CHAPTER 7

ENVIRONMENTAL IMPACT ASSESSMENT OF MILLING PROCESS

This chapter presents life cycle analysis of a milling process using Umberto NXT LCA software.

7.1 INTRODUCTION

Life cycle assessment (LCA) is a proven technique for scientifically evaluating the environmental impacts of products and processes. The assessment generally starts from raw materials extraction and ends up after the final disposal of the used product (Klöpffer, 1997). Every product/process life cycle involves consumption of various natural resources and energy; and emission of hazardous pollutants to the environment (Huijbregts et al., 2016). LCA is used to measure the environmental impacts across the product and process life cycles (Sangwan, 2006). LCA visualizes the major hotspots throughout the life cycle stages of a product/process, thereby supporting the decision makers to reduce the environmental impacts by alternative materials and/or processes. In this context, this chapter presents a life cycle analysis of a milling process to evaluate and quantify its environmental impacts.

The research community has addressed the life cycle analysis of machine tools to quantify their environmental emissions during their life cycle (Cao et al., 2012; Diaz et al., 2010; Song et al., 2010), but the environmental impacts of actual machining process have not been addressed effectively. Cao et al. (2012) presented a carbon efficiency approach to quantify the carbon emissions caused by the machine tools during their life cycle. It was observed that the fixed emissions can be reduced by light weight design and remanufacturing, while the variable emissions can be reduced by improving the machining process planning. Diaz et al. (2010) calculated the energy consumption and CO_2 emissions for two machine tools during four life cycle phases of manufacturing, transportation, use, and end of life (EOL). The life cycle assessment studies for a machining process are not available. In the present study, life cycle analysis of a milling process was conducted to evaluate the environmental impacts to produce a sample product, which was used in the case study of chapter 5. The life cycle analysis of milling process encompassed raw material (aluminum), consumables (cutting tool, coolant, lubricating oil), transportation (raw material, consumables, finished goods, waste), electricity (machining and HVAC), treatment/disposal (used product, chip processing, worn out cutting tool, used coolant and lubricant), and share of machine tool and factory infrastructure. A sequence of milling operations was performed on a workpiece to produce the sample part, as explained in chapter 5. The case study found the major hotspots and appropriate strategies to mitigate the environmental emissions and hence, saving energy and natural resources. The materials and method section discusses the LCA approach in details.

7.2 MATERIALS AND METHOD

The LCA analysis of the milling process was carried out by utilizing ISO 14040 standard (ISO 14040, 1997). LCA consists of four steps in its systematic approach as suggested by the ISO 14040 series standards – goal and scope definition, inventory analysis, impact assessment, and interpretation (Kellens et al., 2012) – as shown in Figure 7.1. Rebitzer et al. (2004) discussed the ISO 14040 series standards in detail for different applications as: ISO 14040 (1997) for principles and framework, ISO 14041 (1998) for goal and scope definition and inventory analysis, ISO 14042 (2000) for life cycle impact assessment, and ISO 14043 (2000) for life cycle interpretation.

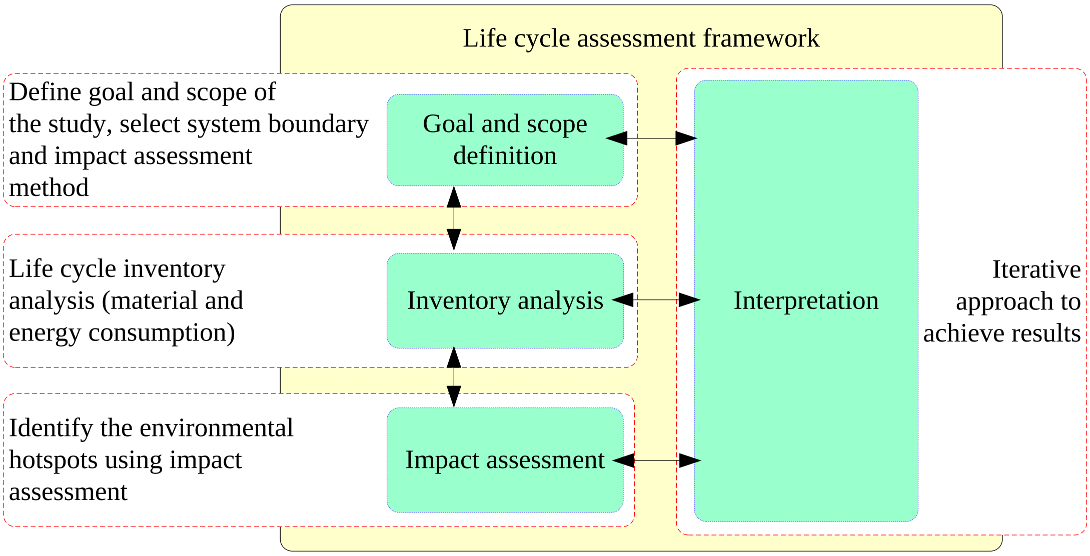

Figure 7.1 Life cycle assessment framework (adapted from Rebitzer et al., (2004))

The environmental impacts of the milling process were assessed with the help of Umberto NXT universal (IFU Hamburg, 2015) software tool and Eco-invent dataset version 3 (Swiss Centre for Life Cycle Inventories, 2017). The well-known ReCiPe method was employed for both midpoint and endpoint assessments of inventories. ReCiPe method is known for its harmonization at both midpoint and endpoint levels (Huijbregts et al., 2016). It covers a wide range of midpoint and endpoint categories, which are useful to envisage the several environmental impacts. The ReCiPe method of impact assessment is an upgrade of eco-indicator and CML method (Goedkoop et al., 2009).

7.2.1 Goal and Scope Definition

The goal of the study is to analyze the environmental impacts generated by milling process for production of the sample part.

7.2.2 Functional Unit and System Boundary

The functional unit selected for the study is removal of 0.1 kg of aluminum as chips using end mill machining to generate the desired component shape. The system boundary for the study is shown in Figure 7.2. It consists of pre-manufacturing (raw material acquisition and transportation), manufacturing, and post-manufacturing (delivery, use and end of life). The end of life of the milling process involves chip processing, treatment/disposal of worn out cutting tool, used lubricant and coolant. The system boundary also includes the effect of infrastructure (technical building services, equipment, and compressed air) and machine tool depreciation. The operational system boundary of the analysis is considered as one year.

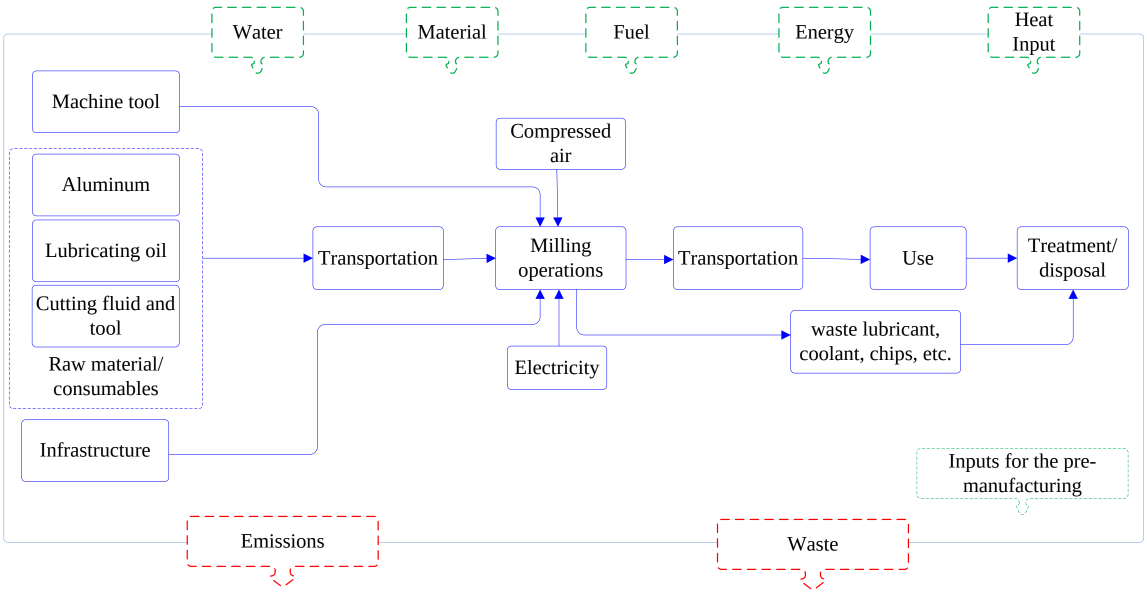

Figure 7.2 System boundary for the life cycle analysis of the milling process

7.2.3 Reference Factory and HVAC System

The energy and resource requirement for the milling process to produce the sample part were identified by experimental evaluation and empirical relations. For the calculation of the heating, ventilation and air conditioning (HVAC) system, a reference factory with a floor size of 20 x 50 m^2 for 10 CNC machines has been defined. Small logistics places close to the machine tools are included as shown in Figure 7.3. The insulation technology used in the reference factory meets the current state-of-the-art for new non-residual buildings, which is 0.28 [W/m^2*K] for opaque parts in areas with temperatures above 19 °C.

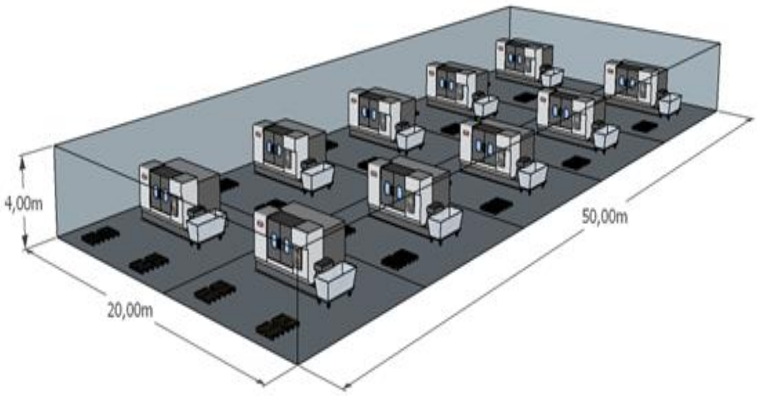

Figure 7.3 Schematic outline of the reference factory building

The air conditioning need of the reference factory was assessed based on the degree days. The degree days are widely used to assess the heating and cooling needs as this data is easily available for most of the locations in the world and further local measurements are not needed. Heating degree days (HDD) describe how much and how long the temperature was below a base temperature, while cooling degree days (CDD) describe how much and how long the temperature was above a base temperature (CIBSE, 2006). The energy demand for cooling (Q_C) is estimated as follows (CIBSE, 2006):

$$Q_C = \frac{\dot{m} * c * 24 * CDD}{COP} \qquad (7.1)$$

where $\dot{m}$ is the mass flow rate through the cooling system, c is the heat capacity of air, COP is the coefficient of performance. In the present study, the local electricity mix was used for the cooling purpose and a base temperature of 26°C was selected for calculation of the energy required for temperature conditioning. The energy demand of HVAC system for machining of 1 kg aluminum in the reference factory was calculated to be 0.955 kWh.

7.2.4 Inventory Analysis

The inventory analysis for 0.1 kg aluminum machining was carried out as described in Table 7.1. Primary data for the inventory analysis was collected using real time experimentations on a vertical milling center (details of the machine tool are given in chapter 3). Secondary process and material specific data was collected using contemporary literature and lab manuals. The coolant used was a mixture of mineral based soluble oil and water.

The inventory analysis, as shown in the Table 7.1, was divided into basic resources (materials, energy sources and water) and related waste. The main aim of the study is to assess environmental impacts of the milling process and therefore man and money resources were not included in the scope of the study. The aluminum material removed in the form of chips was considered for calculation of raw material processing and disposal.

Table 7.1 Inventory table for LCA of a milling process

Inventory	Unit	Quantity
Lubricating oil	kg	0.00382
Aluminum	kg	0.10
Share of metal working factory	unit	2.02E-10
Share of metal working machine	kg	0.000174
Transportation of raw material	kg-km	200
Compressed air	m^3	1.28
Water cooling	m^3	0.02
Mineral oil	kg	0.132
Electricity for environment conditioning	kWh	0.01
Electricity for milling	kWh	0.57
High speed steel for cutting tool	kg	0.014
Transportation of finished part to consumer	kg-km	200
Aluminum scrap	kg	0.10
Waste mineral oil	kg	0.1352
Transportation of chips for treatment	kg-km	50
Waste water treatment	m^3	0.02

The inventory data shown in Table 7.1 was assumed to provide essential process requirements to carry out the milling process and associated transportation activities. Life of the vertical milling machine tool was assumed to be 20 years for estimation of the share of the machine tool depreciation during the milling process of the sample product. The cutting tool used for the milling process was measured to have a capability to produce 10 similar components with the same sequence of operations as considered in the study, without compromising the surface characteristics. The electricity used for environmental conditioning was calculated as explained in section 7.3.4. The electricity consumption for the study was considered as Indian electricity mix from the eco-invent dataset version 3 (Swiss Centre for Life Cycle Inventories, 2017). The inventory dataset for raw material acquisition (aluminum, lubricating oil, water, mineral oil, compressed air, etc.) was obtained from eco-invent dataset contained in Umberto NXT Universal software.

7.3 RESULTS AND DISCUSSION

The environmental impacts of the milling process were assessed using both midpoint and endpoint impact assessment methods. The well know ReCiPe method for both midpoint and endpoint impact assessment was utilized to assess the local, regional and global environmental impacts of the milling process. Local impacts majorly include: air and noise emissions, land area changes, and impacts on local ecosystem by means of metal mining or other related activities. If the metal mining activities are carried out at far off locations rather than the vicinity region, the effect will be more regional than local. The effect of NO_x and SO_x pollutants in the environment due to the manufacturing activities may cause acid rains, which is also a regional impact. The various environmental emissions by manufacturing activities, which result in long-term distortion of environment, are global level impacts. These environmental burdens are classified as climate change or sometimes as global warming, acidification, eutrophication, human toxicity, etc.

The environmental impacts categories selected in the endpoint assessment are: resources, human health and ecosystem quality. The environmental impacts categories selected to carry out the midpoint assessment are: climate change (CC), fossil depletion (FDP), human toxicity (HTP), metal depletion (MDP), natural land transformation (NLTP), ozone depletion (ODP), particulate matter formation (PMFP), and water depletion (WDP).

7.3.1 Endpoint Assessment

The endpoint assessment results for the major activities of the milling process are shown in Figure 7.4. It is observed that the aluminum production and electricity consumption are major environmental impacting factors for the milling process followed by compressed air and cutting fluid. Figure 7.4 shows that the highest impacts are found in the human health category, particularly from the aluminum production and electricity consumption. Figure 7.5 shows the endpoint assessment results for five phases (raw material, transportation, machining, delivery, and end of life).

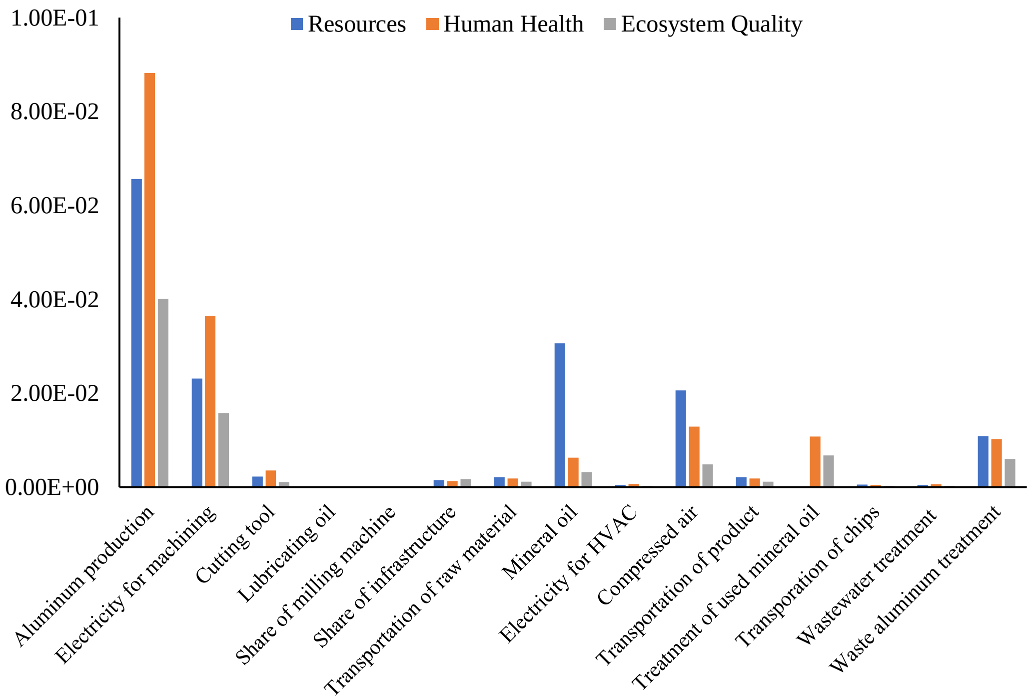

Figure 7.4 Endpoint environmental impact assessment of the three categories

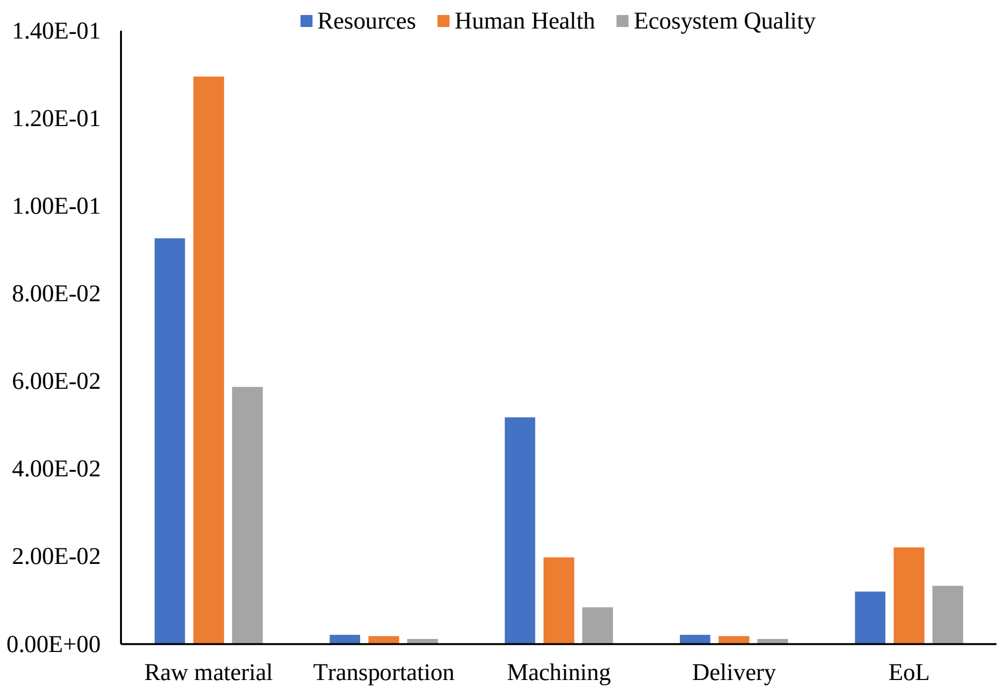

Figure 7.5 Endpoint environmental impact assessment of five life cycle phases

It is clearly visible from Figure 7.5 that raw material phase has major environmental impacts followed by the milling process and end of life disposal/treatment. Tables 7.2 and 7.3 present the actual values of endpoint assessment results of milling process in terms of the life cycle phases and activities, respectively.

Table 7.2 Endpoint assessment results of LCA phases

Phase↓	Resources	Human Health	Ecosystem Quality
Unit→	Points	Points	Points
Raw material	9.26E-02	1.30E-01	5.87E-02
Transportation	2.13E-03	1.81E-03	1.14E-03
Machining	5.17E-02	1.98E-02	8.37E-03
Delivery	2.13E-03	1.81E-03	1.14E-03
EoL	1.20E-02	2.21E-02	1.33E-02

Table 7.3 Endpoint assessment results of the milling process

Activity↓	Resources	Human Health	Ecosystem Quality
Unit→	Points	Points	Points
Aluminum production	6.56E-02	8.82E-02	4.01E-02
Electricity for milling	2.32E-02	3.65E-02	1.57E-02
High speed steel for cutting tool	2.24E-03	3.52E-03	1.12E-03
Lubricating oil	9.03E-05	1.61E-05	2.00E-05
Share of milling machine tool	1.61E-05	7.37E-06	2.88E-06
Share of infrastructure	1.50E-03	1.31E-03	1.72E-03
Transportation of raw material to facility	2.13E-03	1.81E-03	1.14E-03
Mineral oil for coolant	3.07E-02	6.25E-03	3.21E-03
Electricity for environment conditioning	4.46E-04	6.95E-04	2.99E-04
Compressed air	2.06E-02	1.29E-02	4.86E-03
Transportation of finished material to consumer	2.13E-03	1.81E-03	1.14E-03
Treatment of waste mineral oil	1.59E-04	1.08E-02	6.75E-03
Transportation of waste to treatment	5.33E-04	4.53E-04	2.84E-04
Wastewater treatment	4.47E-04	6.24E-04	2.68E-04
Waste aluminum treatment	1.08E-02	1.02E-02	6.01E-03

7.3.2 Midpoint Assessment

The midpoint assessment results of the study show similar trends as the endpoint assessment results. The high impact activities in descending order are as follows: aluminum production, electricity consumption, treatment and production of cutting fluid, compressed air, chip processing, and cutting tool production. Figure 7.6 presents the midpoint impact assessment of the milling process in the selected categories (CC, FDP, HTP, MDP, NLTP, ODP, PMFP, and WDP). It is observed that in natural land transformation (NLTP), ozone depletion potential (ODP), particulate matter formulation (PMFP), and water depletion potential (WDP) categories, the environmental impacts are negligible as compared to the other categories. The majority of the environmental impacts are in terms of climate change (CC) followed by the fossil depletion potential (FDP), metal depletion potential (MDP), and human toxicity potential (HTP).

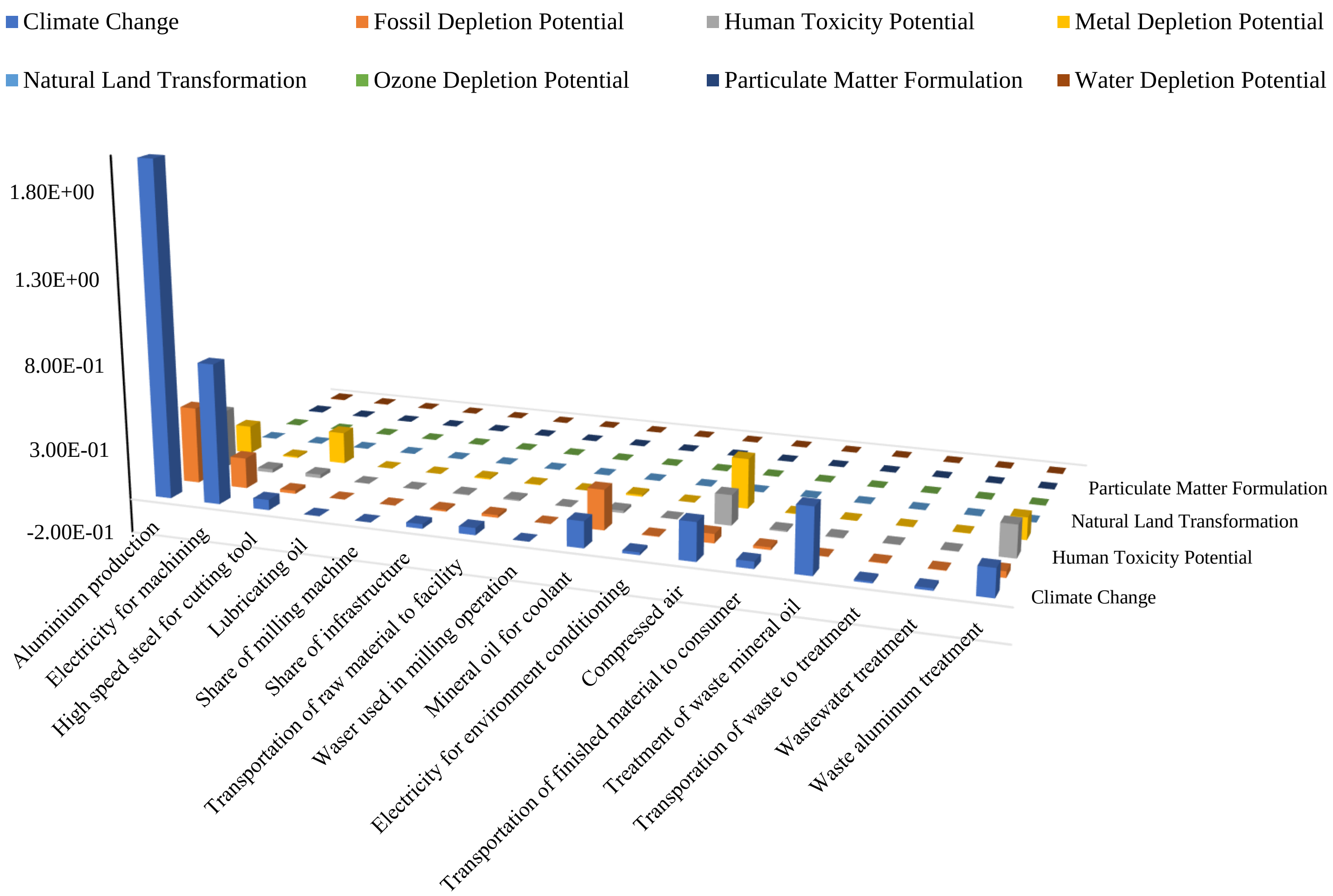

Figure 7.6 Midpoint environmental impact assessment results

Figure 7.7 shows the midpoint assessment results of various phases of the milling process. It is observed here that the raw material phase is again the high impact phase in the milling process, followed by milling process and end of life. The transportation and delivery of raw material and finished goods have relatively less impacts. The climate change, fossil depletion potential, human toxicity, and metal depletion potential categories show significant impacts. The absolute values of the environmental impacts for all LCA phases and activities under eight mid-point assessment categories are given in Tables 7.4 and 7.5, respectively.

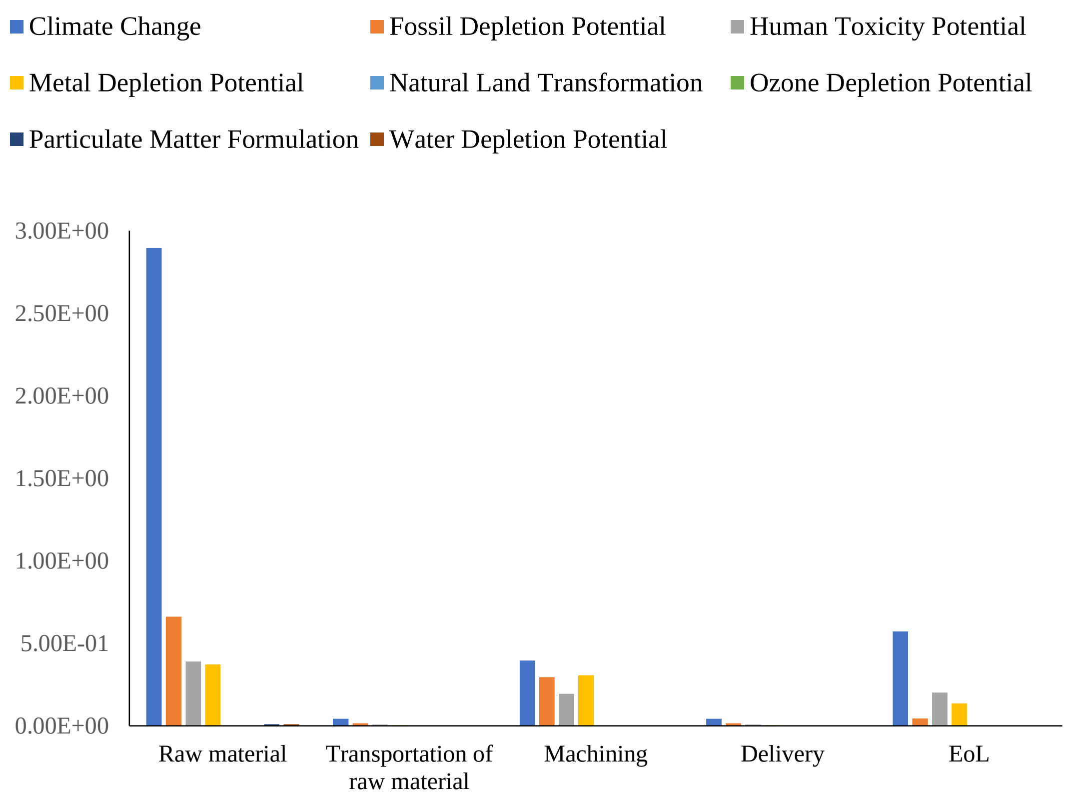

Figure 7.7 Midpoint assessment results of as per machining phases

7.4 PRACTICAL IMPLICATIONS AND RECOMMENDATIONS

The LCA analysis of the milling process provided a clear visualization of hotspots for environmental impacts. The aluminum production, electricity consumption, cutting fluid production and disposal, compressed air, and chip treatment are found major factors causing environmental impacts. It is observed from the results that the major impacts in aluminum production are due to carbon dioxide emissions, sulfur hexafluoride, methane, ethane-hexafluoro (HFC-116), and dinitrogen monoxide emissions. However, the focus of the present study is assessment of environmental impacts of the milling process and therefore the material processing impacts and their reduction strategies are not discussed in detail. It is evident from the analysis that the energy consumption plays a major role in the environmental impacts by the milling process directly (for material removal) and indirectly (compressed air production and HVAC system). Therefore, reduction in energy consumption plays a major role in reducing the environmental impacts of the milling process.

Table 7.4 Midpoint assessment results for the milling process (phase wise)

Activities↓	**Climate Change**	**Fossil Depletion Potential**	**Human Toxicity Potential**	**Metal Depletion Potential**	**Natural Land Transformation**	**Ozone Depletion Potential**	**Particulate Matter Formulation**	**Water Depletion Potential**
Units→	kgCO_2 Eq.	kgOil -Eq	kg1,4-DCB Eq.	kgFe-Eq.	m^2	kgCFC-11-Eq	kg PM10-Eq	m^3
Raw material	2.90E+00	6.60E-01	3.89E-01	3.73E-01	2.97E-04	6.19E-08	8.43E-03	8.84E-03
Transportation	4.18E-02	1.57E-02	8.05E-03	3.20E-03	1.58E-05	8.02E-09	1.04E-04	3.73E-05
Milling	3.96E-01	2.94E-01	1.94E-01	3.06E-01	2.20E-04	5.99E-08	1.13E-03	1.77E-03
Delivery	4.18E-02	1.57E-02	8.05E-03	3.20E-03	1.58E-05	8.02E-09	1.04E-04	3.73E-05
EoL	5.72E-01	4.45E-02	2.02E-01	1.35E-01	1.53E-04	3.53E-08	6.43E-04	1.52E-03

Table 7.5 Midpoint assessment results for the milling process

	Category							
Activities↓	**Climate Change**	**Fossil Depletion Potential**	**Human Toxicity Potential**	**Metal Depletion Potential**	**Natural Land Transformation**	**Ozone Depletion Potential**	**Particulate Matter Formulation**	**Water Depletion Potential**
Units→	**kgCO_2 Eq.**	**kgOil -Eq**	**kg1,4-DCB Eq.**	**kgFe-Eq.**	**m^2**	**kgCFC-11-Eq**	**kg PM10-Eq**	**m^3**
Aluminum production	1.98E+00	4.52E-01	3.42E-01	1.67E-01	1.89E-04	4.93E-08	5.47E-03	5.84E-03
Electricity for milling	8.28E-01	1.80E-01	2.08E-02	8.25E-03	3.40E-05	5.73E-09	2.57E-03	2.55E-03
High speed steel for cutting tool	6.06E-02	1.79E-02	2.17E-02	1.90E-01	-2.74E-06	2.98E-09	2.98E-04	3.71E-04
Lubricating oil	3.20E-04	6.94E-04	1.08E-04	5.65E-05	7.10E-07	3.68E-10	1.02E-06	8.07E-07
Share of milling machine	9.82E-05	2.44E-05	1.31E-04	2.80E-04	1.30E-08	6.97E-12	5.43E-07	6.81E-07
Share of infrastructure	2.70E-02	8.96E-03	4.15E-03	7.73E-03	7.60E-05	3.52E-09	9.47E-05	7.20E-05
Transportation of raw material to facility	4.18E-02	1.57E-02	8.05E-03	3.20E-03	1.58E-05	8.02E-09	1.04E-04	3.73E-05
Water used in milling process	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.56E-07
Mineral oil for coolant	1.55E-01	2.36E-01	1.49E-02	1.03E-02	2.01E-04	4.64E-08	2.96E-04	4.09E-04
Electricity for environment conditioning	1.57E-02	3.43E-03	4.86E-04	3.03E-04	6.48E-07	1.10E-10	4.90E-05	4.86E-05
Compressed air	2.25E-01	5.45E-02	1.79E-01	2.95E-01	1.81E-05	1.34E-08	7.83E-04	1.31E-03
Transportation of finished material to consumer	4.18E-02	1.57E-02	8.05E-03	3.20E-03	1.58E-05	8.02E-09	1.04E-04	3.73E-05
Treatment of waste mineral oil	3.84E-01	8.04E-04	4.29E-03	1.10E-03	3.57E-07	3.39E-10	1.37E-05	5.82E-04
Transportation of waste to treatment	1.04E-02	3.92E-03	2.01E-03	8.00E-04	3.96E-06	2.01E-09	2.60E-05	9.32E-06
Wastewater treatment	1.37E-02	2.76E-03	2.86E-03	2.02E-03	9.51E-07	5.56E-10	3.60E-05	1.25E-04
Waste aluminum treatment	1.64E-01	3.70E-02	1.92E-01	1.31E-01	1.48E-04	3.24E-08	5.68E-04	8.03E-04

7.5 SENSITIVITY ANALYSIS

Sensitivity analysis has been carried out to assess the robustness of the results obtained from the machining LCA study. In sensitivity analysis independent variable's value are varied and their effect on dependent variable is measured. Sensitivity analysis helps in establishing clear interpretation of results and assessing the robustness and transparency of results (Niero et al. 2014). Sensitivity analysis is carried out by varying the amount of materials and process inputs. In this study, the sensitivity analysis is performed by varying the values of seven materials and process inputs. The variation includes both increase and decrease in the values as presented in the Table 7.6.

Table 7.6 Actual and changed values of input variables for conducting sensitivity analysis

Process/ Raw material (percentage change in values)	**Unit**	**Actual values**	**Changed values for sensitivity analysis**
Lubricating oil (10% increase)	kg	0.00382	0.004202
Lubricating oil (10% decrease)			0.003438
Compressed air (10% increase)	m^3	1.28	1.408
Compressed air (10% decrease)			1.152
Mineral oil (10% increase)	kg	0.132	0.1452
Mineral oil (10% decrease)			0.1188
Transportation of finished part to consumer (10% increase)	kg-km	200	220
Transportation of finished part to consumer (10% decrease)			180
Waste mineral oil (10% increase)	kg	0.1352	0.1487
Waste mineral oil (10% decrease)			0.1217
Transportation of chips for treatment (10% increase)	kg-km	50	55
Transportation of chips for treatment (10% decrease)			45
Waste water treatment (10% increase)	m^3	0.02	0.022
Waste water treatment (10% decrease)			0.018

The sensitivity analysis results showed that the environmental impact results obtained in the LCA analysis are robust, as shown in Figure 7.8. The error bars show the variation in Climate Change impact with variation in input process parameters as mentioned in the Table 7.6.

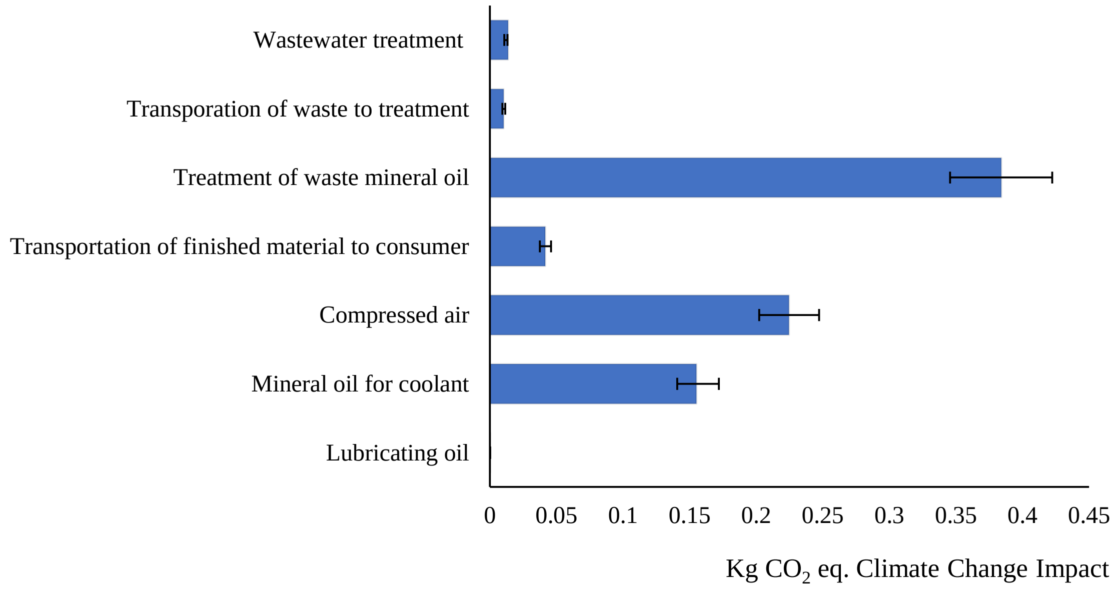

Figure 7.8 Sensitivity analysis results with actual and changed values of input variables

7.6 SUMMARY

This chapter presents life cycle analysis of a milling process to visualize the major hotspots contributing to the environmental impacts. The study was conducted to assess the environmental impacts of aluminum milling process for production of a sample part. The LCA analysis was carried out as per ISO 14040 standard by using Umberto NXT software tool and eco-invent dataset version 3.0. The scope of the study includes the production of raw material and consumables (cutting tool, coolant, lubricating oil), transportation (raw material, consumables, finished goods), electricity (machining and HVAC), treatment/disposal (used product, chip processing, worn out cutting tool, waste coolant and lubricant), and share of machine tool and factory infrastructure for machining. The environmental impacts were assessed in both endpoint and midpoint impact assessment categories by using ReCiPe method. Raw material production, electricity consumption, cutting fluid production and disposal, chip processing, and compressed air production are the high impact generating activities of the milling process. The major impacts are in terms human health and resources depletion. The effects on climate change, fossil depletion, human toxicity, and metal depletion categories are also high. This analysis can be used as a foundation for formulation of the key plans for environmental sustainability improvement of machining processes.