Life Cycle Assessment of a Rock Crusher

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ABSTRACT

Nordberg, Inc., a capital equipment manufacturer, performed a Life Cycle Assessment study on its rock crusher to aid in making decisions on product design and energy improvements. Life Cycle Assessment (LCA) is a relatively new cutting edge environmental tool recently standardized by ISO that provides quantitative environmental and energy data on products or processes. This paper commences with a brief introduction to LCA and presents the system boundaries, modeling and assumptions for the rock crusher study. System boundaries include all life major cycle stages except manufacturing and assembly of the crusher.

Results of the LCA show that over 99% of most of the flows into and out of the system may be attributed to the use phase of the rock crusher. Within the use phase itself, over 95% of each environmental inflow and outflow (with some exceptions) are attributed to electricity consumption, and not the replacement of spares/wears or lubricating oil over the lifetime of the crusher. Results tables and charts present selected environmental flows, including CO_2 NOx, SOx, particulate matter, and energy consumption, for each of the rock crusher life cycle stages and the use phase.

This paper aims to demonstrate the benefits of adopting a rigorous scientific approach to assess energy and environmental impacts over the life cycle of capital equipment. Nordberg has used these results to enhance its engineering efforts toward developing an even more energy efficient machine to further progress its vision of providing economic solutions to its customers by reducing the crusher operating (mainly electricity) costs.

Introduction to LCA

Over the last 15 years, environmental issues have assumed an increasing priority for government and industry alike. In the United States as well as in Europe, the emphasis has gradually broadened from a site-specific focus to include a product-specific focus. Regulations and schemes have progressively been put in place addressing the intertwining between environmental issues and industrial systems. Life Cycle Assessment (LCA) is now recognized as part of a category of tools providing quantitative and scientific analyses on some environmental impacts of industrial systems. By providing an unbiased analysis LCA has shown that the reality behind widely held beliefs regarding "green" issues such as reusable vs. one way products, recycling vs. incineration, and "natural" vs. synthetic products, were far more complex than expected and not always as "green" as assumed.

In order for LCA to be an effective and well accepted approach, standard LCA guidelines have been developed: first by the Society for Environmental Toxicology and Chemistry (SETAC 1993), then by the United States Environmental Protection Agency (EPA 1993), and the most recent, the International Standards Organization Standards 14040 and

14041 (ISO 1997; ISO 1998). Among the points emphasized by these guidelines is the need to clearly list all the assumptions and data sources used in the LCA in an objective and transparent manner.

LCA studies produce a detailed and quantitative balance sheet or inventory of inputs (i.e., energy, materials) and outputs (i.e., emissions to the environment) of a carefully defined system describing a product or a set of processes. The system encompasses the entire "life cycle" of a product or process, expanding the typical boundaries of manufacturing to include transportation steps, raw materials extraction, use, and different end of life management alternatives (landfilling, incineration, recycling, re-using, etc.).

LCA inventory results can be used by industries and organizations to:

- Identify life cycle stages in which environmental improvements can be made;
- Strategize on cost-effective management options;
- Benchmark on an industry-wide or process-by-process basis for environmental performance; and
- Communicate externally to the public and private sectors, and internally to industry members.

Goals and Scope of the Rock Crusher LCA Study

Nordberg, Inc. (Nordberg) commissioned Ecobalance, Inc. (Ecobalance) to perform an LCA on one of its products, the conical rock crusher model HP400 SX, with the ultimate goal of identifying where environmental and product improvements can be made and aiding in making decisions on product design and energy efficiency improvements. The way to achieve this goal was to quantitatively assess the environmental trade-offs of the life cycle of the rock crusher, including the upstream production of the materials contained in the rock crusher itself, the use phase, the end of life phase, and transportation. The main component of LCA, Life Cycle Inventory (LCI) assessment, was used for the evaluation, and follows the accepted LCA methodology as defined by ISO (ISO 1997; ISO 1998) and SETAC (SETAC 1993). The modeling for this study was performed in TEAM™, Ecobalance's LCA software.[1]

System Boundaries and Modeling

System Boundaries: General Principle

Life Cycle Assessment (LCA) is an analytical tool used to comprehensively quantify (and optionally to interpret) the material and energy flows (to and from the environment, including air emissions, water effluents, solid waste, and the consumption/depletion of energy and other resources), over the entire life cycle of a product or process. The life cycle is meant to be studied comprehensively, including production and extraction of raw materials, intermediate products manufacturing, transportation, distribution, use, and final

[1] Tools for Environmental Analysis and Management. TEAM™ was rated by Environment Canada in a December 1996 study of 37 LCA software programs as the "most powerful and flexible" life cycle tool. For more information on TEAM™, go to www.ecobalance.com.

disposal. This general principle for extending the system boundaries is illustrated in Figure 1:

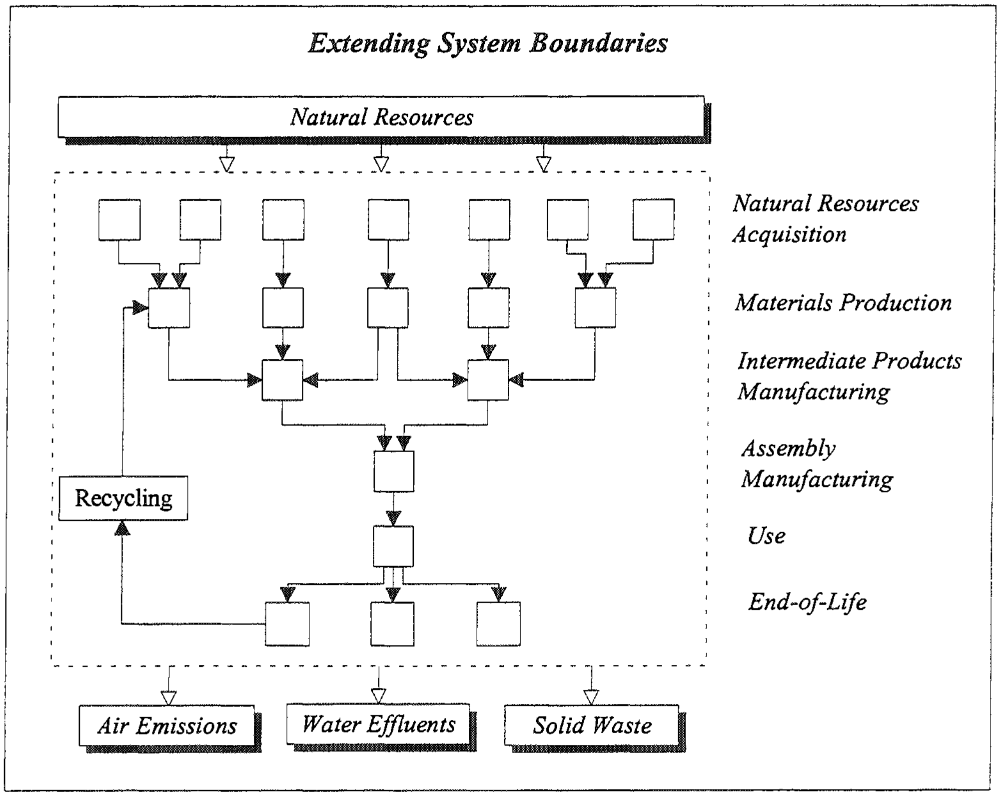

Figure 1 Extending System Boundaries

All flows within the system are normalized to a unit summarizing a *function* of the system. This allows for the comparison of different industrial systems performing the same function. Once this shared function is defined, a unit has to be chosen in order to compare the systems on the same quantitative basis.

System Boundaries and Modeling: Rock Crusher

The data within the system boundaries of the Nordberg rock crusher included the following (also provided in Figure 2): production phase of the material components; use phase; end-of-life phase; and transportation.[2] Each of these are discussed below.

[2] Note on rock crusher manufacturing: There were preliminary discussions for a third phase of this life cycle study which would focus on crusher manufacturing, including energy and materials used in manufacturing, assembling the rock crusher, and transportation of the materials to build the crusher. However, results have pointed to the conclusion that manufacturing energy and materials would be negligible over the life cycle.

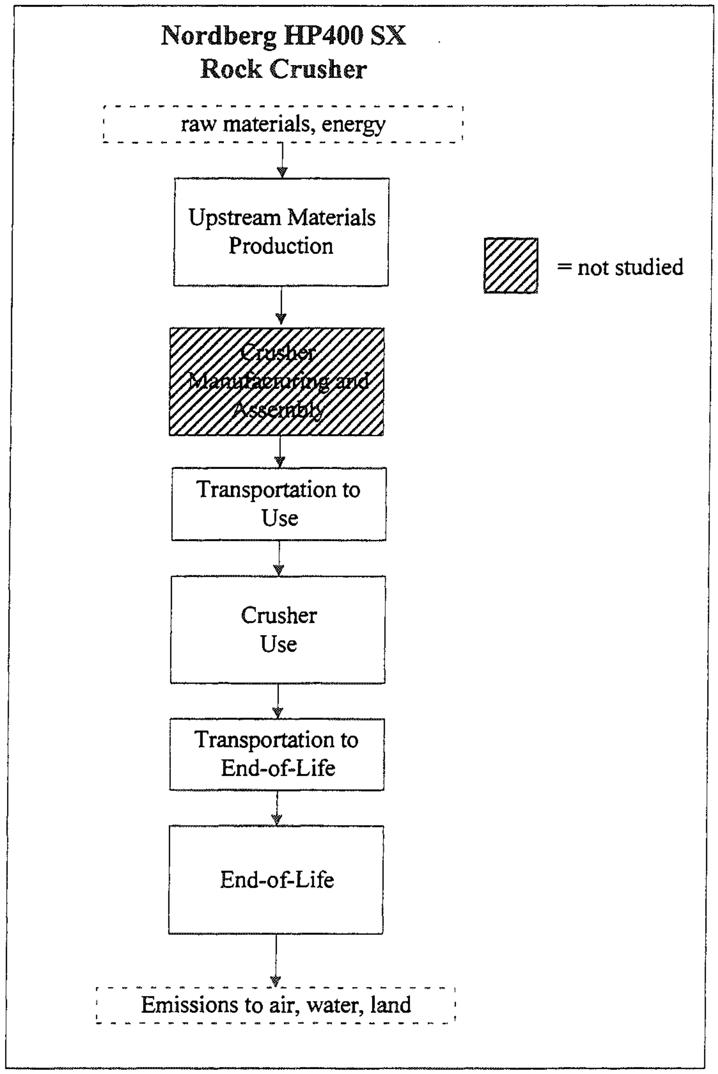

Figure 2 Phase 1 System Boundaries

The function of the rock crusher system was defined to be **crushing glacier round rock to pieces of 1¼-inches and below.**[3] The functional unit to which the rock crusher was normalized is **1000 short tons of crushed glacier round rock of 1¼-inches and below**. All energy and materials consumed, as well as emissions to the environment, were normalized to this functional unit.

Materials production phase. The materials production phase of the life cycle of the rock crusher entailed collecting information on the key materials contained in the rock crusher itself. Ninety-six percent of the mass of the materials in the crusher were identified, with the remaining 4% of the components in the rock crusher making up miscellaneous metal items

[3] Glacier round rock is the rock crushed by the company who contributed data.

(such as nuts and bolts). The materials contained in the rock crusher, along with their contribution to the total mass, is provided in Table 1:

Table 1 HP400 SX Rock Crusher Materials

Material in the HP400 SX	Weight (lb.)	% of the Total Weight
Steel	45,600	87%
Iron	3820	7.3%
Bronze	746	1.3%
Epoxy Resin	177	0.3%
Aluminum	38	0.07%
Brass	1.4	0.003%

Ecobalance's materials database, DEAM™ was used to model the production of the upstream components provided in Table 1.[4] Steel consumed was assumed to be 50% primary (virgin steel production in the basic oxygen furnace) and 50% secondary (recycled steel from the electric arc furnace). The 50/50 BOF/EAF mix was chosen due to limited available data on actual origin of the steel.

Use phase. The life span of the rock crusher was assumed to be 25 years. Use phase modeling included power, oil and lubricant consumption, and parts replacement requirements of the crusher. Actual Nordberg HP400 SX rock crusher use data were measured and provided by a Nordberg HP400 SX user. Table 2 provides a combination of actual use data and Nordberg HP400 SX manufacturer specifications.

Table 2 Characteristics of the Nordberg HP400 SX

Nordberg HP400 SX	
Type of rock crushed	Glacier Round Rock
Crusher discharge (final product)	1 ¼ x 0 inches
Crusher throughput capacity measured at the plant (s.t./hour)	500
Crusher production (hours/year)	5,000
Electricity consumption measured at the plant (kWh/year)	1,625,000
Spare parts ("spares") part name and weight in lbs.	Liner: 1,550(see note 1 below)
Wear parts ("wears"): part name and weight in lbs.	Mantle: 2400 Bowl liner: 2370 Torch ring: 15 **Each wear changed 7x per year.**
Lubricating oil (gallons)	150 (changed 2x/yr.)

[4] DEAM™: Database for Environmental Analysis and Management, whose data are used within TEAM™.

Some notes regarding these data:

1. The Nordberg HP400 SX is one of Nordberg's newest models of rock crushers and has only been in use by this company for about four to five months at the time of data collection, so these data are based on specifications and limited use.
2. The power consumed for a full 8-hour shift was monitored to obtain the total quantity of electricity consumed during one day.
3. The total mass of the spares and wears, over the span of 25 years comes to about 876,000 lbs. The spares and wears are assumed to be steel, and were modeled as a 50/50 BOF/EAF mix.

The power consumption of the rock crusher, normalized to the functional unit of 1000 short tons of crushed rock, was 650 kWh.

Particulate matter from the rock crushing plant itself was accounted for, and AP-42 (EPA 1996) provided the emission factor: 0.0024 pounds of particulate matter (PM10) emitted per ton of crushed rock in tertiary rock processing and crushing operations.

No inefficiency of the machine due to age and parts wearing down (i.e., a higher replacement rate as the machine gets older) was taken into account due to lack of available data for this state-of-the-art machine.

End-of-life. The assumption was made that the metal components of the rock crusher, therefore nearly its entire mass, are recovered and recycled. This recovered material was assumed to be reused in applications outside the rock crusher system boundaries. For this reason, the recycling energy, materials, and emissions due to materials recovery and the environmental offsets of primary steel production were not quantified in this model.

Transportation. Transportation of the Nordberg rock crusher from assembly plant to the rock crushing plant as well as from the rock crushing plant to the metal recycler was taken into account, using a heavy duty diesel truck (20 metric tons maximum load) as the transportation mode. The transportation distances assumed are shown in Table 3:

Table 3 Transportation Distances

Phase of the life of the crusher	Distance (miles)
Assembly plant to the rock crushing plant	800 miles
Rock crushing plant to the secondary metal producer	50 miles

Capital equipment exclusion. In life cycle assessment, one might include capital equipment, such as production and transportation of concrete and steel, as well as building energy, in the system boundaries of a study product. However, capital equipment was excluded as it is expected to be small. This kind of result would be consistent with Ecobalance's experience.[5]

[5] For example, a study performed for the Integrated Waste Services Association (IWSA) that compared energy production of municipal solid waste with other combustible fuels excluded capital equipment of the utilities. The CO_2 emissions due to the production of steel and cement of the waste-to-energy (WTE)

Electricity production modeling. The US Department of Energy, Energy Information Administration (EIA 1996) provided the amount of each type of fuel that contributes to each of the U.S. component NERC regions (the US average grid mix was used). Table 4 presents the share of these five major fuels, normalized to 100%, according to the EIA data:

Table 4 Share of Each Fuel in the Electricity Grid

	Coal	Fuel Oil	NG	Nuclear	Hydro
US Average[6]	57%	2%	9%	22%	11%

For each of these fuel sources, production, combustion at a power generation utility, and post-combustion (where applicable, such as handling of coal ash and slags) was modeled.

Steel production modeling. The model for primary steel production includes iron ore mining and coal carbonization (distillation in the absence of air). Processes at the sinter plant and blast furnace are also included in the model. The secondary steel production model includes steel scrap processing through the electric arc furnace (EAF). Electricity, natural gas, and coal are modeled as the fuel sources. The steel models do not take into account parts fabrication.

Data Sources. To provide all of the data sources (i.e., production of materials, electricity, diesel fuel, etc.) in this study is out of the scope of this paper. As a summary, data comes primarily from an exhaustive list of U.S. and European published data, including: EPA, EIA and other U.S. DOE sources, Gas Research Institute, and Swiss Federal Office of the Environment. Data are contained in Ecobalance's database, DEAM™, and are regularly updated as new and/or improved data become available.

Results and Discussion

Life Cycle Breakdown

Table 5 presents each of the major life cycle stages of the Nordberg rock crusher. The flows selected for this paper include NOx, SOx, CO_2, particulate matter, iron as a natural resource input, and total energy, and are presented in the first column of the table.[7] This first column contains the actual flow quantity in the appropriate units, while subsequent columns present the percent contribution of each of the major life cycle stages: upstream material production, use, transportation, and end-of-life. Each row adds up to 100%.

plant were found to contribute about 0.2% of the total CO_2 emitted from the entire life cycle of WTE (Ecobalance 1997).

[6] Note: Percentages might not add to 100 due to rounding.

[7] Although a limited number of flows are presented here, for the most part, these are typical of the results as a whole.

Table 5 Life Cycle Results

For 1000 short tons crushed rock			Nordberg Crusher	Upstream Mat'l Prod.	Use	End-of-Life	Transport-ation
InFlow:	(r) Iron (Fe, ore)	kg	4.0	6%	94%		
OutFlows:	(a) Carbon Dioxide (CO2, fossil)	g	586,333	0.1%	100%	0%	0%
	(a) Nitrogen Oxides (NOx as NO2)	g	1,902	0%	100%	0%	0%
	(a) Sulfur Oxides (SOx as SO2)	g	3,261	0.1%	100%	0%	0%
	(a) Particulates (unspecified)	g	3,410	0.1%	100%	0%	0%
Energy:	Total Primary Energy	MJ	8,906	0.1%	100%	0%	0%

Notes: 1) 0% indicates a percentage of less than 0.1%.
2) Blank spaces indicate no data on those flows for that stage.

As is evidenced by Table 5, the use phase is the dominating phase on impact to the environment for iron ore and energy consumed as well as the air emissions. For all of these flows, the use phase contributes over 94% of the life cycle emissions.

It would seem as though the steel and iron contained in the rock crusher itself (about 50,000 lb.) would make a larger environmental impact on the life cycle of the rock crusher. However, the requirements to replace spares and wears over the 25 years of the rock crusher (8.76 E+5) greatly exceeds the primary quantity of steel and iron.

Use Phase Breakdown

Table 6 breaks down the use phase into electricity, spares and wears, and lubricants consumed, the three main components modeled in the use phase. The first column of this table contains the actual flow quantity of the use phase (in the appropriate units), and subsequent columns present the percent contribution of each of these main components.[8]

Table 6 Use Phase Results

For 1000 short tons crushed rock			Nordberg Use Phase	Steel	Electricity	Lubricating Oil
InFlows:	(r) Iron (Fe, ore)	kg	3.7	100%		
OutFlows:	(a) Carbon Dioxide (CO2, fossil)	g	585,530	1.3%	99%	0%
	(a) Nitrogen Oxides (NOx as NO2)	g	1,899	1%	99%	0%
	(a) Sulfur Oxides (SOx as SO2)	g	3,257	0.7%	99%	0%
	(a) Particulates (unspecified)	g	3,405	2.0%	66%	0%
Energy:	Total Primary Energy	MJ	8,894	1.1%	99%	0.3%

Notes: 1) 0% indicates a percentage of less than 0.1%.
2) Blank spaces indicate no data on those flows for that stage.

[8] The rows should add to 100% If some of the numbers do not add to 100%, that portion of the flow quantity is considered to be an emission at the plant itself, and not contained in the three main components.

Table 6 demonstrates that electricity consumption is the most dominant component of the use phase, which implies that the spares and wears replacement over the lifetime of the crusher is insignificant compared to the energy the crusher consumes.

The electricity component and particulate matter each deserve a comment. Recall from the electricity discussion that the mix of fuel sources in the electricity grid are based on the U.S. average mix. So depending on the use in different areas of the country, the environmental profile might be different. The particulate matter contribution in Table 6 does not add up to 100%. The remaining particulate matter actually comes from the plant itself, and not from the upstream components listed in the table.

Conclusions

Based on the data and assumptions, it is concluded that the use phase, and specifically electricity consumption, is the dominating phase in the life cycle of the rock crusher in terms of impacts to the environment. As such, Nordberg is placing its environmental engineering and designing efforts on the *use* phase, rather than the manufacturing stage, of the machine.

Before the launch of the LCA study, Nordberg had directed its efforts to improving energy efficiency of its conical crushers by increasing productivity, with the goal of lowering operating costs to its customers. This productivity approach yielded important innovations like the HP® (High Performance) Cones, such as the HP400 SX, to substitute some of the earlier crusher models. As a result, the HP® family was chosen as the benchmark for the development of next generation crushers, which include increasing the feed to product size reduction ratio per unit of energy consumed and improving overall size reduction energy efficiency [these efforts are in the pilot testing phase and are showing great promise for providing significant energy and cost efficient flossiest for rock and ore size reduction].

Introducing LCA into the picture validated the need to focus on the use phase of its products to carry through the Nordberg vision, i.e., lower energy costs for its customers while also taking into account environmental considerations: energy efficient products lower total primary energy consumed and decrease the life cycle emissions to the environment.

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