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EVALUATING THE ENERGY USAGE AND ENVIRONMENTAL IMPACTS OF A SAND CASTING USING LIFE CYCLE ASSESSMENT

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ABSTRACT

Metal casting is a primary manufacturing process that produces parts of intricate shapes. More than 90% of these castings are produced by sand casting process; however this process is energy intensive and associated with high environmental impacts. In this work, Life cycle Assessment (LCA) tool is employed to quantitatively evaluate and compare the energy usage and its environmental impacts by a cast iron component of 1 kg over the complete lifecycle using Eco-indicator-99 methodology. The system boundary includes all the phases, extraction, manufacturing, use and disposal phase. The energy data for sub-processes: core and mould making, mould handling, melting and pouring, fettling, finishing operations is obtained from foundries. The comparison is done on the basis of use of 25% to 100% scrap proportions. The results reveal that shifting to 100% scrap use, the energy usage and environmental impacts are drastically reduced.

Keywords: *Life cycle assessment, Inventory characterization and Eco-Indicator 99(E).*

1. Introduction

Metal casting process is widely used for producing complicated shapes in any metal that can be melted. India with 7.8 MT per annum is the second largest producer of castings in the world. It is an energy intensive process. Although the metal casting industry is renowned for using recycled metal, ferrous as well non-ferrous foundries are considered major sources of hazardous air pollutants (HAP's) from processes such as melting, pouring, cooling, and shakeout. Traditionally, products are designed and developed without considering their adverse impacts on environment. The adverse effects on the environment also occur during other stages of product's life cycle such as use phase, raw material extraction, distribution or disposal phase as well. Life cycle assessment is an effective tool to quantitatively analyze the environmental effects arising from different stages of a product [1]. By energy use mix, electricity is the largest source with a share of 59% and more than half of the energy consumed in foundry is required in metal melting [2]. The specific energy intensity for steelmaking by basic oxygen furnace is calculated to be 0.9 million Btu per net ton of raw steel. The electricity requirements of oxygen generation are estimated to be about 0.01 kWh per cubic foot of oxygen [3]. The overall environmental impact may be reduced by de-materialization or material substitution as merely using lighter material may only reduce emissions in use phase [4]. Product's life cycle is divided into four phases- raw material acquisition or extraction, manufacturing, use and disposal or end of life. The analysis helps to identify the critical stage and the sub-process/sub-processes within it.

2. Methodology

The four steps of Life cycle assessment method [1] are discussed as under.

2.1 Defining goal and scope

The goal is to assess and compare the effect of energy use on environmental impact by a hypothetical cast iron part produced by sand casting process under different scrap proportions. The scope is depicted in the figure 1 by a system boundary showing what processes are included in the study.

2.2 Life cycle inventory analysis

The inventory data has been collected from different sources. Casting emission reduction program (CERP) have evaluated and documented HAP and VOC emission data for pouring cooling, shakeout of cast iron and steel castings [5], emission data for sand mixing, making and storage of green sand mould making [6] and core mixing, making and storage of phenolic urethane

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cold box cores [7]. The databases developed by the experts of National Renewable Energy Laboratory (NREL) include the energy and material inflows to and outflow of product, byproduct and emissions for extraction and processing of various types of fuels, extraction and processing of ferrous and nonferrous metals, transportation by different modes, combustion of various fuels in utility and industrial boilers etc., iron ore sintering and palletizing [8]. The other data sources

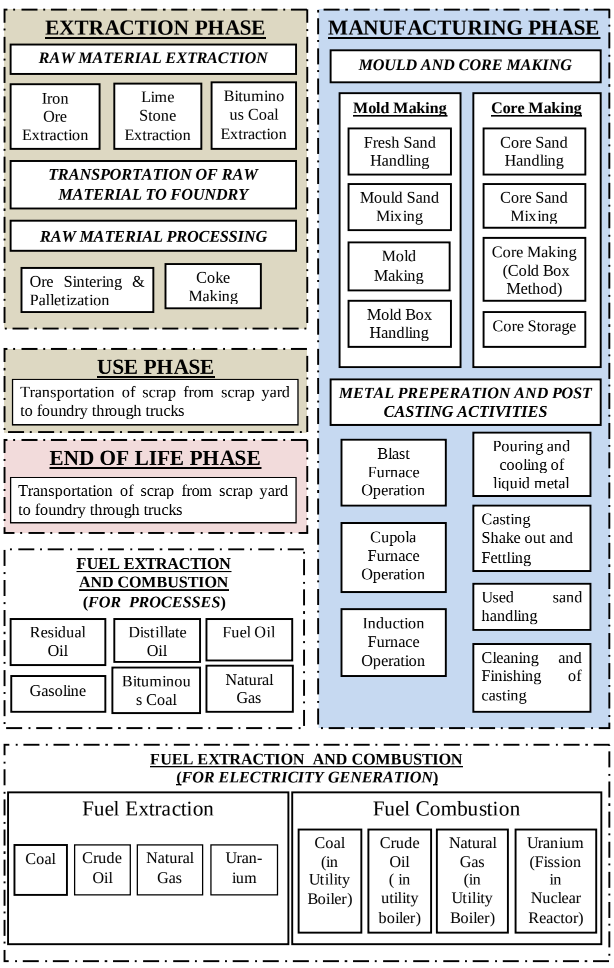


Fig. 1 System Boundary for LCA Study

include coke making data [9], emissions from blast furnace operation and basic oxygen furnace [3] [10], emission data for cleaning and finishing [11], the environmental effect of hydraulic energy used for electricity generation [12]. The energy data for the various processes like - mould making, core making, melting, pouring, cooling, shakeout and finishing operations in the manufacturing phase has been collected from an established cast iron foundry. The sequence of processes in manufacturing phase for producing 1 kg of the casting is shown in figure 2 and the assumptions made for the study for various phases are given in table 1.

Table 1: Input Specifications in Various Phases

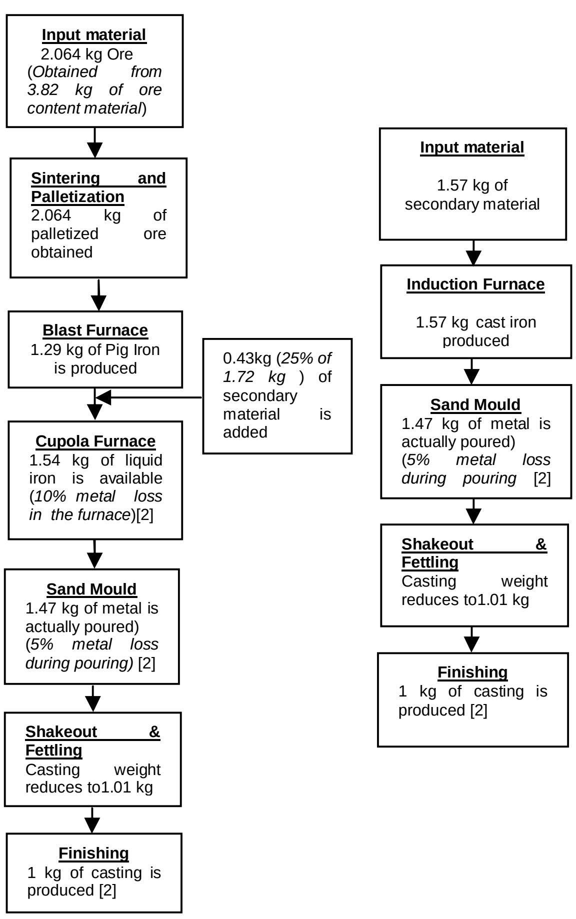
Extraction Phase	Manufacturing Phase
a) **Location of coal and iron ore resources from foundry -** 200 kms [Assumption] b) **Mode of transportation** – GoodsTrain (Mileage-3 kms/lits) [Assumption] c) **Location of limestone and fresh sand resources from foundry -** 200 kms d) **Mode of transportation-** Truck (Mileage-4 Kms/lits.) [Assumption] e)Energy consumption is based on weight of vehicle as the part weight is considerably less than vehicle weight [Assumption] f) Construction, mining, process equipments, in foundry ,electric generation facilities are excluded in the study [Assumption]	a)**Sand to metal ratio -** 1:8 [Foundry Data] b)90% of sand is recycled in a each mould cycle [Foundry Data] c) **Cores-** Made of cold box method d) Densities of core and mould sand- 1480kg/m^3 and 1530kg/m^3 [Foundry Data] e) **Scrap proportion considered** – 25% and 100% [Assumption] f) **Casting yield considered-** 68% [Foundry Data] g) Pattern making is not included in the study. [Assumption]
Use Phase	**End of Life Phase**
a) **Automobile considered-** TATA make LPT709 diesel truck Mileage-4 kms/lit.) [Assumption] b**) Full load of the vehicle-**7500kg c) The vehicle always run on full load [Assumption] d) Energy consumption is proportional to weight of the component. e) Life of the vehicle is 500000 kms. [Assumption]	a) **Location of Scrap yard -**100 kms from foundry. [Assumption] b) **Mode of transportation of scrap-** Truck (Mileage-4 kms/lit.) [Assumption]

A suitable electricity mix is selected for the study based on various methods of producing electricity-Coal-

53.3%, Natural gas 10.5%, Oil 0.9%, Hydro 24.7%, Nuclear 2.9 % and Renewable 7.7%. The environmental emissions for producing 1 kWh of electricity is evaluated and incorporated for each sub-process of every phase [13]. The characterization factors are taken from SimaPro software [14].

2.2.1 Inventory classification & characterization

The inventories calculated as per the functional unit are then classified as per the impact categories of the Eco-Indicator 99, the LCA method selected for the study. It is to be noted that one inventory parameter can affect more than one impact categories and so parallel impacts are selected. For instance, methane affects not only respiratory organics but is also responsible for climatic change; NOx is responsible not only for respiratory in-organics but also for acidification.



25% scrap use **100% scrap use**

Fig. 2 Manufacturing Phase -25% & 100% Scrap Use

Once the classification step is completed, quantification of environmental impacts by each inventory parameter on the impact category is assessed. Characterization factors selected from SimaPro software address the relative contribution among inventory parameters assigned to a given impact category. Once the contribution of each parameter is quantified, the quantified impacts within the same impact category are aggregated.

2.3 Life cycle assessment

The corresponding impacts for different processes of each phase are added up to evaluate the gross impacts. In the present study, Eco-indicator-99(E) method is selected for LCA. It incorporates 11 impact categories under three damage categories (table 2). The energy required with the two different proportions of secondary material used and their effect on environmental impacts is studied by considering the production of 1 kg of casting.

Table 2: Categories in Eco-Indicator 99(E)[15]

Impact Categories	Damage Categories	Units
Carcinogens Respiratory organics Respiratory In-organics Climate change Radiation Ozone Layer	Human Health	Disability adjusted life years (DALY)
Ecotoxicity Acidification Land use	Eco System Quality	Potentially Disappeared Fraction of plant species (PDF/m^2/year)
Minerals Fossil fuels	Resources	MJ surplus energy

3. Results and Discussion

The energy usage and environmental damage caused are compared for both 25% and 100% secondary material use. The energy usage for all the four phases is given in table 3 and figure 3. Table 4 and figure 4 show the comparison of environmental damage. A drastic reduction in the energy usage and environmental damage is observed while using 100% secondary material for producing the casting.

3.1 Energy use

With use of only 25% re-cycled material in the charge, the extraction and manufacturing phases still include many sub-processes to produce fresh material for the charge. Extraction phase involves activities like extraction of iron ore, coal and lime stone , their transportation from mines to foundry, sintering and palletization of iron ore, conversion of bituminous coal into coke in coke making plants, lime stone crushing in foundry premises and transportation of fresh sand as makeup sand to the foundry. A mix of fuels- coal, distillate oil, residual oils, gasoline, and natural gas along with direct electricity is used in extraction activities. The energy use in these activities is proportional to the quantity of material extracted. The transportation activity however is dominant in energy consumption due to fact that the energy consumed is proportional to vehicle weight which is high enough compared to material being carried in the vehicle. Manufacturing phase involves blast and cupola furnace operations, mould and core making, metal pouring, shakeout, fettling and finishing operations on castings. Blast and cupola furnace operations are energy intensive and use coke oven gas, blast furnace gas, natural gas, fuel oil, coke and direct electricity as sources of energy. Blast furnace includes conversion of ore into pig iron and consumes 77% more energy than cupola. The mould and core making, shakeout, fettling and finishing processes use electricity as the source of energy. Compared to mould and core making, the metal preparation processes consume 98% more energy.

Table 3: Energy Usage with Scrap Use (kWh)

Phases	Percentage of Secondary Material		% reduction in energy
	25%	100%	
Extraction phase	1.97E+03	2.68E+02	83.4
Mfg. phase	1.23E+01	1.87E+00	84.8
Use phase	1.92E+02	1.92E+02	0%
End of life phase	2.68E+02	2.68E+02	0%

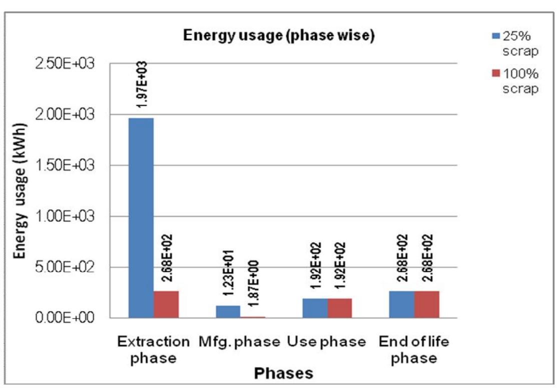


Fig. 3 Phase wise Comparison of Energy Usage

With use of 100% re-cycled material, energy usage in extraction and transportation of ore, limestone and coal is altogether eliminated except for the energy usage in carrying fresh mould sand to the foundry in the extraction phase. In manufacturing phase, electric induction furnace replaces the energy intensive blast and cupola furnaces and consumes nearly 87% less energy than that consumed by these furnaces combined. The post casting activities remain unaltered. The energy usage in extraction and manufacturing phases are reduced by 83% and 85% as compared to that for 25% secondary material usage. The use and end of life phases are not affected by the proportion of secondary material usage. In total, the energy usage with 100% recycled material is 70% lower than that for using only 25% recycled material.

3.2 Environmental Impact

With a proportion of only 25% recycled material in the charge, the extraction phase involves all the activities above mentioned. Transportation activities dominate all impact categories especially in ecotoxicity, acidificationand fossil fuel extraction. Emissions during diesel extraction for transportation activity mainly cause ecotoxicity and acidification. Emissions of nitrogen oxide due to diesel combustion during transportation cause acidification. Fossil fuel extraction for its use in transportation of raw material and coal to the foundry by vehicles causes emissions to the environment. The contributions of other processes are not significant. In manufacturing phase, blast and cupola furnace together cause ecotoxicity due to methane emission during natural gas extraction used as a fuel in blast furnace and acidification due to lead emissions during cupola operation. Foundry emissions from mould and core making include many hazardous air pollutants (HAPs) and volatile organic chemicals (VOCs) and cause impacts of carcinogens and respiratory organics. The electricity used in these processes however produces a much larger impact of ecotoxicity and acidification. Impacts of ecotoxicity and acidification are dominant in post casting activities also. In use phase, the diesel extraction causes emissions to affect fossil fuel category. Its use as fuel for running the vehicle fitted with the cast part under consideration adds to ecotoxicity and acidification. End of phase only involves transportation activity which again adds to impacts of fossil fuel extraction along with ecotoxicity and acidification without much affecting other impact categories.

Table 4: Environmental Damage with Scrap Use

Damage Categories	Percentage of Secondary Material		% Reduction in Environ-mental Damage
	25%	100%	
Human Health	1.89E-03	1.98E-04	89.5
Eco System Quality	1.04E+02	2.51E+01	75.8
Resources	5.08E+02	3.09E+02	39.1

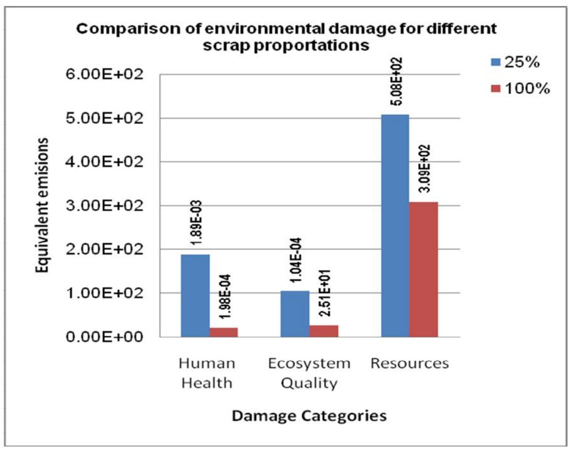


Fig. 4 Comparison of Environmental Damage

With the use of 100% re-cycled material as charge , the fresh sand transportation in extraction phase affects fossil fuel extraction, ecotoxicity and acidification. Emissions from manufacturing phase mainly add to eco-toxicity and acidification. In induction furnace, it is due to emissions of sulphur and nitrous oxide during furnace operation and nickel, lead, nitrous oxide, chromium and sulphur dioxide during electricity production which is used to melt the charge. In all other processes, it is mainly due to the emissions of electricity production as mentioned above. The environmental emissions during use and end of life phase are unaffected by the proportion of secondary material use. In total, the damage to human health, ecosystem quality and resources are each reduced by 90%, 76% and 39% respectively while using 100% re-cycled material.

4. Conclusion and Recommendations

The present study provides a quantitative comparison of the energy usage and environmental damage for a hypothetical automobile component produced by sand casting with two different proportions of recycled material using Eco-indicator 99 (E) method. The energy and environmental performance of the cast product improves with the use of 100% re-cycled material. For a proportion of 25% secondary material in the charge, extraction phase dominates in energy usage compared to manufacturing phase due to energy used in transportation of raw materials and fuels. To reduce transportation energy and improve the performance in fossil fuel impact category, the foundry must be located as close to the raw material, fresh sand and fuel supply vendors. Energy usage in manufacturing phase is dominated by blast and cupola furnace due to large amount of coke usage. The use phase energy depends on the vehicle life and is proportional to part weight for same volume. The location of scrap yard from foundry affects energy use in end of life phase. Emissions in the various phases mostly affect resources damage category mainly due to the extraction of fuel for transportation in extraction and use phases and that of ore and coal for its use in manufacturing phase. A variety of emissions during all the four phases mainly add to impacts of ecotoxicity, acidication and fossil fuel.

LCA is a tool that must be used at the early stages of product design to improve its the energy and environmental performance. The designers can choose the alternative materials/processes which satisfy environmental aspects apart from other functional aspects. Part design modification for material saving is one way to control energy usage and environmental impacts. This is referred to as de-materialization. Choosing lighter material without affecting the intended function may be another way to do so but needs careful evaluation of all the phases . This analysis is based on some logical assumptions and the databases developed and used by various international agencies like CERP, NREL and the data collected from industries. These data may be updated from time to time along with the electricity mix which may also change and so the analysis must be updated accordingly. The choice of process parameters like core and mould making methods, sand to metal ratio and casting yield are yet to be explored. The study can be extended to other materials and processes like pressure die, lost wax and centrifugal casting.

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