2011 [41].

The mining industry is a significant user of diesel fuel. Optimising truck payload ensures each carrying optimum material tonnage to increase fuel efficiency. This can reduce the number of trucks required. The number of trucks required needed. Savings included 117,300 GJ and 8200 tonnes CO2 emissions per year in one case, and in another increasing the truck payload on 785 trucks led to energy savings of approximately 3.685 TJ and $4.9 million per year.

In 2008–09, 40 Australian mining companies consumed 308 PJ of energy of which 52.5 PJ was diesel (17%) for haulage and electricity generation. 3 PJ (or 6%) were saved by decreasing diesel use [42]. In one case, the energy costs associated with stopping trucks unnecessarily for a stop sign was 361 kL (13,935 GJ) of diesel per year for a truck fleet, each having 765 kW (1025HP), in another case 15,710 GJ(407 kL) of diesel per year were consumed for a 2,797 kW (3,750 hp) truck fleet. There was a 2.3% reduction in fuel consumption, with a fuel savings of 232 kL (8,955 GJ) of diesel per year. In-pit crushing and conveying (IPCC), where ore is crushed in the pit and brought to surface via conveyor, results in reductions in energy use and shifts the energy source from diesel to electric. IPCC is gaining in popularity, particularly in deep and high production rate mines. One study identified a specific energy requirement of 1.09-1.117 kW/t/km for truck haulage versus just 0.14-0.25kW/t/km for conveyors [43]. Increased payload per unit weight of equipment and reduced support equipment needs contribute to the improvement. High capital costs and increased planning complexity limit the applications of IPCC. Electric trolley-assist also reduces energy use and shifts the source from diesel to electricity. Trolley systems require electric drive trucks and are normally installed to aid in uphill segments of the haul cycle. Energy savings are through improved utilization of truck wheel-motor capacity, and reductions in the total number of trucks required due to increases in truck speed. One South African study indicated an overall increase in truck productivity of 10% and a 50% decrease in fuel consumption using a trolley [44]. Such systems can also generate electricity when trucks are travelling downhill [45].

6. Conclusion

The mining industry has been working to decrease energy consumption. A recent study revealed reductions in energy use and emissions, in Canada: 24% reduction in energy and 28% reduction in GHG’s from 2000 to 2009 [37].

Rock transport uses 30% energy for waste and 24% energy for ore removal in an open pit. See figure 3(b). Addressing open pit transport issues provides an opportunity to decrease energy consumption and CO2 emissions at an open pit mine.

Underground mining uses 25% of the energy consumed for HVAC systems. If windmill farms are installed by a mine [46], it reduces the dependence upon fossil fuel and decreases the volume of diesel fuel that needs to be delivered.

Electric powered LDH’s are now being tried in underground mines [47, 48], but are in the development phase. There has been success with using fuel cells as a power source. In either case, this will decrease the ventilation requirements and HVAC energy needs. Electric powered jumbo’s are also being considered.

Although mining does not meet the goals of the Brundtland commission [11], mining is necessary to meet the material needs of modern society, and it has been shown that with respect to energy consumption, the mining sector has made substantial reductions in decreasing this consumption.

7. References


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