CHAPTER 8
CONCLUSIONS

Energy efficiency is a matter of concern for manufacturing industries due to ever increasing energy costs and new environmental policies. Machine tools are dominant electrical energy consumers in manufacturing industries and responsible for high carbon emissions. The complex structure and large number of energy consuming components in a machine tool provide a constant challenge to the researchers to characterize and model the energy consumption during a machining process. This study analyzed the energy consumption behavior of the machine tools to understand the energy flow during the machining process. The carbon emissions caused by the machine tools are also studied. The thesis addressed the strategies to reduce the cutting and non-cutting energy during a machining process.

A systematic literature review of 226 articles relevant to the energy aspects of the machining processes is presented in **Chapter 2**. The descriptive analysis of the reference articles showed an exponential rise in the articles during last decade. The environmental aspects of the machining energy need more research attention. The literature review was conducted to address four research areas as follows:

- The classification of the machining energy.
- The energy modelling approaches for the machining energy.
- The strategies used for reducing the machining energy at various levels.
- The evaluation of the machining energy efficiency.

Based on the different energy classification approaches used by the researchers, the research can be divided into six hierarchies; from machining system level to component/Therblig level. The researchers have used analytical, numerical and experimental modelling techniques for estimation of machining energy at different levels.

Based on the expression of energy and the level of assessment, the energy models can be divided into five groups: machine tool energy models, cutting energy models, operational state based models, component based models, and Therblig based models. It was observed that Therblig based models provide higher level of classification and help to develop precise and accurate energy models. It was found that the machining energy saving strategies have been researched at design, macro process planning, and micro process planning phases. Some important energy saving strategies in design phase include replacing bulky mechanical drives with light and direct drives, incorporating electrical actuators, integrating safety controller for moving parts, reducing transformer losses, and use of lighter and efficient machine tool components. The energy saving strategies at macro process planning include selection of machine tool and energy efficient scheduling of machining operations. At micro process planning phase, the energy can be reduced by benchmarking the energy consumption of machine tool components, using modular programs, optimizing the tool path and machining parameters, efficient loading of the electric drives, and retrofitting the machine/components. The four major energy efficiency evaluation measures used by the researchers are: energy utilization ratio, real time energy efficiency, specific energy consumption, and relative energy efficiency.

Chapter 3 provides experimental modelling of the energy consumption and carbon emissions during a milling process. Since modern machine tools are equipped with customized components to perform complex operations with high precision, accuracy, flexibility, and degree of automation; therefore, focus was on experimental modelling instead of analytical and numerical modelling. The use of analytical and numerical models is difficult and less accurate for the estimation of machining energy consumption as the machine tools have diverse energy characteristics because of higher level of customization and versatility. Experimental models were developed for various energy consuming components (spindle motor, axis motors, coolant pump, start-up, stand-by, automatic tool changer, and lubrication pump) of a machine tool. A smart metering approach was developed for the classification of energy consumption during different operational states. The smart metering approach was developed in the form of a structured algorithm using a series of feature-extraction and classification algorithms. The smart metering approach was successfully used to classify the machining energy consumption and time during each operating state using the power data at the main supply of the machine tool. It is a user-friendly, cost effective and non-intrusive load monitoring system, which eliminates the high cost and complexity involved with multiple sensor arrangements.

Chapter 4 aimed at reducing the cutting/variable energy consumption of milling process. Multi-objective optimization of machining parameters was conducted for milling process under dry and wet conditions to minimize the specific energy consumption and carbon emissions, maintaining the required surface finish. Taguchi's L_{27} orthogonal array was used for design of experiments to obtain the process responses (specific energy consumption, carbon emissions and surface roughness). Predictive models were developed using response surface methodology to study the effect of cutting parameters (cutting speed, feed, depth of cut, and width of cut) on the three process responses. The adequacy of the models and their fitness was tested using statistical analysis. Multi-objective optimization was performed using two approaches – desirability analysis and multi-objective genetic algorithm. It was found that saving of specific energy consumption and carbon emissions can be achieved by having the pragmatic target values of surface roughness instead of its minimization.

Chapter 5 aimed at reducing the fixed energy consumption and carbon emissions of a machining process. A Therblig based micro analysis methodology was developed to analyze, quantify and reduce fixed energy consumption of a milling process. A value stream mapping technique in conjunction with Therblig based model was developed to assess the energy consumption, time to process and carbon emissions of a milling process. A case study was presented to validate the methodology. The case study shows the reduction in energy consumption, machining time and carbon emissions by the proposed methodology. The proposed methodology does not alter the machining parameters or the value added time. Therefore, the product quality and tool life are not compromised. The proposed methodology can also be used to develop energy stream maps for more than one machines in parallel to obtain the energy flow with respect to time, and identify the peak load at the factory level. It can assist decision making for scheduling the various machining operations to reduce the peak load at factory level and developing potential energy and carbon emission reduction strategies during product design and process planning stages without compromising the product quality.

A machining sustainability assessment index was developed in **chapter 6** 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 sustainability performance of a machining process. AHP technique was used to assign weights to the performance indicators. A sustainability assessment index was proposed to assess the sustainability of milling process under varying cutting conditions. It was observed that the cutting parameters and coolant conditions play important roles in the sustainability performance during milling. Dry machining performs better than wet machining in environmental dimension at the same parameter settings because of lesser energy consumption and absence of coolant. However, wet machining performs better in economic dimension at the same parameter setting. The proposed sustainability assessment index can be used for the development of sustainability performance labels for machine tools, which can provide decision support information to machine tool manufacturers and production managers to objectively investigate the sustainability performance of the machine tools and assist decision makers for the procurement of suitable machine tools.

Chapter 7 presents life cycle analysis of a milling process to visualize the major hotspots contributing to the environmental impacts. The study was conducted to assess the environmental impacts of aluminum milling process for production of a sample part. The LCA analysis was carried out as per ISO 14040 standard by using Umberto NXT software tool and eco-invent dataset version 3.0. The scope of the study included the production of raw material and consumables (cutting tool, coolant and lubricating oil), transportation (raw material, consumables and finished goods), electricity (machining and HVAC), treatment/disposal (used product, chip processing, worn out cutting tool, and waste coolant and lubricant), and share of machine tool and factory infrastructure for machining. The environmental impacts were assessed in both endpoint and midpoint impact assessment categories by using ReCiPe method. Raw material production, electricity consumption, cutting fluid production and disposal, chip processing, and compressed air production are the high environmental impact generating activities. The major impacts are in terms human health and resource depletion. The effects on climate change, fossil depletion, human toxicity, and metal depletion categories are also high.

Specific Research Contributions

- This study provides a systematic literature review of 226 reference articles, from 1994 to 2018, in the area of machining energy to understand the current state of knowledge and research gaps in the area.
- Experimental models for energy consumption and carbon emissions during the machining process are provided, which can be used to analyze the energy consumption and carbon emissions up to component level.

- A smart metering approach for the machining energy consumption is developed for monitoring and quantifying the machining energy consumption. The proposed smart metering is user-friendly, cost effective and non-intrusive solution unlike multi-sensor deployments.
- The study proposes a more practical multi-objective optimization approach for the selection of process responses and assignment of optimization objectives for machining operations, where the surface roughness is targeted and not minimized.
- Therblig based value stream mapping is developed for a milling process. The proposed VSM provides a kaleidoscopic view of energy consumption and carbon emissions during milling process at micro level.
- The machining performance is assessed beyond the economic and environmental dimensions and a sustainability assessment index is developed for the machining process including the social aspects of the machining processes.
- Life cycle analysis of milling process is conducted to analyze its environmental performance under different end-point and mid-point assessment categories.

Limitations and Future Scope

The analysis of multi machine systems is important to reduce the stand-by energy, which accounts for a significant portion of the machining energy. However, the current study focused on the machining energy analysis at machine tool level. The tool life under varying cutting parameters is not experimentally measured in the study and coefficients from literature were used for estimation of cutting tool life. The actual results may vary depending on the specific cutting conditions and tool-workpiece combination. The carbon emission factors for energy and other factors (cutting tool production, coolant production and disposal) were taken from literature. Different carbon emission factors are reported by different sources and there is lack of standard data set for carbon emission factors. This may cause variation in the result analysis for carbon emissions caused by machining processes. The energy consumption during the transient states is not considered for the analysis of cutting and non- cutting energy consumption, which may cause slight variation in the results.

In future, more efforts should be made to integrate the energy information with industry 4.0 applications for easy accessibility, quantification and visualization of energy data. The future research in the area of machining energy analysis should focus on analysis of the non-cutting energy consumption for multi machine systems. Cyber physical production systems can be developed for better communication among the machine tools and efficient job scheduling to reduce the idle time and stand-by energy consumption of the machine tools. The smart metering system can be integrated with industry 4.0 applications for real time energy monitoring and quantification. Comprehensive and standard data set should be developed for carbon emission factors. Therblig based analysis can be extended to other machining processes and coolant conditions such as minimum quantity lubrication or mist cooling. Future studies can focus on the effect of the tool path and feature processing sequence on energy consumption at the micro level. The current study is conducted at the machine tool level. In future, the research can be extended to the production line level. The future work should consider the energy consumption by the transient states to improve the energy prediction accuracy. The technological intervention for improving the energy efficiency and carbon emissions of the machining processes can be studied. Also, a comprehensive list of indicators can be developed for machining sustainability assessment. The energy models can be used for development of energy labels for the machine tools.