CHAPTER 6

DEVELOPMENT OF A MACHINING SUSTAINABILITY ASSESSMENT INDEX

In this chapter, a sustainability assessment index is developed, which is envisaged to help manufacturers and users to objectively investigate the sustainability performance of a machining process and a machine tool.

6.1 INTRODUCTION

In the recent years, the traditional machining objectives are substituted by sustainable strategies covering environmental and social dimensions along with economic considerations (Peng and Xu, 2014). Improving energy efficiency of machine tools has been considered as a viable way to improve the economic and environmental performance of the machining processes (Jia et al., 2017; Moradnazhad and Unver, 2017; Zhou et al., 2018). Some studies have been proposed to quantify the energy consumption and environmental emissions caused by machine tools; strategies have been proposed to improve the energy efficiency and reduce environmental emissions (Cai et al., 2018; Duflou et al., 2012; Hu et al., 2017; Jeswiet and Kara, 2008; Lenz et al., 2017; Li et al., 2015; Liu et al., 2017; Teiwes et al., 2018). However, only a few studies have considered the social sustainability aspects in context of machine tools (Bhanot et al., 2016; De Araujo and De Oliveira, 2012).

Different parameters or indexes have been proposed in the literature to evaluate the performance of the machine tools in various dimensions. Schudeleit et al. (2016) proposed a metric – total energy efficiency index (TEEI) – considering sufficiency, consistency, and efficiency of all the components of a machine tool. This index was used to evaluate the design of a machine tool in context of energy efficiency.

Hegab et al. (2018) proposed an algorithm for sustainability assessment of machining processes considering energy consumption, tool life, and surface roughness as performance metrics. Bhanot et al. (2016) proposed a sustainability assessment framework for a turning process. The economic and environmental indices were computed empirically and social index was computed based on responses from experts.

Sustainability performance evaluation of the machine tools is an essential prerequisite for development of greener machine tools as well as selection of an appropriate machine tool for procurement. Quantification of the sustainability performance of machine tools is a challenge for manufacturers. In this chapter, a machining sustainability assessment index (SAI) was developed considering the three dimensions of sustainability. Fourteen performance indicators were identified from the literature to evaluate the sustainability performance of a machining process. A case study was conducted to compute SAI of a milling process under different cutting conditions using the proposed approach. The indicators were either calculated empirically or determined experimentally. The different indicators may have different weightage depending upon the user preferences. The weights were assigned to each indicator using analytical hierarchy process (AHP). The proposed index can be used to develop sustainability performance labels for machine tools, select suitable machine tools, design greener machine tools in the design phase, and select sustainable machining conditions.

6.2 SELECTION OF INDICATORS FOR SUSTAINABLE MACHINING

The manufacturing industries primarily assess their performance based on financial aspects. However, with increasing sustainability awareness in recent years, environmental and social aspects have also gained attention. Machine tool, as a key element of manufacturing industry, has emerged as an important product group for the improvement of sustainability. This section presents the selection of key performance indicators for sustainability assessment of machining. Though a large number of indicators have been proposed in the literature for sustainability assessment of machine tools, guidance for a meaningful selection of indicators is lacking. In the present study, the key indicators were selected based on measurability, accessibility, understandability, reliability, and relevance of the indicators. Measurability of the data implies that the data should be easy to measure, acquire and quantify. Accessibility implies the data should be easily available and can be shared. The selected indicators should be easy to understand by various stakeholders. The indicator data was either taken from the published literature or collected from the stakeholders to ensure the reliability of the data. These indicators were used to develop a sustainability assessment index for a milling process in section 6.3. The selected indicators and their source literature are given in Table 6.1.

6.2.1 Economic Indicators

The economic indicators such as cost, quality and productivity are related to financial aspects of a machining process. The indicators considered in the present study for the evaluation of economic performance of a milling process are explained as:

a) Production cost

Production cost includes machine tool depreciation and usage cost, labor cost, electricity cost, cutting tool cost, and coolant cost. It is calculated using equation (6.1):

$$C_p = C_{MT} + C_L + C_{elec} + C_{tool} + C_{coolant} \tag{6.1}$$

where C_p is the production cost, C_{MT} is the machine tool depreciation cost, C_L is the labor cost, C_{elec} is the electricity cost, C_{tool} is the cutting tool cost, and $C_{coolant}$ is the coolant cost.

Table 6.1 List of machining sustainability indicators and reference studies

Sustainability dimensions	**Indicators**	**Reference studies**
Economic	Production cost	An (2003), Bhanot et al. (2016), De Araujo and De Oliveira (2012), Fang et al. (2016), Hegab et al. (2018), Jawahir et al. (2005), Kim et al. (2012), Pušavec and Kopač (2011), Pušavec et al. (2010), Shivakoti et al. (2012), Shokrani et al. (2012), Yusup et al. (2012), Zhang and Haapala (2012)
	Surface roughness	Avram et al. (2011), Bhanot et al. (2016), De Araujo and De Oliveira (2012), Dureja et al. (2010), Linke et al. (2014), Murthy and Rajendran (2010), Pontes et al. (2010), Shokrani et al. (2012), Suhail et al. (2010), Yan and Li (2013), Yusup et al. (2012)
	Material removal rate	Bhanot et al. (2016), De Araujo and De Oliveira (2012), Fratila (2013), Linke et al. (2014), Shivakoti et al. (2012), Yan and Li (2013), Yusup et al. (2012)
	Air-cutting power	Li et al. (2017a), Tuo et al. (2018a)
Environmental	Carbon emissions	Avram et al. (2011), Bhanot et al. (2016), Heilala et al. (2008), Kim et al. (2012), Lu et al. (2012), Shao et al. (2014)
	Cutting fluid consumption	Kim et al. (2012), Lu et al. (2012, 2011), Singh et al. (2007)
	Cutting temperature	Bhanot et al. (2016), Shokrani et al. (2012), Suhail et al. (2010), Yusup et al. (2012)
	Energy consumption	Avram et al. (2011), Bhanot et al. (2016), De Araujo and De Oliveira (2012), Fang et al. (2016), Hegab et al. (2018), Jawahir et al. (2005), Kim et al. (2012), Linke et al. (2014), Shao et al. (2014), Tuo et al. (2018a)
	Energy utilization ratio	Li et al. (2017a), Liu et al. (2015), Tuo et al. (2018b), Hu et al. (2012), Kumar et al. (2017), Li et al. (2017b), Lv et al. (2016), Ma et al. (2017), Sealy et al. (2016), Zhao et al. (2016)
Social	Job satisfaction level	Kim et al. (2012), Linke et al. (2014)
	Physical load index	Bhanot et al. (2016), Kim et al. (2012), Lu et al. (2012, 2011)
	Noise level	Bhanot et al. (2016), De Araujo and De Oliveira (2012), Fang et al. (2016), Hegab et al. (2018), Kim et al. (2012), Linke et al. (2014), Lu et al. (2012)
	Mist/ Dust level	Bhanot et al. (2016), Hegab et al. (2018), Kim et al. (2012), Lu et al. (2012, 2011)
	Working environment pollution	Bhanot et al. (2016), Jawahir et al. (2005)
	Exposure to harmful chemicals	Bhanot et al. (2016), Kim et al. (2012), Lu et al. (2012, 2011)
	Operator comfort	Bhanot et al. (2016), Hegab et al. (2018), Jawahir et al. (2005)

The different costs are calculated using the equations given below:

$$C_{MT} = \frac{Machine\ tool\ cost}{Machine\ tool\ life} \times processing\ time \tag{6.2}$$

$$C_{elec} = Electricity\ cost\ per\ KWh \times Energy\ consumption \tag{6.3}$$

$$C_{tool} = \frac{Cutting\ tool\ cost}{Cutting\ tool\ life} \times cutting\ time \tag{6.4}$$

The cutting tool life can be calculated using Taylor's tool life equation.

$$C_{Coolant} = Coolant\ cost\ per\ litre \times V_{coolant} \times \frac{Processing\ time}{Coolant\ replacement\ interval} \tag{6.5}$$

b) Surface roughness (R_a)

Surface roughness is a measure of product quality in terms of product life, aesthetics, tribological considerations, precision fit of mating components, and fatigue life (Kant and Sangwan, 2014). The surface roughness is an important economic aspect of the machining process. As discussed in Chapter 4, the energy consumption for manufacturing a product increases when the surface finish is higher. This results into higher manufacturing cost. On the other hand, if the surface finish of a product is poor, it will lead to more rejects and rework and the manufacturing cost will increase. Therefore, careful selection of surface roughness of the product is an important aspect of product design and machining. In this study, the surface roughness was measured experimentally using Taylor Hobson's Talysurf.

c) Material removal rate (MRR)

Material removal rate directly affects the productivity and hence is an important economic aspect of a machining process. It is calculated as:

$$\text{MRR} = \frac{Volume\ of\ material\ removed\ (mm^3)}{processing\ time\ (s)} \tag{6.6}$$

d) Air cutting power ($P_{air\text{-}cut}$)

The air cutting power ($P_{air\text{-}cut}$) is the power consumed by a machine tool when all the components are active but no material is removed. It ensures the operational readiness of a machine tool. It consists of the unloaded spindle power, power consumed by coolant pump, chip conveyor, feed motor, mechanical transmission system, and other auxiliary components such as control panel, CNC system, inverters, servo drives, fan, display, etc. The air cutting power depends on the technical specifications of the machine tool and does not depend on the workpiece – cutting tool material or cutting process. In the present study, the air cutting power was experimentally measured as explained in chapter 3 (section 3.3).

6.2.2 Environmental Indicators

The environmental impacts of a machining process are mostly caused due to the energy consumption and pollution generation. The indicators selected for environmental dimension are: energy consumption, environmental emissions, energy efficiency, and cooling conditions.

a) Carbon emissions (CE)

The carbon emissions of a machining process is a measure of environmental emissions. It consists of the carbon emissions caused during machine tool production, production and consumption of electricity, cutting tool and raw material, production and disposal of used coolant, and treatment of chips. It can be calculated using the equation given below:

$$\text{CE} = CE_{energy} + CE_{cuttingtool} + CE_{material} + CE_{coolant} + CE_{chip\ process} \tag{6.7}$$

The carbon emissions modelling has been provided in chapter 3 (section 3.5). Since, the carbon emission caused by water usage is negligible as compared to soluble oil, it was not considered for the calculations in the present study.

b) Cutting fluid consumption (V_{CF})

The cutting fluid usage in machine tools is a major source for environmental pollution. In the present study, cutting fluid refers to the mixture of coolant and water used for machining operations under wet cutting conditions. In the present study, mineral based oil was used as coolant and the cutting fluid was prepared as a mixture of coolant and water (5% coolant + 95% water). The cutting fluid consumption is an important factor for environmental performance of a machining process. It is calculated as follows:

$$Cutting\ fluid\ consumption = V_{CF}\ \times \frac{Processing\ time}{Coolant\ replacement\ interval} \tag{6.8}$$

c) Cutting temperature (T_c)

The cutting temperature significantly affects the environmental performance of a machining process as high cutting temperature leads to reduced tool life, increased coolant consumption, and poor machining quality. In the present study, the temperature at the tool-workpiece contact was measured experimentally using Infrared thermal imaging camera.

d) Energy consumption

Energy consumption refers to the amount of energy consumed by a machine tool during the machining process. The energy consumption can be calculated by integrating the power curve over time. In the present study, the power was experimentally measured. The details of the power measurement system and energy calculations are provided in chapter 3 (sections 3.2 – 3.3). The energy consumption is calculated as

$$Energy\ consumption = \int_0^{PT} P(t)\, dt \tag{6.9}$$

e) Energy utilization ratio (U)

The energy utilization ratio (U) is the proportion of energy which is actually consumed for material removal. Mathematically, it is represented as the ratio of cutting energy to the total energy consumed during a machining process.

$$U = \frac{Cutting\ energy}{Total\ energy\ consumption} \tag{6.10}$$

6.2.3 Social Indicators

The influence of the machining processes on society is assessed using social indicators. In this study, social sustainability considered the human and social performance during machining. The key indicators for the assessment of social sustainability have been identified from the literature (Table 6.1). The social indicators used in the study are related to the work environment and the safety of the employees working on the machine tools. The data for the social indicators was collected using an offline survey form combined with in-person discussion with the shop floor employees. The indicators were rated on a scale of 1-5 by various machine tool operators, supervisors and line managers working on the shop floor at automotive component manufacturing firms located in the Delhi/NCR region of India. A total of 35 forms were filled and the average work experience of these employees was seven years. The number of forms are sufficient considering the data was taken after having in-person discussion with the employees and the number of questions were seven only.

The important social performance indicators considered in this study are:

- Job satisfaction level
- Physical load index

- Noise level
- Mist/Dust level
- Exposure to harmful chemicals
- Work environmental pollution
- Operator comfort

The data for social indicators may contain comparatively higher uncertainties as it is based on an individual's perception/perspective. The uncertainty of the data can be reduced by increasing the number of respondents. This also improves the reliability of the data. The data collected for environmental and economic indicators were quantitative; hence contained less uncertainties as compared to the social indicator data. The quantitative indicators also have uncertainty due to the effect of region and location specificity. For example, the carbon emission factor (CEF) for electricity may vary depending upon the location and the type of energy source such as coal, hydro, wind, solar, or nuclear.

6.3 DEVELOPMENT OF A SUSTAINABILITY ASSESSMENT INDEX (SAI)

The methodology adopted for the calculation of sustainability assessment index is explained in Figure 6.1. In the first step, the key performance indicators for sustainability performance of a machining process were identified, as explained in section 6.2. The indicator values were then computed using empirical relations provided in section 6.2 or by experimental evaluation. The normalization and weight calculation approaches used in this study are explained next.

6.3.1 Normalization of the Indicator Data

The indicator data had variations in the dimension and scope. Therefore, it was necessary to normalize the data for direct comparison. The indicator data was converted into a dimensionless quantity ranging from 0 to 1. The indicators were classified as positive type and negative type indicators. For positive type indicators, higher value of the indicator is favorable. For negative type indicators, lower value of the indicator is favorable.

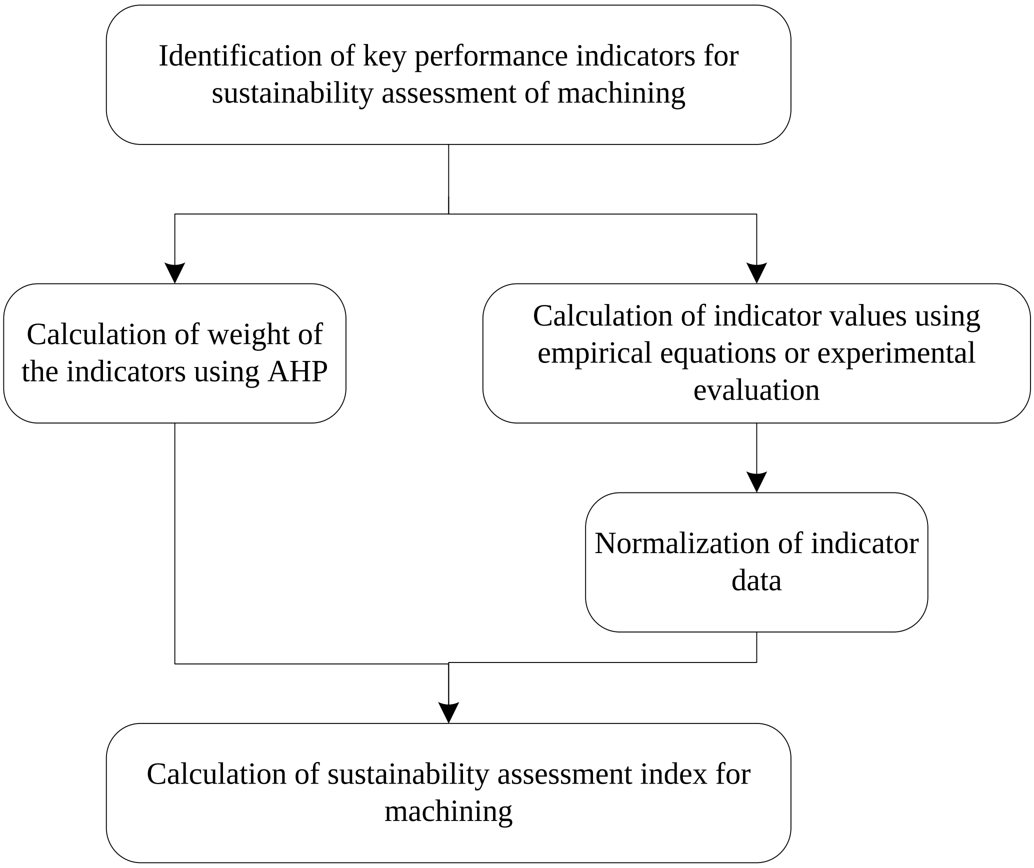

Figure 6.1 Methodology for machining sustainability assessment

Data normalization was done based on the indicator characteristics using the following equations:

For positive type indicators (larger is better):

$$x_i^* = \frac{x_i - \min x_i}{\max x_i - \min x_i} \tag{6.11}$$

For negative type indicators (smaller is better):

$$x_i^* = \frac{\max x_i - x_i}{\max x_i - \min x_i} \tag{6.12}$$

where x_i is the empirical value of the indicator and x_i^* is the normalized value of the indicator.

6.3.2 Calculation of Indicator Weights Using Analytical Hierarchy Process

In the next step, the weights of the indicators were computed using analytical hierarchy process (AHP). AHP is a multi-criteria decision making approach, developed by Saaty (1980), to derive weights of various indicators using pairwise comparisons. AHP is a philosophy of estimation, which offers the capability to include both quantitative and qualitative features in the decision process.

Application of this methodology has been found in numerous fields. The general approach of AHP model is to decompose the problem and make pairwise comparison of all the elements on a given level with the related elements in the level just above to which it belongs. AHP enables the decision maker to represent the simultaneous interaction of many factors in complex and unstructured situations. The AHP has four main phases – development of a hierarchical structure, pairwise comparison of elements, determination of priorities, and aggregation of results. The objective of each phase and the steps to follow in each phase are given below:

Phase 1 Development of a hierarchical structure

A hierarchy structure is developed for the identified problem. At the top of the hierarchy is the objective and the bottom of the hierarchy consists of all the alternatives to be evaluated. The second level of the hierarchy consists of indicators selected for the assessment of the objective. In this study, the objective is to evaluate the sustainability assessment index for a machining process.

Phase 2 Pairwise comparison of elements

The indicators are assigned importance ratings based on pairwise comparison of the indicators carried out by experts. It is easier for a decision maker or expert to evaluate/judge two options in a single trade-off from one perspective. The pairwise comparison is done for each criterion level of hierarchy and a set of pairwise comparison matrices is constructed for each of the lower levels. An element in the higher level is said to be a governing element for those in the lower level, since it contributes to it or affects it. The elements in the lower level are then compared to each other based on their effect on the governing element above. This yields a square matrix of judgments. The pairwise comparisons are done in terms of relative dominance of elements using Saaty scale as follows:

Saaty Scale	**Definition**
1	Equally important
3	Weakly important
5	Fairly important
7	Strongly important
9	Absolutely important

If element A dominates over element B, then the whole number integer is entered in row A, column B and reciprocal is entered in row B, column A. If the elements being compared are equal, a one is assigned to both positions. In this study, the relative importance of the three sustainability dimensions was assessed and the pairwise comparison matrix was formulated as:

$$\text{Reciprocal matrix} = \begin{array}{l|lll|} & \text{Economic} & \text{Environmental} & \text{Social} \\ \hline \text{Economic} & 1.00 & 3.00 & 5.00 \\ \text{Environmental} & 1/3 & 1.00 & 3 \\ \text{Social} & 1/5 & 1/3 & 1.00 \\ \hline \textbf{Sum} & \mathbf{1.53} & \mathbf{4.33} & \mathbf{9.00} \end{array}$$

Phase 3 Determination of priorities

This phase aims to obtain the principal eigenvalue or weightage of all the criteria or sub-criteria or alternatives separately for each level. This converts the pairwise comparison of decision makers to an overall weightage of each criteria/sub-criteria/alternative. The decisions are checked for consistency and any inconsistency more than 10% is removed to obtain coherent data.

For this, the normalized relative weight is calculated by dividing each element with sum of corresponding column, as follows:

$$\text{Normalized relative weight matrix} = \begin{array}{l} \\ \text{Economic} \\ \text{Environmental} \\ \text{Social} \end{array} \begin{array}{c} \begin{array}{ccc} \text{Economic} & \text{Environmental} & \text{Social} \end{array} \\ \begin{bmatrix} 0.65 & 0.69 & 0.56 \\ 0.22 & 0.23 & 0.33 \\ 0.13 & 0.08 & 0.11 \end{bmatrix} \end{array}$$

The average across the rows provides the Principal Eigen vector or Priority vector. The priority vector represents the weights of the three sustainability dimensions.

$$\text{Priority Vector} = \begin{array}{l} \text{Economic} \\ \text{Environmental} \\ \text{Social} \end{array} \begin{bmatrix} 0.6333 \\ 0.2605 \\ 0.1062 \end{bmatrix}$$

The consistency of the data is verified by computing the consistency ratio and consistency index. The Principal Eigen value is calculated as the sum of products of each element of Eigen vector with the sum of columns of the reciprocal matrix. The principal Eigen value obtained here was 3.055.

$$\text{Consistency Index } = \frac{\text{Principal Eigen value} - \text{n}}{n-1} \tag{6.13}$$

$$\text{Consistency ratio} = \frac{\text{CI}}{RI} \tag{6.14}$$

where RI is random consistency index, obtained from the Table 6.2.

Table 6.2 Standard random consistency index values

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

n is the number of factors (here, n = 3).

The computed consistency index and consistency ratio were 0.0276 and 0.0477, respectively. The consistency of the data is acceptable of the CR≤10%. In this case, CR was 4.77% and therefore the data was consistent. Similarly, the weights of the indicators in each sustainability dimension were calculated. More details of AHP technique can be found in (Sangwan, 2011).

Phase 4 Aggregation of results

The weightage obtained for each criteria/sub-criteria/alternatives is aggregated to obtain the final decision of the decision maker with respect to all alternatives. For example, in the present study, the aggregate of global weight of the indicators were calculated as the product of local weight of the indicator with the weight of the corresponding sustainability dimension. In this study, the environmental and economic indicators were quantitative values from machining experiments whereas the social indicators were qualitative values obtained using a survey questionnaire as explained in section 6.2.3.

6.3.3 Calculation of the Sustainability Assessment Index (SAI)

Once, the normalized values and weights of the indicators were obtained, the machining sustainability assessment index was computed as:

$$S_{MT} = \sum_{i=1}^{n} w_i * x_i^* \tag{6.15}$$

The sustainability performance in economic, environmental and social dimensions was computed using indicators and weights in respective dimensions. The overall sustainability assessment index was calculated by summation of the three performance indexes.

6.4 CASE STUDY

In this section, application of the proposed SAI is illustrated through a machining case study using a vertical machining center (LMW KODI 40). A cuboidal aluminum block (75 x 75 x 70 mm^3) was selected as the test workpiece. Face milling operation was performed under dry and wet cutting conditions at the three parameter settings:

1) n = 1000 RPM, f = 200 mm/min (dry 1 and wet 1)
2) n = 2000 RPM, f = 600 mm/min (dry 2 and wet 2)

3) n = 3000 RPM, f = 400 mm/min (dry 3 and wet 3)

The depth of cut (d) and width of cut (w) were kept constant at 1.5 mm and 4 mm, respectively. An HSS end mill of 16 mm diameter was selected to remove a layer of 1 mm from the workpiece. The energy consumption for machining was measured using Fluke 435 power quality and energy analyser. The surface roughness of the machined workpieces was measured using Taylor Hobson’s Talysurf. The economic and environmental performance indicators were either computed using the empirical models provided in section 6.2 or measured experimentally. The data used for indicator calculations and the calculation of economic and environmental performance indicators are given in Tables 6.3 and 6.4, respectively. The social indicators were assessed on a scale of 1 to 5 and graded accordingly. The indicator results for the six cases are given in Table 6.5.

Table 6.3 Data used for indicator calculation

Measure	**Value**
CNC machine tool life	15 years
Machine tool cost (LMW KODI 40)	INR 3300000
Production hours per day	16 hours (2 shifts of 8 hours each)
Workpiece density	2.7 g/cm^3
Labor cost	INR 1/min
Electricity cost	INR 9/kWh
Cutting tool cost	INR 1200
Coolant cost	INR 250/litre
V_{in}	12.5 litre
V_{ad}	5.5 litre
Average coolant replacement interval	4 months
CEF_{elec}	1.41 kgCO$_2$/kWh
CEF_{tool} (Li et al., 2015)	104.6 kgCO$_2$/kg
$CEF_{material}$ (Li et al., 2015)	16.13 kgCO$_2$/kg
$CEF_{coolant}$ (Li et al., 2015)	2.85 kgCO$_2$/litre
$CEF_{coolant\text{-}dis}$ (Li et al., 2015)	0.2 kgCO$_2$/litre
CEF_{chip} (Li et al., 2015)	0.256 kgCO$_2$/kg

Table 6.4 Calculation of economic and environmental performance indicators

S. No.	Indicator	Calculation	Value
1	C_{MT}	$=\frac{3.3 * 10^6 * 360.5}{15 * 300 * 16 * 3600}$	INR 4.59
2	C_L	$=\frac{360.5}{60}$	INR 6
3	C_{elec} (dry 3)	=0.1096 * 9	INR 0.99
4	C_{elec} (wet 3)	=0.223 * 9	INR 2.0
5	C_{tool} (dry 3)	$=\frac{1200}{40 * 60} \times 202.5$	INR 101.25
6	C_{tool} (wet 3)	$=\frac{1200}{90 * 60} \times 202.5$	INR 45
7	$C_{Coolant}$ (wet 3)	$= 250 \times 18 \times \frac{360.5}{4*25*16*3600}$	INR 0.28
8	C_p (dry 3)	= 4.59 + 6 + 0.98 + 101.25	INR 112.83
9	C_p (wet 3)	= 4.59 + 6 + 2 + 45 + 0.28	INR 57.87
10	R_a (dry 3)	Experimental	1.3177 µm
11	R_a (wet 3)	Experimental	0.5576 µm
12	MRR (dry 3 and wet 3)	$=\frac{400 * 1.5 * 4}{60}$	40 mm^3/sec
13	$P_{air\text{-}cut}$ (dry 3)	Experimental	0.93 kW
14	$P_{air\text{-}cut}$ (wet 3)	Experimental	2.206 kW
15	CE_{elec} (dry 3)	= 1.41 * 0.1096	0.1545 $kgCO_2$
16	CE_{elec} (wet 3)	= 1.41 * 0.2219	0.3128 $kgCO_2$
17	$CE_{cuttingtool}$ (dry 3)	$= 104.6 * 0.1 * \frac{202.5}{40 * 60}$	0.8826 $kgCO_2$
18	$CE_{cuttingtool}$ (coolant 3)	$= 104.6 * 0.1 * \frac{202.5}{90 * 60}$	0.3923 $kgCO_2$
19	$CE_{material}$	$=\frac{16.13 *(7.5 * 7.5 * 0.15) *2.7}{1000}$	0.3674 $kgCO_2$
20	$CE_{coolant}$	$=\frac{360.5}{T_{coolant}} \times \left[2.85 \times 18 + 0.2 \times \frac{18}{5}\right]$	0.0033 $kgCO_2$
21	$CE_{chip\ process}$	$=\frac{0.256 * (7.5 * 7.5 * 0.15) * 2.7}{1000}$	5.83 * 10^{-3} $kgCO_2$
22	CE (dry 3)	= 0.1545 + 1.7651 + 0.3674 + 0.0058	2.293 $kgCO_2$
23	CE (coolant 3)	= 0.3128 + 0.7845 + 0.3674 + 0.0033 + 0.0058	1.4738 $kgCO_2$
24	Coolant consumption (wet 3)	$= (18 + 342) * 1000 * \frac{360.5}{4*25*16*3600}$	22.53 ml
25	Cutting Temperature (dry 3)	Experimental	52.5 °C
26	Cutting Temperature (wet 3)	Experimental	24.8 °C
27	Energy consumption (dry 3)	0.1096	kWh
28	Energy consumption (wet 3)	0.2219	kWh
29	U (wet 3)	$=\frac{5.68 * 10^{-3}}{0.2219}$	0.0256
30	U (dry 3)	$=\frac{6.75 * 10^{-3}}{0.1096}$	0.0616

Table 6.5 The empirical data of SA indicators

Indicator	**Dry 1**	**Dry 2**	**Dry 3**	**Wet 1**	**Wet 2**	**Wet 3**	**Unit**
C_{MT}	9.06	3.17	4.59	9.06	3.17	4.59	INR
C_L	11.86	4.15	6.01	11.86	4.15	6.01	INR
C_{elec}	1.30	0.55	0.99	3.57	1.29	2.00	INR
C_{tool}	202.5	67.5	101.25	90	30	45	INR
$C_{coolant}$	0	0	0	0.56	0.19	0.28	INR
C_P	224.71	75.366	112.83	115.04	38.803	57.877	INR
R_a	2.4889	2.3718	1.3177	0.7294	0.8759	0.5576	µm
MRR	20	60	40	20	60	40	mm^3/sec
$P_{air\text{-}cut}$	0.69	0.82	0.93	2.01	2.21	2.206	kW
CE_{elec}	0.2029	0.0862	0.1545	0.5593	0.2026	0.3129	$kgCO_2$
CE_{tool}	1.7651	0.5884	0.8826	0.7845	0.2615	0.3923	$kgCO_2$
$CE_{material}$	0.3674	0.3674	0.3674	0.3674	0.3674	0.3674	$kgCO_2$
$CE_{coolant}$	0	0	0	0.0064	0.0022	0.0033	$kgCO_2$
CE_{chip}	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	$kgCO_2$
CE	2.3413	1.0478	1.4103	1.7235	0.8396	1.0816	$kgCO_2$
V_{CF}	0	0	0	44.469	15.547	22.531	ml
T_c	28.5	41.3	52.5	23.5	25.3	25.6	°C
Energy consumption	0.1439	0.0611	0.1096	0.3967	0.1437	0.2219	kWh
U	0.0508	0.0771	0.0616	0.0111	0.0200	0.0256	
Job satisfaction level	3	3	3	3	3	3	3
Physical load index	4	4	4	4	4	4	4
Noise level	3	4	3	2	3	2	3
Mist/Dust level	2	2	2	3	4	3	2
Exposure to harmful chemicals	3	3	3	4	4	4	3
Work environment pollution	3	2	3	4	3	4	3
Operator comfort	3	2	3	3	2	3	3

The social indicators were dimensionless ratios and hence normalization was not needed. However, to facilitate the integration with quantitative results, these values were also converted to 0-1 scale using equation (6.16).

$$X = \frac{(x-a)}{(b-a)} \tag{6.16}$$

where x is the indicator value provided by stakeholders, X is the transformed value on the new scale, a is the minimum value and b is the maximum value of indicators. The economic and environmental indicators were normalized using equations 6.11 –6.12 and results are presented in Table 6.6.

Table 6.6 The normalized data of SA indicators

Indicator	**Dry 1**	**Dry 2**	**Dry 3**	**Wet 1**	**Wet 2**	**Wet 3**
C_P	0	0.8033	0.6018	0.5899	1	0.8974
R_a	0	0.0606	0.6064	0.911	0.8352	1
MRR	0	1	0.5	0	1	0.5
$P_{air\text{-}cut}$	1	0.9145	0.8421	0.1316	0	0.0026
CE	0	0.8614	0.6199	0.4114	1	0.8388
$V_{coolant}$	1	1	1	0	0.6504	0.4933
T_c	0.8276	0.3862	0	1	0.9379	0.9276
SEC	0.7533	1	0.8555	0	0.7539	0.5209
U	0.6018	1	0.7652	0	0.1359	0.2201
Job satisfaction level	0.50	0.50	0.50	0.50	0.50	0.50
Physical load index	0.75	0.75	0.75	0.75	0.75	0.75
Noise level	0.50	0.75	0.50	0.25	0.50	0.25
Mist/Dust level	0.25	0.25	0.25	0.50	0.75	0.50
Exposure to harmful chemicals	0.50	0.50	0.50	0.75	0.75	0.75
Work environment pollution	0.50	0.25	0.50	0.75	0.50	0.75
Operator comfort	0.50	0.25	0.50	0.50	0.25	0.50

The weights of the indicators were calculated using AHP and the indicator rankings are presented in Table 6.7. It is evident here that R_a, MRR, and C_p are at first, second and fourth positions, respectively among 14 indicators. The SEC, energy utilization ratio and carbon emissions are ranked at third, fifth and sixth positions, respectively.

Table 6.7 Global weights and AHP ranking of SA indicators

Sustainability dimension	**Weight**	**Indicator**	**Weight**	**Global weight**	**Rank**
Economic	0.633	C_P	0.1364	0.0864	4
		R_a	0.474	0.3002	1
		MRR	0.3247	0.2056	2
		$P_{air\text{-}cut}$	0.0649	0.0411	7
Environmental	0.26	CE	0.1639	0.0427	6
		$V_{coolant}$	0.0797	0.0208	10
		T_c	0.0423	0.011	12
		SEC	0.4697	0.1224	3
		U	0.2444	0.0637	5
Social	0.11	Job satisfaction level	0.3711	0.0394	8
		Physical load index	0.0413	0.0044	15
		Noise level	0.2371	0.0252	9
		Mist/Dust level	0.0909	0.0097	13
		Exposure to harmful chemicals	0.0599	0.0064	14
		Work environment pollution	0.1737	0.0184	11
		Operator comfort	0.0260	0.0028	16

It implies that financial aspects are still given high weightage, but the environmental emissions and energy consumption are also getting high importance. The ranks of social sustainability indicators are observed to be relatively low. The calculation for the 'Wet 1' case is shown here in detail and the results for all six cases are given in Table 6.8.

- $Economic\ performance = \sum(\text{dimensionless indicator} * \text{global weight of indicator}) = (0.5899 * 0.0864 + 0.911 * 0.3002 + 0 * 0.2056 + 0.1316 * 0.0649) = 0.3299$

- $Environmental\ performance = (0.4114 * 0.0427 + 1 * 0.011) = 0.0286$

- $\text{Social}\ performance = (0.5 * 0.0394\ +\ 0.75 * 0.0044\ + 0.25 * 0.0252 + 0.5 * 0.0097\ +\ 0.75 * 0.0064 +\ 0.75 * 0.0184 +\ 0.5 * 0.0028)\ =\ 0.0542$

- $Overall\ sustainability = 0.3299\ +\ 0.0286\ +\ 0.0542\ =\ 0.4126$

Table 6.8 Calculation of the machining sustainability assessment index

	Dry 1	Dry 2	Dry 3	Wet 1	Wet 2	Wet 3
Economic	0.0411	0.3308	0.3715	0.3299	0.5427	0.4806
Environmental	0.1604	0.2479	0.2007	0.0286	0.1675	0.1341
Social	0.0518	0.0528	0.0518	0.0542	0.0576	0.0542
Sustainability	0.2534	0.6315	0.6240	0.4126	0.7678	0.6688

It is observed here that the case ‘wet 2’ performed the best in economic dimensions followed by ‘wet 3’ and ‘dry 3’. The cutting tool cost is a dominating factor for the economic performance of machining process. The case “wet 2’ had better tool life, higher productivity and better surface finish, which resulted into better economic performance. However, the case ‘dry 3’ performed better than ‘dry 2’ and ‘wet 1’ in economic dimension because of better surface finish obtained in this case.

In environmental dimension, dry cutting performed better than wet cutting because of lower specific energy consumption, better energy utilization ratio, and absence of coolant. Also, it can be observed that the parameter settings also played an important role in the sustainability performance of the machining process. The better environmental performance of ‘wet 2’ (0.2479) as compared to ‘dry 1’ (0.1604) and ‘dry 3’ (0.2007) is explained by better tool life, lesser environmental emissions, and lower cutting temperature at these parameter settings.

The social indicators were consistently getting lower weightage. This is due to the less weightage given to the social indicators in India. However, it is observed that the wet cutting conditions performed slightly better than dry cutting conditions because of lower noise levels in wet cutting. Though the exposure to mist and harmful chemicals was higher in case of wet cutting conditions.

6.5 SUMMARY

In this chapter, a sustainability assessment index was developed for a machining process in order to transform the abstract sustainability concept into quantified measures of sustainability performance in economic, environmental, and social dimensions. A set of key performance indicators were identified from literature to assess the machining sustainability performance. AHP technique was used to assign weights to the indicators. The proposed sustainability assessment index was implemented to assess the sustainability of milling process. It was observed that the cutting parameters and coolant conditions play important roles in the sustainability performance of the machining process. Dry machining performed better than wet machining in environmental dimension at the same parameter settings because of lesser energy consumption (absence of high energy consuming coolant pump) and absence of coolant. However, tool life decreased for the dry machining and hence wet machining performed better in economic dimension at the same parameter setting.

The proposed SA index can be used to develop sustainability performance labels for machine tools, which can provide decision support information to machine tool manufacturers and production managers to assess the sustainability performance of the machine tools and assist decision makers regarding procurement of suitable machine tools. The SA index can also be used as an optimization objective for machining systems. The future studies should focus on development of comprehensive list of indicators for sustainability assessment of machine tools.