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The Influence of Manufacturing Plant Site Selection on Environmental Impact of Machining Processes

Nitesh Sihag[a]*, Alexander Leiden[b], Vikrant Bhakar[c], Sebastian Thiede[b], Kuldip Singh Sangwan[a], Christoph Herrmann[b]

[a]*Birla Institute of Technology and Science Pilani, Pilani Campus, Rajasthan, India - 333031*
[b]*Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, Langer Kamp 19b, 38106 Braunschweig, Germany*
[c]*Indian Institute of Technology Ropar, India- 140001*

* Corresponding author. Tel.:+91-9461245852; fax: +91-1596-244183. E-mail address: p2014009@pilani.bits-pilani.ac.in

Abstract

Sustainability has become an important aspect in the strategic planning of manufacturing organizations due to rising energy cost, climate change, environmental emissions, and carbon tax policies. Most of the large manufacturing organizations have a worldwide network of factories, which is mainly driven by financial and political aspects. In past few decades, many attempts have been made to improve the sustainability of the manufacturing processes with consideration of carbon efficiency, energy efficiency, and cost effectiveness. The influence of the manufacturing plant site on the environmental sustainability of the manufacturing process is not considered in most site selection decisions despite its importance in improving the sustainability of production networks. This paper investigates the site based factors to influence the environmental sustainability of a machining process and the effect of these factors is analyzed using life cycle assessment. A case study is conducted with eight different cases based on the location of raw material, manufacturing site, and customers in India and Germany. Four key influencing factors are identified and the environmental impact of the milling process is assessed. One of the key findings is the significant influence of climate and the supply chain on the environmental sustainability of the machining process. This study can be used to include the environmental performance of the machining process into the strategic planning of new manufacturing plants.

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Keywords: Sustainability; Machining; Manufacturing; Location Planning, Life Cycle Assessment.

1. Introduction

Manufacturing activities are inherently connected with the consumption of energy and resources. In 2012, the industrial sector consumed 54.4% of the net global energy consumption; with manufacturing as key energy consuming subsector [1]. The manufacturing activities also release large amounts of solid, liquid and gaseous wastes, and pollutants leading to significant environmental impacts [2]. In this context, the motivation towards a more sustainable manufacturing approach to reduce the environmental impact of the manufacturing sector arises. The most cited definition for sustainable manufacturing comes from the US Department of Commerce as “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” [3-4]. Responsible consumption and production is also one of the 17 sustainable development goals from the United Nations [5]. Mittal et al. [6] showed that Indian and German manufacturing companies show a high interest in environmentally conscious manufacturing and are motivated to consider the environmental performance of manufacturing processes into their decisions.

Manufacturing outsourcing is an important factor for successful business strategies. Although outsourcing to

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developing economies is cost efficient, but it has serious environmental concerns [7]. The manufacturing facility location and outsourcing are likely to influence the manufacturing activities and their environmental impacts [8].

Nowadays, financial and market aspects are the main drivers for strategic location planning. The facility site is selected based on labor cost, market access, raw material availability, tax incentives, and government subsidies [9-11]. The unforeseen environmental aspects of facility site are rarely considered [8]. A few studies presented generic approaches to consider environmental aspects in facility location selection [7,12]. But the machining processes were not focused.

In sustainable manufacturing context, the environmental impact is defined as all adverse or beneficial changes to the environment as a result of an organizations aspects [13]. The environmental impact of machining processes might be influenced by site specific factors such as climatic conditions, supply chain, energy mix, and waste recycling technologies. Machining processes are realized worldwide and involve global supply chain network to procure the required raw and auxiliary materials. In the present study, the important factors influencing environmental impacts of a machining process are identified and their influence is quantified. This study can be used to include the environmental perspective into the strategic facility site planning.

2. Methodology

A three step approach is used in the present study to investigate the environmental impacts of a machining process based on facility site specific factors.

- Identification of the site specific environmental factors
- Development of mathematical models for these factors.
- Assessment of the environmental impacts generated by a machining process based on these factors using life cycle assessment.

2.1. Identification of site specific environmental factors

In the first step, the factors influencing the environmental sustainability of a machining process are identified. Fig. 1 shows the energy and resource flows for a machining process. Additionally, the Technical Building System (TBS) of a factory with Heating, Ventilation and Air conditioning system (HVAC) and the supply chain are important aspects affecting the environmental performance of a machining process.

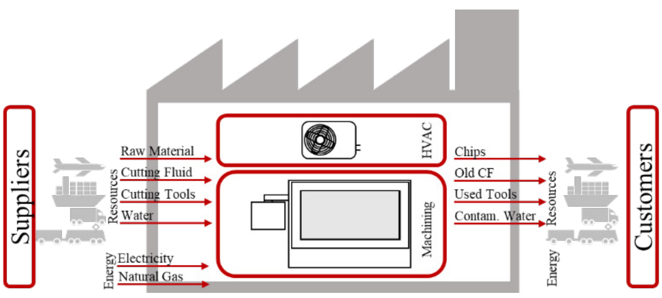

Fig. 1. Energy and Resource Flows

Each element of energy and resource flows is influenced by multiple factors depending on the site of the factory. The energy efficiency of manufacturing processes and the technical building systems is influenced significantly by the climate, energy source and cost, and distance travelled [14]. Four key influencing factors are identified in the present study, which affect the environmental performance of machining process: supply chain, climate, available energy type, and waste recycling technology (Fig.2).

The supply chain involves the distance from the factory to raw material suppliers and customers, and mode of transportation. The availability of transport facilities (e.g. port, airport, and rail network), the distance to support facilities (e.g. maintenance services, spare part warehouses) and availability of auxiliary resources (e.g. cutting fluids and tools) depend on the factory location. The climatic conditions influence the energy required for HVAC system of the factory building and the machine tools. Especially, facility sites with extreme climatic conditions require intensive heating or cooling activities. Availability of water resources is also important as it is an important resource for material processing and cooling during machining processes.

The third important factor influencing the environmental impact of a machining process is the type of energy mix available at the factory site. CNC machine tools consume electrical energy for various operations. The environmental emissions generated due to electricity production depend on the plant location, resources and technology used. Fossil fuel based power plants generate significantly higher emissions as compared to renewable energy (wind, solar etc.) based power plants. Fourth key factor is the distance of the disposal and recycling facilities from the facility site; and recycling technology used. Strict environmental policies generally enforce the availability of high standard recycling and disposal facilities.

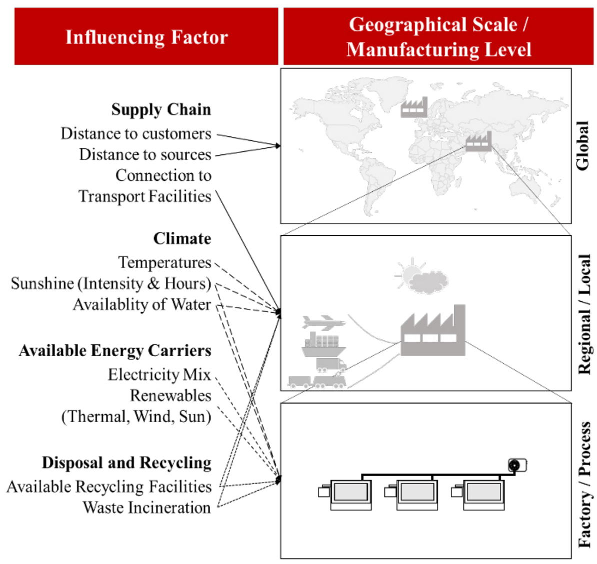

Fig. 2. Factors influencing the sustainability of a machining process

2.2. Development of mathematical models of influencing factors

In the second step, the identified influencing factors are computed by experimental evaluation and empirical models. The impact of supply chain is computed based on the mode of transportation, weight of the material, and distance travelled.

The energy and resource consumption for machining process are determined experimentally. A reference factory design is developed to calculate the energy demand for the HVAC system. The details of the reference factory and HVAC system are given below.

2.2.1. HVAC and reference factory

The energy demand for heating and cooling a factory building depends on the factory building design and the building materials [10, 15]. Degree days are considered as a measure to compare the temperature variations between different locations Heating Degree Days (HDD) describe the degree and duration for which the temperature was below a base temperature. Cooling Degree Days (CDD) describe the degree and duration for which the temperature was above a base temperature [16]. The energy demand for heating can be estimated by the following formula (1).

$$Q_h = \frac{U' * HDD * 24}{\eta} \ [kWh] \quad (1)$$

where, *U'* is the specific thermal transmittance of the factory which describes the heating or cooling losses coefficient of the factory building (W*m²/K), and η is the efficiency of the heating system. The specific U-value depends on the building shell and the HVAC system. It is calculated as

$$U' = \frac{A * U + {}^{1}/_{3} * N * V}{1{,}000} \ [\frac{kW}{K}] \quad (2)$$

where, *A* is the total building area, *U* is the average thermal transmittance of the building components, *N* is the air infiltration rate per hour and *V* is the volume of the factory. The energy demand for cooling is calculated as

$$Q_C = \frac{\dot{m} * c * 24 * CDD}{COP} [kWh] \quad (3)$$

where, $\dot{m}$ is the air mass flow through the cooling system, *c* the heat capacity of air, and *COP* is the coefficient of performance. The air mass flow $\dot{m}$ depends on the design of the cooling system. [16].

For this study, it has been assumed that heating is done using a natural gas system and cooling is done using electrical energy. Base temperatures for heating and cooling are selected as 18 °C and 26 °C respectively. Both temperatures meet the German requirements for temperatures in factories and ensure a convenient environment for the workers [17].

2.2.2. Supply Chain

The transportation of raw materials and finished goods to and from the manufacturing plant is directly influenced by the plant location. At present, most of the transportation modes (rail, road, water, air) operate using fossil fuels. The transportation of the raw materials and manufactured products is facilitated using trucks, trains and vessels. Air transport is rarely used because of high cost per weight and strict security requirements. The selection of the transportation mode for international transfers is often based on the natural environment of the location [18].

2.3. Life cycle assessment

The environmental impacts of a machining process based on the four site specific factors is analyzed using life cycle assessment (LCA) method. LCA is a tool to quantify the environmental impacts associated with a process or product throughout its life cycle [19-21]. Hauschild [22] provides the two important reasons to adopt LCA approach: (i) LCA offers a sound methodology to interlink life cycle phases and (ii) LCA framework offers a sound scientific basis for quantitative assessment of environmental impacts generated under different mutually exclusive categories (i.e. climate change, ozone depletion, acidification, etc.). The LCA provides the impacts beyond the carbon footprint analysis. It has been widely used for environmental impact assessment of various products and processes [23-25]. In the present study, LCA is used to compare the environmental impacts of machining processes located at different sites (see section 3.1-3.4). It can assist in selection of a suitable factory location from an environmental perspective.

3. Application of the proposed methodology

The application of the proposed methodology is illustrated with a case study to compare the environmental impacts caused by machining activities based at two different factory locations; Braunschweig (Germany) and Jaipur (India). In both cities typical manufacturing plants of small, medium and large scale are located. The environmental sustainability of machining activities at the two locations is investigated under eight different scenarios based on the location of raw material availability, manufacturing facility, and market, as given in Table 1.

In the present study, the environmental impact of a unit milling process was assessed for a standard milling operation. The machining activities commonly use recycled metals as the raw materials. It is assumed here that the raw material is available in either Jaipur or Braunschweig. The energy and resources consumed for removing one kg of the material by milling are calculated by experimental evaluation and empirical relations.

For energy calculation of milling process, a simple face milling operation is performed on an aluminum block (10cm*10cm*10cm). The cutting parameters are set as, cutting speed = 2000 RPM, feed = 200 mm/min, depth of cut = 1 mm, and width of cut = 6mm.

Table 1. Location of raw material, factory, and consumer in eight scenarios

Case	Raw material	Manufacturing	Consumer
1	GER	GER	GER
2	IN	GER	GER
3	IN	IN	GER
4	IN	IN	IN
5	IN	GER	IN
6	GER	GER	IN
7	GER	IN	GER
8	GER	IN	IN

The machining constraints within the system boundary like the production schedule, process parameters, and cutting conditions are kept same for both locations to ensure the comparability. A reference factory of 20*30 m² (total volume of 4,000 m³) with 10 CNC machine tools is defined to calculate the energy demand of HVAC system. Small logistics places close to the machine tools are included in the design (see visualisation in Fig.3). The insulation technology used for the reference factory meets the current requirements for new German non-residual buildings, i.e. 0.28 [W/m²*K] for opaque areas with temperatures above 19 °C [26]. The air is filtered two times per hour (N=2). The energy demand of HVAC system is calculated as explained in section *2.2.2*. The two plant locations selected for the present study lie in very different climatic conditions. According to the climate classification system defined by Köppen and Geiger [27], Braunschweig is located in a temperate climate zone without dry season and warm summer (Cfb) whereas Jaipur is located in a semi-arid hot climate zone (BSh). Therefore, the HVAC system consumes more energy in Braunschweig for heating in winter whereas in Jaipur energy consumption is higher in summer for cooling the factory. The energy calculation for heating and cooling at both locations is shown in Table 2. The energy demand in Braunschweig is higher due to the intensive heating activities in winter, but the energy demand for cooling is negligible. In Jaipur, the energy demand for cooling dominates, but is still lower than the heating energy demand in Braunschweig. These factors are considered carefully to carry out the LCA of machining processes. LCA analysis is carried out using Umberto NXT software and Ecoinvent 3 database.

The supply chain between these locations is realized with trucks and vessels. Trucks are used for road transportation, i.e. From Braunschweig to Hamburg port (250 km) and from Mumbai port to Jaipur (1,200 km). The transportation between Hamburg and Mumbai (12,500 km) is facilitated with container ships. The goods to be transported for the machining process include raw material, chips and finished product.

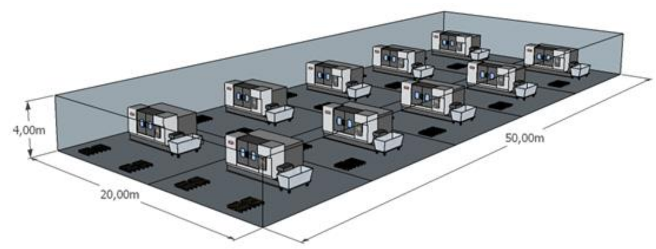

Fig. 3. Sketch of reference factory building

Table 2. Energy demand of HVAC for machining 1 kg aluminum.

	Cooling to 26 °C (MJ)	Heating to 18°C (MJ)
Braunschweig	0.09	6.51
Jaipur	3.44	0.28

3.1 Goal and scope

The objective of the present study is to assess the impact of factory location on the environmental sustainability of a machining process. In this study, the environmental sustainability of a milling process at a factory located in Germany (Braunschweig) and India (Jaipur) is investigated under eight different scenarios. The focus is set on the processes which are influenced by location specific factors. The study models the differences among the eight manufacturing cases and hence the processes which are same for each case are excluded from the analysis (for example, raw material extraction, cutting tool production, etc.). However, the transportation of raw material is included in the analysis. The LCA has been carried out using ISO 14040 (ISO, 1997) framework. The LCA framework from ISO 14040 contains four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation.

3.2 System boundary and functional unit

The functional unit for conducting LCA is defined as 1 [kg] of aluminum removed by milling. 5 [kg] of raw material is used to obtain 4 [kg] of final product assuming 20% of material loss in form of chips, with identical process parameters at both locations. The reference factory has been defined in section 2.2.

The impacts generated due to consumption of direct electricity, lubricating oil, compressed air, HVAC system, machine and factory infrastructure and operation has been included in the analysis. The treatment of waste lubricant oil is also included. Raw material extraction, cutting tool production and disposal, chip treatment has been excluded from the system boundary. However, the supply chain for raw material and chips has been included in the study. The system boundary for the present study is shown in Fig. 4.

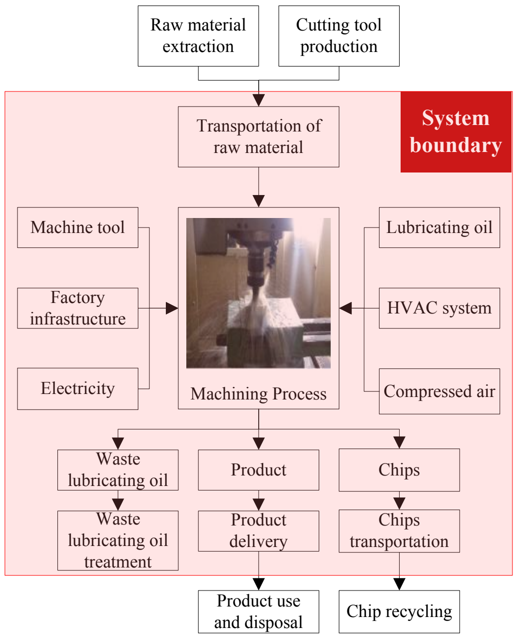

Fig. 4. System boundary

3.3 Inventory analysis

The primary data for the LCA study is collected by performing actual machining experiments and measuring the different energy and resource flow. The secondary data for the study have been collected using online data sources, literature, etc. Both primary and secondary data has been combined to develop the life cycle inventory analysis for the study.

3.4 Impact assessment

For the impact assessment, well known ReCiPe method with end-point and mid-point assessment categories has been used. The categories used for end-point assessment are human health and resources. For mid-point seven categories are selected: climate change (CC) [kg CO_2-eq.], fossil depletion (FP) [kg oil-eq.], human toxicity (HT) [kg1,4-DCB-eq.], metal depletion (MD) [kg Fe-eq.], natural land transformation (NLT) [m^2], ozone depletion (ODP) [kg CFC11-eq.], and particulate matter formation (PMF) [kg PM10-eq.].

4. Results and Discussion

4.1 Mid-point assessment

Mid-point assessment is used to explain the environmental impacts with different units for each impact category unlike a single unit index in end-point assessment. The mid-point assessment results for only Case 1 are shown in Fig. 5 and discussed in detail here for brevity. It is observed that electricity consumption is the most dominating process for the impacts generated in climate change category followed by heating, road transportation and lubricating oil production. The impact on climate change is majorly due to emission of harmful gases like CO_2, CH_4, and N_2O. Fossil depletion also has a major share of electricity followed by heating and road transportation.

Compressed air is responsible for almost 70% of the impacts generated in metal depletion category. Detailed inventory analysis shows that extraction and usage of metals like copper, nickel, chromium, iron for compressed air production causes high impacts on metal depletion. Also, more than 70% of the impacts generated in human toxicity category is caused by compressed air consumption. This is because of extraction of Arsenic, lead, cadmium, mercury, hydrogen fluoride, phosphorous, and manganese. Natural land transformation is majorly impacted by the factory infrastructure due to forest transformation. Ozone depletion has a major share of road transportation and heating activities. Compresses air production, factory infrastructure, and road transportation are the key activities to affect particulate matter formation. Similarly, the results of mid-point assessment for other cases can be analyzed.

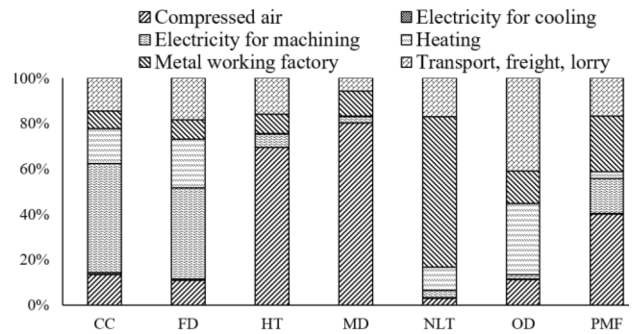

Fig. 5. Mid-point assessment results

4.2 End-point assessment

The end-point assessment results under human health and resources categories are shown in Fig.6. It is observed that the maximum environmental impacts are generated in case 7. Land transportation and electricity consumption for machining and cooling are dominant activities here. The travel distance in India is high and therefore more fossil fuels are consumed resulting high environmental impact. The electricity consumption for cooling is also more in the high temperature conditions like India. In addition, the emission factor of Indian electricity mix is higher because of dominance of coal based power plants. Therefore, electricity consumption generates high impact in human health and resources categories. The impact caused by cases 3 and 8 are similar because of equal transportation and same working conditions. In case 4, road transportation dominates in the resources category and electricity consumption dominates in human health.

Case 5 generates second highest impact in resources category after case 7. This is because cases 5 and 7 involve highest land and water transportation. Land transportation generates high impact in resource category because of fossil fuel consumption. Sea transportation causes more impact in human health category because of high emission of CO_2, NO_2, SO_2, CH_4, and particulate matters during sea transportations. In cases 2 and 6, road transportation is the most impacting activity followed by electricity consumption. In case 1, electricity consumption is the most impacting activity in both categories, whereas in the other cases the impact of transportation is high due to large travel distances. It is observed here that the transportation activities play a significant role in generating environmental impacts in various categories. In case 1, the transportation distances are less and hence, the environmental impacts in both the end-point assessment categories are the least.

Further, it is observed that road transportation, compressed air, electricity, and heating processes generate more impact on resources due to consumption of fossil fuels for these activities. More than 95% of the impacts generated in the resources category are due to consumption of coal, crude oil, and natural gases. The other processes like electricity consumption and sea transportation affect human health more. This can be explained as electricity production and sea transportation results in high emission of harmful gases and particulate matter. Similarly, the impacts due to each activity in the end-point assessment categories can be assessed.

5. Conclusions

The strategies adopted for selection of location for a manufacturing facility is traditionally based on the economic objectives. However, in the last decades, with degradation of eco system and increasing sustainability concerns, environmental aspects have gained importance for location selection of a manufacturing facility. The environmental impact of supply chain operations of manufacturing facilities has also become a governing factor for selecting the factory location. This paper investigates the impact of location of manufacturing plants on the environmental sustainability of machining processes. The important influencing factors in context of the environmental impacts caused by machining process are identified and modeled. LCA has been used to assess and compare the environmental performance of machining operations at manufacturing plants located at two different locations. It helps to identify the factors or hotspots, which have the highest impact on the environmental performance of milling operations.

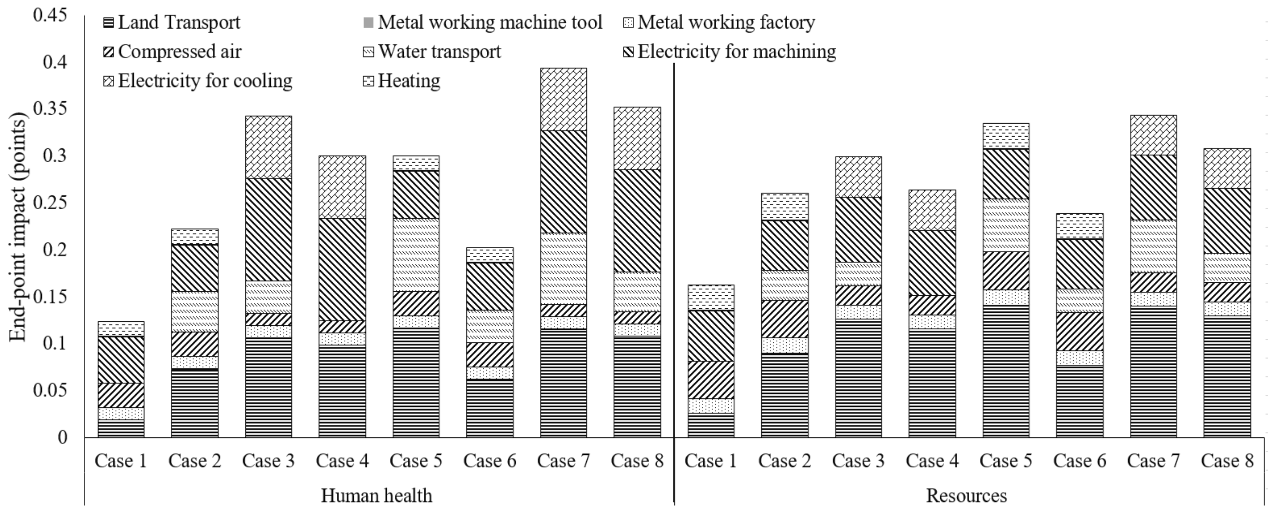

Fig. 6. End-point assessment results

The LCA results are presented in end-point and mid-point categories. It is observed that in Germany, more energy is required for HVAC system of the factory as compared to India. However, due to the difference in energy policies and energy mix at both the locations, the impacts caused by electricity consumption is higher at a facility located in Jaipur as compared with Braunschweig. Transportation is also reported to be a significant factor causing high environmental impacts on climate change, resources and human health. Hence, the results reveal that the location decision has a relevant impact on the environmental sustainability of the machining process and should be considered in future strategic location planning

Acknowledgements

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