MECHANICAL ENGINEERING | RESEARCH ARTICLE

Optimization of machining parameters for green manufacturing

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Abstract: Energy crisis is affecting the world badly. While the production in developed countries stabilizes, in the developing world it continues to expand. This results in higher energy use, thereby releasing higher CO₂. Thus, a pilot experiment was conducted to check and subsequently take corrective measures to reduce the energy consumption of manufacturing industry. Here, the emphasis is laid particularly on the turning operation for the cutting parameters, and effort has been made to optimize them, using Design Expert, with regard to the energy consumed. Also the optimized values, from the, for the different parameters under study have been checked and compared by those being generally used. For experimental studies, the machining was first carried on mild steel and then after aluminum and brass were also considered for study. All the values show an appreciable reduction in the energy consumption, thus reducing the carbon emission, for all the materials.

Subjects: Manufacturing Engineering; Mechanical Engineering; Sustainable Engineering & Manufacturing

Keywords: carbon footprints; design expert software; energy crisis; economic growth; manufacturing industry

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PUBLIC INTEREST STATEMENT

As we know that the world is dealing with Energy crisis. But the energy demands have risen manifolds, thus increasing the risks of global climate change which is primarily due to the release of carbon dioxide from power plants. The work presented here, is an attempt to ponder upon optimizing the manufacturing process in an industry to reduce the energy consumed during the manufacturing process using Design Expert Software. This way the rise in the energy efficiency can be obtained and also the carbon dioxide dispersion to the atmosphere can be reduced. A pilot experiment was conducted to check and subsequently take corrective measures to reduce the energy consumption of manufacturing industry. Results show an appreciable reduction in the energy consumption, thus reducing the carbon emission, for the tested materials.
1. Introduction
Scientific evidence points to increasing risks of serious, irreversible impact from climate change associated with business as usual (BAU) paths for emissions (Acemoglu, Aghion, Bursztyn, & Hemous, 2012; Stern, 2006). Sustainable manufacturing was specifically defined by the USA, Department of Commerce as the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers (Reddy & Ray, 2010; Roy, 1992; Sudhakara Reddy & Kumar Ray, 2011; Tandon & Ahmed, 2015). In literature, it is generally now accepted that sustainable development should include three pillars which are economical, environmental, and social issues (Das, Mehra, & Iyer, 1993; Garg, Lam, & Gao, 2015; Hanafi, Khamlichi, Cabrera, Almansa, & Jabbouri, 2012; Rajemi & Mativenga, 2008; Rajemi, Mativenga, & Aramcharoen, 2010, 2010; Yan & Li, 2013). The industrial sector of India consumes about 44% of the total final energy consumption, out of which, 66% goes to the manufacturing sector, Figure 1. The manufacturing sector is one of the energy-intensive industries among other industries in India, Figure 2 because these technologies and processes (like, automobile (47%), lighting (4%), electrical heating/melting (28%), and air compression (10%) (Al-Sulaiman, Baseer, & Sheikh, 2005; Peng & Xu, 2014; Stanley, Ulutan, & Mears, 2014; Zhou et al., 2016) end up utilizing much greater energy than their respective theoretical requirement.

It is also worth mentioning that along with all these factors if efficient machining techniques are adopted for the different operations taking place inside an industry then at least some part of the energy can be saved. Higher energy consumption increases production cost and carbon dioxide (CO₂) emissions. Carbon dioxide (CO₂) is the major greenhouse gas (GHG) that affects global warming (Lashof and Ahuja, 1990), Kirschbaum (2014). (Gutowski, 2007) and also some recent reports (Carbon Dioxide Information Analysis Centre, 2012) suggest split carbon emissions into four contributing factors of population, GDP per energy use, energy use per population, and the carbon intensity of energy. Also it is worth referring that the CO₂ emissions have also increased drastically from 1975 to 2011.

The CO₂ emission is a hot issue in today’s world with the major contributor being the fossil fuel combustion. In India, CO₂ emissions have registered a 4.4% increase in the world’s share from 1990 to 1998 (Campatelli, Lorenzini, & Scippa, 2014; Kant & Sangwan, 2014; Pusavec, Krajnik, & Kopac, 2010; Sarıkaya & Güllü, 2014). Some researchers have worked for the improvement of the machining processes, viz. (Ghani, Rizal, & Che Haron, 2014; Prasanna, Karunamoorthy, Venkat Raman, Prashanth, & Raj Chordia, 2014; Sreejith & Ngoi, 2000), and reported that dry machining is the machining of future. They concluded that the dry machining can eliminate cutting fluids and this is possible due to the advancement of the cutting tool materials, but the small- and medium-scale industries do not comply with such a scheme and thus are also losing an appreciable amount of energy in the long run. (Benardos & Vosniakos, 2003; Öktem, Erzurumlu, & Kurtaran, 2005; Sood, Sehgal, & Dwivedi,
2011; Suresh, Venkateswara Rao, & Deshmukh, 2002) used response surface methodology (RSM) to develop a surface roughness prediction model for turning mild steel. Statistical methods and Taguchi’s technique were used for investigating mach inability and optimizing power consumption. In another study, it was observed that power consumption is one of the most important parameters for condition monitoring. The study revealed that the use of the cutting fluid in a cryogenic environment significantly minimizes the power consumption, and also reduces the cutting speed and depth of cut (DoC) (Carbon Dioxide Information Analysis Centre, 2012; Gutowski, 2007; Pusavec et al., 2010). The RSM model was used to predict the power used in for machining/turning the EN-31 Steel (Abhang & Hameedullah, 2010; Garg & Lam, 2015; Kant & Sangwan, 2014). It was found that RSM is found to be a successful technique to perform trend analysis of power consumption in metal cutting with respect to various combinations of design variables (Anayet, Patwari, Chowdhury, Arif, & Chowdhury, 2015; Patwari, Chowdhury, Arif, & Chowdhury, 2012). Optimization of cutting parameters using Taguchi (Das, Nayak, & Dhupal, 2012; Nanda, Kumar, & Kumar, 2014; Ojolo & Ogunkomaaya, 2014; Senthilkumar & Tamizharasan, 2014) and ANOVA (Hanafi, Khamlichi, Mata Cabrera, Almansa, & Jabbouri, 2011; Kumar, Abbas, Mohammad, & Jafri, 2013) on tool wears and work piece surface temperature in turning of AISI D2 steel and MS1010 was experimentally studied. (Gutowski, 2007) suggested that to reduce the energy requirements for machining process, one should reduce the machining time by increasing throughput (i.e. MRR) rates. Research shows that using dry cutting, energy consumption for machining process can be reduced from 16 to 4% (Rajemi & Mativenga, 2008; Roy, 1992). (Chapman, 1974) and (Hanes, 2015) suggested that energy usage in a machining process can be evaluated and reduced by studying a particular process in detail. For machining processes, the energy requirement decreases as the material removal rate (MRR) increases (Ghani et al., 2014; Prasanna et al., 2014; Sreejith & Ngoi, 2000).

2. Problem identification

From the literature, it is evident that ANOVA and RSM can be used as a tool for optimization of the cutting parameters. Also, as most of the experimentations are carried out on standard machinery which are used in large-scale industries and not often found in small/medium scale industries, there is a necessity to standardize the machining processes, as they may consume lot more energy than the standard machines. In an effort to decrease the energy consumption and hence, the corresponding carbon footprints, an experiment is conducted on Lathe machines as these are used frequently, in any manufacturing industry. Two types of lathes were employed viz., NL 180 center lathe of HMT make and local lathe machine. On these machines a simple turning process is performed.
After completing the literature survey, three parameters, namely the Feed, the Spindle Speed, and the DoC were considered for optimization, using the Design Expert, with respect to the energy consumed (EC) during the cutting process. The range of feed, spindle speed, and DoC is decided on the basis of current working scenario of the workers in the shop floor. The effect of input parameters on the output ones is analyzed and accordingly the optimal set of the input parameters for which the EC is minimum is selected. The MRR is taken as maximum for the minimum resultant force. The Design Expert Software is used for the purpose of finding the most optimum solution. The Design Expert is software designed to help with the design and interpretation of multi-factor experiments. The software offers a wide range of designs, including factorials, fractional factorials, and composite designs. It can handle both process variables, such as rotor speed, and also mixture variables, such as the proportion of resin in a plastic compound. Design Expert offers computer-generated D-optimal designs for cases where standard designs are not applicable, or where we wish to augment an existing design, for example, to fit a more flexible model (Design Expert version 8, 2010).

The experiment consisted of the following steps:

Step 1. The work pieces of the desired materials were prepared.

Step 2. Machine Setup: Dynamometer was installed, for checking the tooling forces in x, y, and z directions, during cutting without coolant being used, as this is the need of the hour.

Step 3. Using DoE: The ranges of different parameters for individual materials were fed to the software for obtaining the set of experiments. RSM was used for obtaining the experiments.

Step 4. Machining: Based on the experiment sets the actual machining was carried out using the HSS tool. The length for the cutting was fixed and the time, forces, and the current drawn (using Clamp type energy meter) were noted for each experimental set.

Step 5. Optimization: The feed thus obtained by running individual experiments were fed to the DoE software for optimization.

Step 6. Confirmatory tests: The optimized sets of values were then performed experimentally for confirmation of the software values.

Step 7. Calculation of Energy: As per the values thus found after running the optimized results the energy saved and the carbon footprints thus saved were calculated.

Also, care has been taken to get the standard tool geometry for the specified materials and hence the cutting tool geometry for various materials listed in Table 1 was achieved.

3. Results and discussions

3.1. Mild steel
The experimental work is carried out using bars of mild steel. A strain gage-based Dynamometer is used to measure the three components of cutting forces namely feed force, thrust force, and radial force. Machining is done under dry machining conditions. The experimental values are obtained

| Material     | Side relief | Front relief | Side rake | Back rake |
|--------------|-------------|--------------|-----------|-----------|
| Mild steel   | 10          | 8            | 12        | 8         |
| Brass        | 10          | 8            | 5         | 0         |
| Aluminum     | 12          | 8            | 15        | 35        |
from the RSM technique of Design Expert software. The machining is done using HSS tool and the investigation for the result of change of the feed, cutting speed, DoC on cutting forces, energy consumption, and MRR for different materials is done. Finally the aim is set to minimize the EC and the resultant force and to maximize the MRR and the corresponding set of optimal values for the same are obtained using the Design Expert software as shown in the Figure 3.

In the goal for each response is defined. EC is minimized, MRR is maximized, and RF is minimized, for the limits specified. The limits are machine-specific and material-specific. So, for these defined limits and for the goal thus suggested for the output parameters shall give the various value combinations for the input variables. Now the output parameters for them are determined through the

![Figure 3. Maximum and minimum criteria.](image)

| Number | Speed  | Feed | DoC  | EC    | MRR    | RF    | Desirability |
|--------|--------|------|------|-------|--------|-------|--------------|
| 1      | 250.715| 0.678| 0.899| 29.145| 108.474| 491.273| 0.779        |
| 2      | 250.715| 0.678| 0.897| 29.279| 108.335| 492.809| 0.776        |
| 3      | 250.718| 0.676| 0.899| 29.267| 107.743| 491.422| 0.776        |
| 4      | 251.764| 0.678| 0.899| 29.205| 107.917| 492.819| 0.775        |
| 5      | 250.76  | 0.678| 0.895| 29.382| 108.207| 494.038| 0.774        |
| 6      | 250.715| 0.675| 0.899| 29.367| 107.142| 491.55  | 0.773        |
| 7      | 250.716| 0.673| 0.899| 29.451| 106.642| 491.671| 0.771        |
| 8      | 252.264| 0.675| 0.899| 29.469| 106.287| 493.822| 0.768        |
| 9      | 254.088| 0.678| 0.899| 29.337| 106.687| 496.281| 0.767        |
| 10     | 255.17  | 0.678| 0.899| 29.398| 106.116| 497.912| 0.764        |
| 11     | 257.71  | 0.678| 0.899| 29.428| 105.831| 498.731| 0.762        |
| 12     | 250.715| 0.667| 0.899| 29.827| 104.435| 492.337| 0.761        |
| 13     | 256.999| 0.678| 0.899| 29.5   | 105.152| 500.696| 0.758        |
| 14     | 250.716| 0.678| 0.899| 29.576| 106.38  | 502.224| 0.754        |
| 15     | 257.993| 0.678| 0.899| 29.839| 104.6   | 505.124| 0.75         |
| 16     | 257.388| 0.678| 0.894| 29.839| 104.6   | 505.124| 0.75         |
| 17     | 250.715| 0.678| 0.876| 30.629| 106.916| 508.603| 0.75         |
| 18     | 250.715| 0.66  | 0.899| 30.309| 101.665| 493.437| 0.749        |
| 19     | 250.716| 0.647| 0.899| 31.078| 97.414 | 495.82  | 0.729        |
| 20     | 265.512| 0.678| 0.899| 29.97 | 100.742| 514.111| 0.728        |
| 21     | 364.285| 0.678| 0.601| 31.284| 74.366 | 367.577| 0.728        |
| 22     | 364.285| 0.678| 0.606| 31.391| 74.668 | 372.894| 0.726        |
experimentation and fed to the software and the analysis is run to get the optimized value combination, as per the goal selected. The optimized set of values for the mild steel is shown in Table 2.

The top most value shown in the table marked as “Selected” shows the most optimized set of Input and output variables, for the experiment. Now, to confirm the result the experiment is performed and the obtained set of values is tabulated in Table 3. The result shows some deviation, which is due to the fact that the machine has some limitations for the selection of the input parameters and also the material is not homogenous. But still the results are appreciable.

3.2. Model graphs for mild steel
Graphs are plotted between the input parameters and the output parameters, keeping one input parameter i.e. DoC constant.

The above graphs show, Figure 4, the variation in EC, MRR, and DoC with the variation in speed, feed, and DoC. (a) the feed and speed varies almost linearly with EC, (b) the variation in speed and feed is almost parabolic with MRR. (c) similarly speed and feed varies parabolic with the RF. This is evident from the fact that as the cutting operation is being performed and the material removal is taking place so the energy consumption should increase and be proportional. The cutting forces are greater and the machining power is higher thus the energy consumption increases. (Skoczynski, Maczka, Wasiak, Roszkowski, & Pres, 2013). The highest MRRs are obtained at the highest values of feed rates and cutting speed. The results showed that the cutting speed has significantly less effect and feed rate has the lowest significant effect on MRR (Elmunafi, Kurniawan, & Noordin, 2015). Also, the resultant forces are affected by the feed and the speed of operation. They increase steadily in the beginning and thereafter they are stagnant and change with non-homogeneity of the material. Similar type of analysis was extended on some other easily available materials like the brass and aluminum. Also a check on whether the change in the material has any affect on the energy consumption or it follows the same trend i.e. it is machine specific, was carried. So, the standard tool geometry for the two materials (Table 4), was checked and tried to be achieved experimentally.

Again the similar type of experiment was designed but this time the tool geometry was changed according to the material, so that good results are obtained. Also the machine and instruments of measurements are kept same, so as to get comparable results.

3.3. Brass
The maximization and minimization of the goals were done and the specific limits were allocated, Figure 5. The optimized values were obtained and the most optimum value was selected.

Table 5 shows that out of the 23 solution found by the software the first solution is the most optimal solution. The confirmatory tests were carried on this value (Table 6).

Table 3. Confirmatory test

| Parameter | Unit | Value | Parameter | Unit | Value |
|-----------|------|-------|-----------|------|-------|
| Speed     | (rpm)| 250.17| $F_x$     |      | 14    |
| Feed      | (mm/rev)| 0.67  | $R_i$     | (N)  | 497.7 |
| DoC       | (mm) | 0.89  | $I_i$     | (A)  | 3.47  |
| V         | (V)  | 415   | $E_1$     | (W)  | 1,440.05 |
| $D_1$     | (mm) | 30    | $I_1$     | (A)  | 3.55  |
| $D_2$     | (mm) | 29.11 | $E_1$     | (W)  | 1,473.25 |
| T         | (s)  | 63    | $E$       | (W)  | 33.2  |
| $F_T$     |      | 47    | MRR       | (mm^3/s)| 103.45 |
| $F_F$     |      | 13    |           |       |       |


Figure 4. Model graphs between input and output parameters (DoC = Constant).
Table 4. Cutting tool geometry for brass and aluminum (Rake and Relief Angles in degrees for HSS Lathe Tools, xxxx)

| Material | Side relief | Front relief | Side rake | Back rake |
|----------|-------------|--------------|-----------|-----------|
| Brass    | 10          | 8            | 5         | 0         |
| Aluminum | 12          | 8            | 15        | 35        |

Figure 5. Maximum and minimum criteria.

Table 5. Optimized results

| Number | Speed   | Feed | DoC  | EC     | MRR      | RF      | Desirability |
|--------|---------|------|------|--------|----------|---------|--------------|
| 1      | 364.665 | 0.678| 0.741| 139.53 | 87.763   | 316.902 | 0.6          |
| 2      | 364.664 | 0.678| 0.742| 139.668| 87.947   | 317.156 | 0.6          |
| 3      | 364.665 | 0.678| 0.736| 139    | 86.849   | 315.628 | 0.6          |
| 4      | 364.665 | 0.678| 0.747| 140.32 | 88.76    | 318.289 | 0.6          |
| 5      | 364.665 | 0.678| 0.732| 138.735| 86.251   | 314.8   | 0.6          |
| 6      | 364.588 | 0.678| 0.749| 140.678| 89.069   | 318.748 | 0.6          |
| 7      | 364.661 | 0.678| 0.73  | 138.647| 85.979   | 314.423 | 0.6          |
| 8      | 364.664 | 0.674| 0.74  | 140.593| 87.141   | 315.436 | 0.6          |
| 9      | 364.665 | 0.672| 0.739| 140.021| 86.662   | 314.453 | 0.599        |
| 10     | 364.664 | 0.678| 0.72  | 138.423| 84.433   | 312.273 | 0.599        |
| 11     | 364.665 | 0.669| 0.732| 141.254| 85.266   | 312.011 | 0.599        |
| 12     | 361.51  | 0.678| 0.75  | 142.499| 88.63    | 319.096 | 0.596        |
| 13     | 364.664 | 0.636| 0.773| 160.87 | 87.933   | 310.602 | 0.588        |
| 14     | 285.31  | 0.322| 0.866| 151.69 | 53.993   | 240.247 | 0.556        |
| 15     | 284.624 | 0.322| 0.866| 151.327| 53.946   | 240.397 | 0.558        |
| 16     | 286.185 | 0.322| 0.865| 152.126| 54.045   | 240.046 | 0.556        |
| 17     | 283.848 | 0.322| 0.866| 150.67 | 53.825   | 240.472 | 0.556        |
| 18     | 283.328 | 0.322| 0.867| 150.545| 53.831   | 240.644 | 0.556        |
| 19     | 290.883 | 0.322| 0.862| 154.481| 54.318   | 238.954 | 0.556        |
| 20     | 279.275 | 0.322| 0.87  | 149.095| 53.735   | 241.78  | 0.556        |
| 21     | 292.932 | 0.322| 0.862| 156.077| 54.598   | 238.701 | 0.556        |
| 22     | 296.124 | 0.322| 0.86  | 157.4   | 54.692   | 237.834 | 0.556        |
| 23     | 318.341 | 0.322| 0.852| 171.972| 56.837   | 233.858 | 0.554        |
Thus, after conducting the confirmatory test it was found that the practical results are very much similar to the solution suggested by the software and the error percentage is very less.

3.4. Model graphs for brass

Graphs are plotted between the input parameters and the output parameters, keeping one input parameter i.e. DoC constant.

The graph shows, Figure 6, the effect of feed and speed on the EC, MRR, and resultant force.

- Graph (a) signifies that as the feed increases the EC increases. Also, with the increase in speed the EC increases linearly.
- Graph (b) signifies that with the increase in feed MRR also increases, with the increase in speed the MRR increases but at a rate less than that of the feed rate. Thus, it can be said that with the increase in feed and speed MRR is increasing.
- Graph (c) As, it can be seen from the above that with the increase in feed the RF increases while as the speed increases there is no substantial change in the RF.

As the cutting forces are greater and the machining power is higher thus the energy consumption increases. (Skoczynski et al., 2013). The MRR is higher at the peak values of cutting speed and feed rate. The results showed that the feed rate has less significant effect and cutting speed has the lowest significant effect on MRR (Elmunafi et al., 2015). Also, the resultant forces are affected by the feed and the speed of operation. They increase steadily in the beginning and thereafter they are stagnant and change with non-homogeneity of the material, also due to ductile and malleable properties of the material.

3.5. Aluminum

Again the maximization and minimization of the goals were done and the specific limits were allocated, Figure 7.

The optimized values were obtained and the most optimum value was selected.

Table 7 shows that out of the 22 solution found by the software the first solution is the most optimal solution. The confirmatory tests were carried on this value (Table 8).

The confirmatory test is again found very close to the solution suggested by the software and the error percentage is very less.
Figure 6. Model graphs between input and output parameters (DoC = Constant).
3.6. Model graphs for aluminum

Graphs are plotted between the input parameters and the output parameters, keeping one input parameter i.e. DoC constant.

The above graphs show, Figure 8, the variation in EC, MRR, and DoC with the variation in speed, feed, and DoC. (a) The feed varies parabolically with EC while the speed varies almost linearly. (b) The variation in DoC is parabolic and feed with almost linear with MRR. (c) Similarly speed and feed varies parabolically with RF.
As the cutting forces increases at the higher machining power the energy consumption increases. (Skoczynski et al., 2013). The MRR is higher at the peak values of cutting speed and feed rate, aluminum being a soft material. The results showed that the feed rate has less significant effect and cutting speed has the lowest significant effect on MRR (Elmunafi et al., 2015). Also, the resultant forces are affected by the feed and the speed of operation.

4. Energy saving calculated
In order to find the energy saved, using the optimized parameters obtained after confirmatory test, firstly the EC when machining is done using non-optimized input parameters was found. For example, for the case of aluminum:

No. of working hours for the lathe/annum = 704 h.

EC while performing the similar operation = 203.35 Watts or 203.35 J/s.

Hence, the annual energy consumed = 203.35 × 3,600 × 704 = 515370240 J.

While using the optimized parameters, the energy consumed is = 186.75 Watts or 186.75 J/s.

Hence, the annual energy consumed = 186.75 × 3,600 × 704 = 473299200 J.

Amount of energy saved annually = 515370240 − 473299200 = 42071040 J or 42071.04 k Wh.

% of energy saved = 8.16%.

After that, the energy consumption, taking the optimized parameters into consideration was obtained (Table 9).

Thereafter, the amount of energy saved was calculated by finding the difference of two and accordingly the corresponding percentage energy saving was calculated. Finally, the equivalent carbon footprints saved were calculated Table 10.

As per the Ministry of Energy, India, the conversion of electricity into carbon footprints is:

| Table 8. Confirmatory test |
|---------------------------|
| Parameter | Unit | Value | Parameter | Unit | Value |
| Speed     | (rpm) | 575.75 | $F_s$       |       | 11    |
| Feed      | (mm/rev) | 0.67  | $R_f$       | (N)   | 269.81|
| DoC       | (mm)  | 0.89   | $I_1$       | (A)   | 4.01  |
| $V_1$     | (V)   | 415    | $E_1$       | (W)   | 1,664.15|
| $D_1$     | (mm)  | 30     | $I_2$       | (A)   | 4.46  |
| $D_2$     | (mm)  | 29.11  | $E_2$       | (W)   | 1,850.9|
| $T_1$     | (s)   | 40     | $E$         | (W)   | 186.75|
| $F_T$     |       | 21     | MRR (mm³/s) |       | 136.94|
| $r_T$     |       | 14     |             |       |       |

| Table 9. Optimized set of input values |
|----------------------------------------|
| S. No. | Material | Speed (rpm) | Feed (mm/rev) | DoC (mm) |
|--------|----------|--------------|----------------|----------|
| 1      | Mild Steel | 250.71       | 0.67           | 0.89     |
| 2      | Brass    | 364.66       | 0.67           | 0.74     |
| 3      | Aluminum | 575.78       | 0.67           | 0.89     |
Figure 8. Model graphs between input and output parameters (DoC = Constant).
1 kWh (Electricity) = 0.523 kg CO₂/kWh.

The result shown in Table 10, give the amount of energy saved for each material in percentage and the Carbon footprints saved in kg.

5. Conclusion

After comparing, the response factors, namely energy consumption, MRR, and resultant forces in case when machining is done on the conventional values and when it is carried out using the optimal parameters obtained from the confirmatory test it is concluded that the energy consumption in case of machining done with optimal parameter is less than what was consumed during machining with conventional values. Thus, it is suggested that if the given values, Table 9, of input parameters (speed, feed, and DoC) are used for machining (turning operation), a considerable amount of energy can be saved.

Now since, this experiment was successful thus, if the same concept can be applied in manufacturing industries then energy consumption of the industries (where automation is not deployed) can be reduced and a substantial portion of energy can be saved. Also, as explained earlier, the reduction in energy consumption of industry will result in decrease in carbon footprints.

It was also observed that the amount of energy saved for each material varies. The reason for this is the difference in the densities, hardness, and grain structure.

| S. No. | Material | Energy consumed by performing single operation with standard inputs (J/s) | Annual energy consumed (J) | Annual energy consumed with optimized values (J) | Energy saved (kWh) | Energy saved (%) | Carbon footprints saved (kg of CO₂) |
|-------|----------|--------------------------------------------------------------------------|-----------------------------|-----------------------------------------------|--------------------|-----------------|------------------------------------|
| 1     | Mild steel | 37.3                                                                     | 94533120                    | 84142080                                      | 10,391.040         | 10.99           | 543,451.51                       |
| 2     | Brass     | 157.7                                                                    | 399674880                   | 368121600                                     | 31,553.28          | 7.89            | 16,502.36                        |
| 3     | Aluminum  | 203.35                                                                   | 515370240                   | 473299200                                     | 42,071.04          | 8.16            | 22,003.15                        |

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