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Application of Sensitivity Analysis on Regression Models for Assessing Optimal Carbon Emissions from CNC Manufacturing Systems

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Abstract

Machining industries always strive to show less hazardous impacts, such as carbon emissions and resource wastages, in overall global emissions. To achieve better reduction of pollution from machining industries, they prefer to utilize the concepts of optimization and stability studies. Hence, this present work deals with determining the sources of carbon emissions from various routes of CNC manufacturing systems, such as CNC lathe and turn-mill center operations and assessing them analytically under dry and wet (aerosol-mist of green fluid such as neem oil) conditions. The analysis of the emission results is used to get an insight into the effect of the chosen manufacturing system on the environment. The impact of the machining parameters (such as cutting speeds, tool feeds, and depth of cuts) in generating the emissions is also studied for optimization. The consistency in stability of the optimality is thus analyzed using sensitivity analysis based on the empirical regression models. The design of experiments is based on Taguchi orthogonal array theory, and the individual optimization is done using the concept of signal-to-noise ratios.

Keywords

Green fluids, Manufacturing systems, Carbon emissions, Mist machining, Optimization, Sensitivity analysis

Introduction

The power derived from non-renewable energy sources (fossil fuels) is the major source of energy for industry, agriculture, domestic needs, and transport. The release of greenhouse gases by these fuels, which leave a carbon footprint, is a chief source of concern, as they produce irreversible global warming. Industries, especially manufacturing companies, are considered one of the major sources of Carbon dioxide (CO_2) emissions. It is therefore consequential to analyze manufacturing processes from the perspective of their effect on the environment. This area of research has gained prominence in the last decade when the international community has given it the much-needed importance and impetus to control the emission levels. The present work is mainly intended to serve this purpose, as it is set to assess the carbon emissions from computerized numerically controlled machining processes. The work aims to compute the carbon emissions from the processes that form a part of CNC machining and identify the optimal emission levels for future generations' survival. This thrust area of research has noteworthy ramifications, as it would lead to the development of low-carbon-emitting manufacturing systems and thereby enhance the utilization of energy resources. This topic of research is indispensable as the entire world is seeking to accelerate the rate of growth in the various sectors by pioneering the development of all-inclusive models that are benign to the environment.

An exhaustive review of the current research work in the area of machining was performed to acquaint ourselves with the topic of study. The authors are illuminated by perusing the research papers that have been profusely published in the area of machining processes. It was viewed that a great deal of investigation has been performed centred on optimizing the machining parameters, minimizing the quantity of cutting fluids, and decreasing the cutting energy consumption. A moderate amount of work was also reported on understanding the repercussions of machining processes on the environment.

Babu et al. [1] performed carbon footprint analysis using graphene nanoparticle based cutting fluids in the machining of hardened steel. Furthermore, the authors have extended the studies for attaining optimized power consumption in the machining process. The results proved that using nanofluids in machining processes would reduce the quantum of coolant fluid required and, moreover, provide safe, clean, and environmentally friendly conditions. Amurtha et al. [2] performed a detailed analysis of using graphene-based self-lubricating tools on cutting forces generated and tool wear in machining of Inconel-718. The authors also estimated the carbon emissions in the machining of Inconel-718 under nanofluid environmental conditions. The results indicated that using nanoparticles (graphene) in cutting fluids has a remarkable effect on the chosen parameters due to the increase in thermal conductivity of the fluid and the lubrication effect induced between the work piece and tool. Okokpujie et al. [3] investigated the effect of using Al_2O_3, titanium oxide, and SiO_2 dispersed in water individually as coolants. The machining process selected for the study was end-milling operation on mild steel. The authors studied the effect produced by nano-based cutting fluids on the machining temperature and surface morphology of chips. Their observations showed that nano-coolant containing Al_2O_3 exhibited superior performance. Emmanual et al. [4] conducted experiments to investigate the effect of using nano-based vegetable oil lubricants in the turning operation of Monel-k-500. The experiments were performed with 2%-silver nanoparticles dispersed in *Pongamia pinnata* oil. The cutting forces, the machining temperatures, surface roughness, and tool wear morphology were the parameters chosen for the analysis.

Dahmus and Gutowski. [5] accomplished a system-level environmental analysis of machining. Their work also included the study of the impact of the auxiliary processes like material and cutting fluid preparation on the environment. The results of their study have proven that the energy consumption for the actual machining processes could only be a small fraction of the total energy associated with the operation. It was interestingly revealed by the authors that the power expended for raw material production far outweighs machine tool operation in some cases. Branker et al. [6] proposed a microeconomic model that could be adopted in manufacturing operations to optimize the machining parameters. The model developed is inclusive of energy and environmental costs. The authors further applied the model to theoretical and experimental results to obtain the implications on carbon emissions and cost sensitivity. A few more papers analogous to this work have also been reported. Hegab et al. [7] presented and discussed the addition of carbon nanofluids and Al_2O_3 gamma nanoparticles as additives to the base fluid to achieve minimum quantity lubrication in machining of Inconel-718. Their results indicated that the flank wear, surface roughness, and energy consumption which were selected as three machining outputs decreased appreciably compared to the normal cutting fluids. The studies also included multi-objective optimization using NSGA-II.

Gutowski's [8] research was the first of its kind in studying the carbon and energy intensity of manufacturing processes. The author deliberated on the strategies that could be adopted by the manufacturing firms to reduce the carbon footprint of their units. Decarbonizing fuels, investing in carbon offsets, augmenting the energy efficiency of the plants, and assessing the carbon footprints associated with the product are the options recommended by the author. Kulkarni et al. [9] conducted research studies to produce alumina-copper nanoparticles suspended coolants. These studies were accomplished with 0.025% to 0.3% (by weight) addition of nanoparticles to strub vulcan futura coolant oil. The results reflected that the thermal conductivity enhanced by 23% compared to the base fluid. Yi et al. [10] performed experiments on turning of Ti-6Al-4V under graphene-oxide based nanofluid environment. The experiments were unique in nature as the authors accomplished studies on the vibration effects produced in turning of hard materials (titanium alloy). The results showed that the tool wear, cutting forces, and the vibrations were considerably lower than those produced using normal based fluids.

Li et al. [11] focused on developing an analytical method for assessing the carbon emissions from the CNC lathe machining system. The work considers an extensive system replete with CNC machines, tool preparation setups, raw material processing, and waste disposal systems and quantifies the carbon emission from each unit separately. Sihag and Sangwan. [12] presented a methodology to quantify the carbon emissions of CNC machine tools. They developed a multi-objective optimization model for minimizing carbon emissions and machining time for a turning process. The model was solved by adopting a genetic algorithm, and the results were validated using experimentally obtained results. Zhou et al. [13] elaborated on the accurate calculation and evaluation of processing carbon emissions based on CNC machines consuming electrical energy by incorporating the role of tool wear effects and influence. They divided the model into two parts: (i) the relationship between processing carbon emissions and cutting power; and (ii) cutting power and tool wear condition. Yakubu and Bello [14] investigated the suitability of neem seed oil as a cutting fluid in metal machining. They compared the performances of neem seed oil and soluble oil under dry machining, presenting the responses in terms of surface finish and tool wear. The authors concluded that the neem oil was a better option as it exhibited remarkable results.

By taking the elaborate findings from the aforementioned literature into cognizance, it is inferred that there exists a scope for intensive research on exploring the environmental impact of machining processes. This line of research is more significant now than ever before, as CO_2 emissions from the manufacturing sector vary between 25% and 45% of the overall CO_2 emissions from the industry. Further, CNC machines are very extensively adopted for applications involving mass production, and hence, it is highly imperative to explore the carbon footprints left by CNC machining systems. The current work mainly focuses on determining the suitable process parameters for lower emission generations, which cannot be externalized. Hence, the technique of optimization, checking its consistency, and further refinement of optimization are elaborated.

Methodology

Methodology for assessing carbon emissions

Though power plants that use fossil fuels in the production of electrical energy emit greenhouse gases continuously, the machine tool system that utilizes this energy will contribute to carbon generation indirectly through its operations. It is therefore necessary to quantify the carbon emissions of a machining system by assessing its rate of power consumption.

A turn-mill center (PMK; TMC-XL-200) using single-point (lathe operation) and multipoint cutting (turn-mill operation) using PVD-coated Ti-Al-N tools for plain face turning processes using Taguchi orthogonal array L_{16} design is used. The concept of designing is used to experiment on Titanium alloy (Grade-5: Ti-6Al-4V) using process variables as spindle speeds (rpm), tool feeds (mm/rev) for lathe facing operation; mm/min for co-axial turn-mill operation), and depth of cut (mm), with levels of four each under dry and aerosol-neem mist environments for assessing carbon emissions, as shown in table 1. The green cutting fluid, such as neem oil, is used in the form of an aerosol-mist with a flow rate of 60 ml/min and a pressure of 5.5 bars. The determined carbon emissions in CNC lathe facing operations and co-axial turn-mill operations are used to determine the optimal combination using the Taguchi signal-to-noise ratio concept. Further, sensitivity analyses, if applied to optimal combinations, check their optimal consistency, and carry out refinement of the optimality.

Formulae and nomenclature used for determining carbon emissions

The present work has adopted values taken from the database of "CO_2 Baseline Database for the Indian Power Sector, User Guide Version 15.0, December 2019", published by Indian Central Electricity Authority. The $CEF_{electrical} = 0.91$ [12, 13]. The boundaries that completely define the CNC machining system considered are as shown in figure 1.

The parameters used in the calculations of carbon emissions are listed below:

Actual cutting time (T_{cut}); *Ambient temperature considered as 25 °C* (T_{ab}); *Auxiliary power in kW* (P_{aux});	*Carbon emission factor of the tool based on its embodied energy and the energy for its production* (CEF_{tool}); *Cutting power in kW* (P_c);	*Latent heat of fusion in kJ/kg (L);* *Melting point temperature of the tool material in °C* (T_m); *Specific heat of tool material in kJ/kg-K* ($C_{P_{tool}}$);
Auxiliary time (T_{aux}): *The tool approach and retract times from its reference position*	*Ideal power in kW* (P_i); *Ideal time* (T_{ideal}); *Energy meter constant (kW-hr/rev) (E)*	*Time for one revolution of energy meter in seconds (t);* *Weight of the chip removed in gram* (W_{chip})

(a) Evaluation of emissions from electrical source ($CE_{electrical}$):

The carbon emissions related to electrical energy consumption ($CE_{electrical)}$ is taken as:

Table 1: Design of experiments and the generated response values.

Exp. No.	Spindle speed: N (rpm)	Tool feed: f	Depth of cut: doc (mm)	Total CO_2 emissions in CNC lathe facing operation		Total CO_2 emissions in co-axial CNC turn-mill operation	
				Dry machining	Aerosol-neem mist machining	Dry machining	Aerosol-mist machining
1	510	0.05	0.25	0.222	0.254	1.66	3.08
2	510	0.10	0.50	0.411	0.415	1.14	1.88
3	510	0.15	0.75	0.590	0.590	1.01	1.46
4	510	0.20	1.00	0.657	0.649	1.03	1.38
5	764	0.05	0.50	0.321	0.357	1.77	3.19
6	764	0.10	0.25	0.169	0.177	0.94	1.65
7	764	0.15	1.00	0.539	0.512	1.23	1.68
8	764	0.20	0.75	0.450	0.385	0.97	1.31
9	1019	0.05	0.75	0.452	0.459	2.15	3.59
10	1019	0.10	1.00	0.538	0.518	1.62	2.29
11	1019	0.15	0.25	0.172	0.159	0.79	1.26
12	1019	0.20	0.50	0.285	0.268	0.92	1.20
13	1273	0.05	1.00	0.643	0.660	2.60	3.87
14	1273	0.10	0.75	0.512	0.501	1.52	2.17
15	1273	0.15	0.50	0.356	0.307	1.15	1.56
16	1273	0.20	0.25	0.227	0.156	0.88	1.18

CO_2 emissions: Carbon emissions (Kg-CO_2).
f: Tool feeds (mm/rev for lathe facing operation; mm/min for co-axial turn-mill operation).

$$CE_{electrical} = 0.91 * \left(P_c * T_{cut} + P_{aux} * T_{aux} + P_i * T_{ideal}\right) \quad (1)$$

(b) Evaluation of emissions from machining tool embodied in tool as well as energy consumed in manufacturing the tool (CE_{tool}):

The CE_{tool} is mathematically represented from literature [12] as:

$$CE_{tool} = \left(CEF_{tool} * \text{weight of the tool}\right) * \left(T_{cut}/T_{tool}\right) \quad (2)$$

Where, $T_{tool} = (N + 1)\,T_o$ [12, 13] is the life cycle of the tool, N being the number of times the tool is grinded, and T_o being the durability time taken from the tool supplier's catalogues and $CEF_{tool} = 0.61086$ (kg-CO_2/Kg).

(c) Evaluation of emissions from work piece material in form of chips (CE_{mat}):

$$CE_{mat} = CEF_{mat} * W_{chip} \quad (3)$$

Where, the CEF_{mat} depends on the embodied energy of the material and is given as 49.5 Kg CO_2/Kg [12, 13].

(d) Evaluation of emissions from cutting and coolant material ($CE_{coolant}$):

The present study evaluates the carbon foot-print leftover from a vegetable oil (i.e., neem oil which is also known as "*Azadirachata indica*"), which is used as a cutting fluid. The emissions associated with the cutting fluids have two components, which are CE_{cfp}- carbon foot-print leftover in the production of the coolant and CE_{cfd} -carbon emissions generated by the disposal of contaminated cutting fluid. Hence:

$$CE_{coolant} = CE_{cfp} + CE_{cfd} \quad (4)$$

$$CEF_{cfd} = \frac{\text{cooling oil consumed in ml}}{1000} * CEF_{cfd} = \frac{x * 44}{v/1000}\left(\text{kg } CO_2/\text{liter of coolant}\right) \quad (4a)$$

Where, "x" is the quantity of coolant used (in ml).

As the molar and volumetric analysis are equivalent, the molar volume of the coolant 'v' c.c will discharge x moles of CO_2 (or) v/1000 liters will produce "x" * 44 gm of CO_2. And thereby, the CEF_{cfd} is:

$$CEF_{cfd} = \frac{\text{cooling oil consumed in ml}}{1000} * CEF_{cfd} = \frac{x * 44}{v/1000}\left(\text{kg } CO_2/\text{liter of coolant}\right) \quad (4b)$$

(e) Evaluation of emissions from worn-out tool (CE_{ctd}):

Assuming 10% loss of heat during this process,

$$CE_{ctd} = 0.91 * \frac{W_{tool} * \left[C_{p_{tool}} * \left(T_m - T_{ab}\right) + L\right]}{0.9}\left(\text{kg } CO_2\right) \quad (5)$$

(f) Evaluation of emissions from chip disposal (CE_{dchip}):

The process of chip disposal is analogous to that adopted for recycling of worn tools.

$$CE_{dchip} = 0.91 * \frac{W_{chip} * \left[C_{p_{tool}} * \left(T_m - T_{ab}\right) + L\right]}{0.9 * 3600}\left(\text{kg } CO_2\right) \quad (6)$$

(g) Evaluation of emissions from air compressor (CE_{acp}):

The carbon emissions associated with air compressor is given by the expression:

$$CE_{air\ comp} = \frac{n * 3600}{E * t} * T_{cut} * 0.91 \quad (7)$$

(h) Evaluation of emissions of pump (CE_{pump}):

Two pumps are adopted, one for pumping the coolant (viz. 0.04 W capacity) from the reservoir to the machining zone, and another for lifting the oil back from sump to the reservoir (viz. 0.017158 W capacity).

$$CE_{pump} = \frac{\text{Pump capacity} * T_{cut}}{3600} * CEF_{electrical} \quad (8)$$

Using the formulae given, the carbon emissions are determined after completing each experiment and recorded as shown in table 1.

The dimensions of the cylindrical workpiece (Ti-6Al-4V) and the experimental setup is as shown in figure 2. The machining process is executed using a selected combination of cutting parameters that are based on the m achine tool specifications and tool manual. The combination of cutting parameters, divided into four levels, is based on Taguchi L_{16} [15-18]. The cutting tool inserts used weigh 8.77 g and 1.56 g for CNC lathe and CNC turn-mill, respectively. A digital clamp meter is used to measure power consumption in the machining systems. The standby time for the set of experiments is assumed to be 60 s.

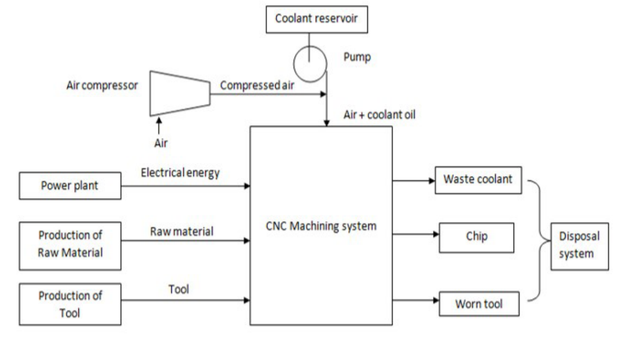


Figure 1: Configuration diagram of the complete machining system.

Methodology for assessing individual optimality

Single cut facial operations were performed on Ti-6Al-4V cylindrical material using a single tool facing operation and multiple teeth cutters co-axial facing operation. The signal-to-noise (S/N ratio) ratio as given in equation 9, which depends on optimization of the quality characteristics, is recorded, and the individual optimality is calculated using equations 10 and 11 [16] and is shown in table 2.

$$(S/N)_{Smaller-is-Better} = -10Log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{9}$$

Where, 'n' is observation number and 'y_i' is observation value.

The formulae for individual optimum response based on the S/N ratios is mentioned in equations 3 and 4.

$$\eta_{optimum} = \eta_{avg} + \sum_{i=1}^{n}\left(\eta_{ideal} - \eta_{avg}\right) \tag{10}$$

$$Response_{optimum} = \sqrt{10^{\pm\frac{\eta_{optimum}}{10}}} \tag{11}$$

Where, 'n' is observation number, 'η_{opt}' is optimum S/N ratio, 'η_{avg}' is average S/N ratio, and 'η_{ideal}'is ideal level of each S/N ratio parameter.

The individual optimality describes that the lower depth of cuts is adoptable in any case of metal machining systems as the load on the tool and work-piece interface will be less for shearing the workpiece materials. On the other hand, if the environmental condition is a fluid medium, then the lubrication can be used for reducing the time of machining by switching the machining to higher feed rates. The ideal speeds are 1019 rpm, 1019 rpm, 510 rpm, and 510 rpm; ideal feeds 0.10 mm/rev, 0.20 mm/rev, 0.20 mm/min, and 0.20 mm/min; ideal depth of cut 0.25 mm for all process; optimum response values are 0.746, 0.659, 0.722, and 1.834 for lathe dry/aerosol mist and turn-mill dry/aerosol, respectively.

Sensitivity analysis using regression models of carbon emissions

Regression models are empirical models that show reality, which is through the data that the confrontation happens. Hence, empirical models that are developed based on the results of experimentation through regression analysis are of much use for statistical analysis. The quality of the fit of the empirical model is measured by the statistical R^2. The surface response parameters in machining can be derived from the experimental data by using the following relations [15]:

$$\text{Response} = C * V^a * f^b * d^e \tag{12}$$

Where, "V" is tool speed (rpm), "f" is the feed rate (mm/min), and "d" is depth of cut (mm). C, a, b, and e are model parameters to be estimated from experimental results. Converting the exponential form of responses to linear model with help of logarithmic transformation and modeled as:

$$\text{Log(Response)} = \log C + a * \log S + b * \log f + e * \log d \tag{13}$$

The second order linear and nonlinear equations thus generated are listed in table 3 with the calculated goodness-of-fit (R^2) values.

Basing on the regression models thus developed, as shown in table 3 are used to estimate the sensitivity of the parameters by altering their levels, observing the deviation of the responses generated, and claiming their sensitivity. The sensitivity

Table 2: Signal-to-noise ratios of the generated response values.

Exp. No.	Actual parameters			S/N ratio of total CO_2 emissions (Kg-CO_2)			
	Spindle speed: N (rpm)	Tool feed: f	Depth of cut: doc (mm)	In CNC facing lathe		In co-axial CNC turn-mill	
				Dry condition	Aerosol-mist condition	Dry condition	Aerosol-mist condition
1	510	0.05	0.25	13.05	11.90	-4.39	-9.78
2	510	0.10	0.50	7.72	7.65	-1.17	-5.48
3	510	0.15	0.75	4.59	4.58	-0.13	-3.29
4	510	0.20	1.00	3.65	3.75	-0.22	-2.83
5	764	0.05	0.50	9.87	8.95	-4.95	-10.07
6	764	0.10	0.25	15.47	15.02	0.56	-4.34
7	764	0.15	1.00	5.37	5.82	-1.83	-4.50
8	764	0.20	0.75	6.93	8.28	0.25	-2.37
9	1019	0.05	0.75	6.90	6.76	-6.65	-11.10
10	1019	0.10	1.00	5.38	5.72	-4.19	-7.20
11	1019	0.15	0.25	15.27	15.97	2.02	-2.03
12	1019	0.20	0.50	10.91	11.44	0.74	-1.60
13	1273	0.05	1.00	3.84	3.60	-8.29	-11.74
14	1273	0.10	0.75	5.82	6.00	-3.64	-6.75
15	1273	0.15	0.50	8.97	10.26	-1.24	-3.86
16	1273	0.20	0.25	12.87	16.12	1.11	-1.42
Optimal combination:				N3-f 2-doc1	N3-f 4-doc1	N1-f 4-doc1	N1-f 4-doc1

analysis attempts to establish significant relations among surveillances, model contributions, and predictions, guiding the development of improved models. A sensitivity analysis defines, beneath a known set of statements, how dissimilar values of a self-determining variable influence a specific dependent variable. Sensitivity analysis also investigates how various sources of ambiguity contribute to overall hesitation inside an arithmetical model. Based on one or more variable efforts, this technology is employed and surrounded by a definite boundary.

The model is often called what-if or simulation analysis.

- Analyzing the sensitivity can help with forecasting.
- Analyzing the sensitivity helps predict how true data will be used.

The sensitivity of the parameter level changes is shown in table 4 and table 5, based on which conclusions are drawn about the sensitivity.

While machining with a lathe under dry conditions, the feed seems to be the most sensitive parameter to changing the response value and deducing the CO_2 emissions from 0.1467 to 0.1415. The contact time between the tool and work piece minimizes due to an increase in feed, and thereby the emission tends to decrease with other parameters being constant. While machining in the mist condition, emission seems to remain the same, as the cutting time remains the same as that of dry machining.

In case of co-axial turn-mill operations, the cutting time is high when compared to lathe-facing operations, and hence, the emissions are much higher. But under the aerosol-mist condition of turn-mill operations, the cutting fluid acts as a lubricating agent due to prolonged machining times, and thereby the load in the machining reduces.

Results and Discussion

The complete experimental work was implemented on CNC machines with the consideration that CNCs are the most commonly used machines in industry. The emissions from two different machining systems, i.e., CNC lathe and CNC turn-mill were evaluated to the core under both dry and wet conditions. The effect of machining parameters on carbon emissions is a much-desired study, as very few reports have been published. A focus on this nature of study is essential, as the quality of products and tool lives are closely related to the phenomenon of emissions in addition to their effect on the environment. As is evident from the following paragraphs, the emissions are substantially influenced by the cutting parameters, viz., spindle speed, depth of cut, and feed rate.

It is observed through this work that the wet machining, as compared to the normal dry machining, escalates the emissions appreciably due to the utility of cooling subsystems like pumps, compressors, etc. This observation is highly pronounced in CNC turning as compared with CNC lathes. The results for both dry and wet conditions at different speeds revealed almost similar facts, except that the emissions are slightly higher in wet machining for CNC lathes and moderately high in CNC turn-mill. Carbon emissions are observed to be mostly influenced by the depth of the cut. A comparative study of carbon emissions from the two machining systems considered for analysis under both dry and wet machining conditions is also illustrated in the form of bar charts (Figure 3a-3d) at different parametric combinations. Though it is evident

Table 3: Regression models and their R^2 values of the responses.

CNC machining system		Regression equation developed for CO_2 emissions	R^2
Lathe facing operation	Dry condition	$0.518 - 0.00124 * N + 0.169 * f + 0.799 * doc + 6.703 * 10^{-7} * N^2 - 0.736 * f^2 - 0.208 * doc^2$	99.7%
	Aerosol-mist condition	$0.617108 - 0.00128 * N - 0.497 * f + 0.781 * doc + 6.747 * 10-7 * N^2 -0.272516 * f^2 -0.1954 * doc^2$	99.3%
Co-axial turn-mill operation	Dry condition	$2.6134 - 0.000592456 * N - 23.0116 * f + 0.604143 * doc + 5.80098 * 10-7 *N^2 + 63.7342 * f^2 + 0.10055 * doc^2$	98.7%
	Aerosol-mist condition	$4.8704 - 0.000375288 * N - 44.2937 * f + 0.652025 * doc + 3.99533 * 10^{-7} * N^2 + 121.226 * f^2 + 0.0263957 * doc^2$	98.5%

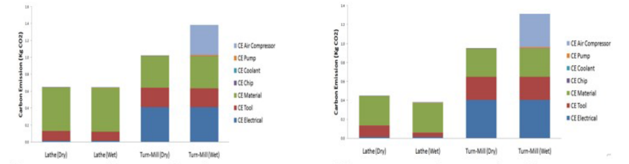
Table 4: Sensitivity analysis of parameters on lathe operating system under various conditions.

Operation with dry condition								Remarks
N: Speed (rpm)	1019	1273	764	1019	1019	1019	1019	The feed parameter shows sensitivity in refining the emissions
f: Feed (mm/rev)	0.10	0.10	0.10	0.05	0.05	0.20	0.20	
DoC: Depth of cut (mm)	0.25	0.25	0.25	0.25	1.00	0.25	0.50	
CO_2 emission ((Kg-CO_2)	0.1467	0.222	0.158	0.1438	0.548	0.1415	0.302	
Facing operation with aerosol-mist condition								
N: Speed (rpm)	1019	1273	510	764	1019	1019	1019	No parameters shows sensitivity in refining the emissions
f: Feed (mm/rev)	0.20	0.20	0.20	0.20	0.05	0.20	0.20	
DoC: Depth of cut (mm)	0.25	0.25	0.25	0.25	0.25	1.00	0.25	
CO_2 emission ((Kg-CO_2)	0.086	0.153	0.212	0.105	0.170	0.488	0.086	

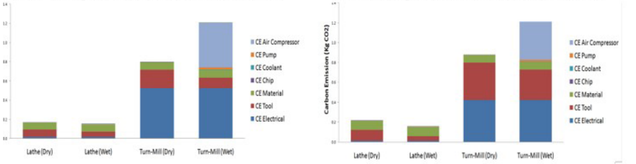
Table 5: Sensitivity analysis of parameters on turn-mill operating system under various conditions.

Co-axial operation with dry condition							**Remarks**
N: Speed (rpm)	510	764	1273	510	510	510	No parameters shows sensitivity in refining the emissions
f: Feed (mm/rev)	0.20	0.20	0.20	0.05	0.05	0.20	
DoC: Depth of cut (mm)	0.25	0.25	0.25	0.25	1.00	0.25	
CO_2 emission (($Kg-CO_2$)	0.566	0.603	0.903	1.628	2.175	0.566	
Co-axial operation with aerosol-mist condition							
N: Speed (rpm)	764	1273	510	510	510		The depth of cut parameter shows sensitivity in refining the emissions
f: Feed (mm/rev)	0.20	0.20	0.05	0.20	0.20		
DoC: Depth of cut (mm)	0.25	0.25	0.25	1.00	0.25		
CO_2 emission (($Kg-CO_2$)	0.971	1.195	3.03	1.45	0.937		

Figure 2: CNC turn-mill and MQL setup.

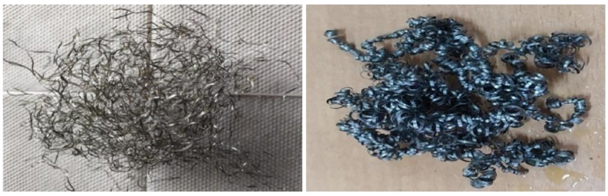


(a): N-510 rpm, f-0.05 mm/rev, doc-0.25 mm (b): N-764 rpm, f-0.05 mm/rev, doc-0.50 mm

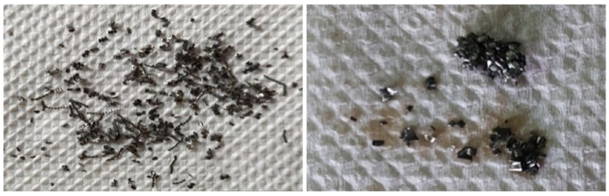


(c): N-1019 rpm, f-0.05 mm/rev, doc-0.75 mm (d): N-1273 rpm, f-0.05 mm/rev, doc-1.00 mm

Figure 3: Comparisons between two machining systems under dry and wet conditions at low emission.



(a) Lathe facing operation under dry condition **(b)** Lathe facing operation under wet condition



(c) Turn-mill co-axial operation under dry condition **(d)** Turn-mill co-axial operation under wet condition

Figure 4: Chips developed under dry and neem aerosol-mist (wet) machining conditions.

from the literature that wet machining produces a superior surface finish and a lesser cutting temperature and tool wear, it produces a deleterious effect through the release of a higher quantum of gases, which has been reflected in our studies.

Interesting facts are revealed from these plots with regards to the quantum of carbon emissions, which are highly contrasting. It can be observed from the plots that turning under wet conditions produces the highest carbon emissions of all cutting conditions. It is in fact 1.72 to 2.3 times higher than dry turn-mill. On a similar comparison, it was interestingly observed that the emissions in CNC lathe don't reflect such magnified variation between dry and wet conditions.

The chips in turn-mill machining makes versatile for handling, as they are broken into small chips due to multi-point cutting tips (Figure 4) and can be filtered easily from the machine sinks with ease. But on the other hand, chips generated in lathe facing operations are in the form of birds-nest which are hazardous to deal with, as shown in figure 4a and moreover, they disturb the surface machined.

When the machining is incorporated with cutting fluid environment (viz. utility of green neem cutting fluids), the chips which are inform of bird`s nest (in dry machining) are prolonged downwards in form of helical strings due to the slippery of contact area and the density of the green neem cutting fluid, which can be seen in figure 4b. Hence, the cutting fluid utility enhance in reduction of the damage in mesoscopic region during the single-point machining operations.

The machining time in turn-milling operations is higher when compared to lathe operations. Hence the carbon emissions associated with the actual machining processes are a considerable part of the total emissions from the turn-mill process. Under dry conditions, it is about 66% and 10% in turn-mill and lathe processes, respectively. An important and critical observation in the wet turning milling process is related to the discharge associated with the air compressor, which contributes to 1/3 of actual machining processes. Under dry conditions, the release of gases related to tool manufacturing and disposal accounts for approximately 45% and 24% of total emissions in the lathe and turn-mill processes, respectively. This could be attributed to the higher weight of the cutting tool insert used in lathes. Therefore, it can be construed that the manufacturing and disposal of tools also involves an appreciable release of gases.

Conclusion

CNC machine tools are the most widely preferred in industries due to their intrinsic capabilities relative to conventional machine tools. This paper has therefore focused on optimizing carbon emissions from these machine tools for lathe-facing operation and co-axial turn-mill operations, including the CNC manufacturing system along with the ancillary systems like material and tool production units, chip disposal systems, etc. The experimentation was executed in both dry and wet conditions to obtain a relative account of CO_2 emissions. The investigation of the results revealed that the emissions became very critical with the increase in machining time. It has been discovered that machining parameters have an unfailing effect on carbon emissions, while cutting fluid acts as a cooling and lubricating agent at the mesoscopic area between tool and workpiece, influencing emission generation. The properties of cutting fluids are vulnerable to change with the addition of appropriately chosen nanoparticles as very few works have been reported. However, the present work has only dealt with studying the effect of using pure neem oil as a coolant on the environment in terms of greenhouse gas emissions. As a future scope, the effect of adding nanoparticles to neem oil could be studied on their role in the emission process.

Acknowledgements

None.

Conflict of Interest

None.

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