CHAPTER 1

INTRODUCTION

1.1 MACHINING: ENERGY CONSUMPTION AND ENVIRONMENTAL IMPACTS

Manufacturing is a prime wealth-creating activity for any nation. Rising environmental and social concerns have made environmental issues pertinent to industry along with development. Since manufacturing processes contribute significantly to energy and resource consumption, they are responsible for large amount of carbon emissions. Natural resources are depleted at a high rate to meet the ever rising demand of industrial development and this also causes rise in carbon emissions. It also contributes to the threat of climate change, waste management, global warming, and eco-system imbalance (Gutowski, 2007). According to a study conducted by International Energy Agency (IEA), manufacturing industries account for one-third of global energy consumption and 36% of net global carbon emissions (IEA, 2007). The growth of manufacturing is expected to continue for a long time to fulfill the aspiring needs of the population in developing and emerging countries.

Energy is one of the key inputs for manufacturing. Sustainable development, energy security, increasing energy cost, and political compulsions force nations and industry to strive for energy efficiency. This has motivated/forced the manufacturing organizations to adapt sustainable manufacturing practices. Sustainable manufacturing as defined by the US department of commerce is 'the creation of manufactured products by using processes which minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound' (EPA, 2011). A large and growing number of manufacturers are realizing that sustainable business practices provide financial and environmental benefits (Haapala et al., 2011). This has led to the development of strategies to improve energy efficiency and reduce environmental impacts in the manufacturing sector. From the industrial perspective, new and improved set of management and production practices are required to identify the sustainable energy options and achieve cleaner production (Sáez-Martínez et al., 2016).

Machining, a key manufacturing activity, has been targeted for energy reduction because of its size and importance. Machining uses electrical energy and natural resources to convert raw materials into useful products, while creating negative environmental impacts (Zhao et al., 2017). CNC machine tools are widely used in modern machining activities for better precision, repeatability, flexibility, and ability to produce complex shapes (Triebe et al., 2018). Machine tools are not only dominant electric energy consumers in manufacturing industries but also responsible for high carbon emissions (Li et al., 2015). Their efficiency is less than 30% (He et al., 2012); hence, machine tools have a major potential for energy efficiency gains and savings. A reduction of 1% in the energy consumption by machining activities will lead to the saving of approximately 200 Petajoules/year (~55TWh/year), which is more than half of the annual electricity generation of Three Gorges Power Station in China. Annual carbon emissions of one CNC machine tool (22 KW capacity) is equivalent to the emissions of 61 SUVs (12000 miles/year and 30.7 miles/gallon) (Jia et al., 2017). Machine tools have been listed as one of the ten important product groups with high potential for energy saving and carbon emission reduction in the Eco-design directive of European Parliament (Ecodesign Directive, 2008). During the last two decades, sustainability of machining processes has emerged as a new perspective for the analysis of manufacturing systems (Peng and Xu, 2014). The contemporary challenge for sustainable machining is simplification, structuring, and complexity reduction in the context of triple bottom line (Álvarez et al., 2016).

Modern machine tools consist of a large number of energy consuming devices which make energy assessment a challenging issue. However, detailed understanding of where and how the energy is consumed in a machine tool during various machining operations can help to reduce its energy consumption and environmental emissions (Lajevardi et al., 2015; Teiwes et al., 2018; Wei et al., 2018; Winter, 2016; Li, 2015). It also helps the designers and manufacturers to develop machine tools with higher energy efficiency. Many researchers have analyzed the CNC machining energy flow (Abele et al., 2011; Behrendt et al., 2012; Li et al., 2011; O'Driscoll et al., 2013; Xie et al., 2016; Yoon et al., 2015; Zhou et al., 2017). Broadly, the energy consumption of machine tools is classified into fixed energy and variable energy as shown in Figure 1.1. Variable energy is the actual energy used for material removal; and fixed energy is the constant energy consumed for supporting operations (Gutowski et al., 2006).

A study on machining energy requirements by Gutowski et al. (2005) states that almost 85% of the energy is consumed as fixed energy in the idling state, including the energy consumed by control systems, lights, axis feed motors, spindle motor, coolant and lubrication pumps, etc. Only 14.8% of the total energy consumed is used for actual cutting. Figure 1.1 presents an overview of the energy decomposition of a machining system and the energy saving strategies, major challenges and knowledge gaps for the machining energy analysis.

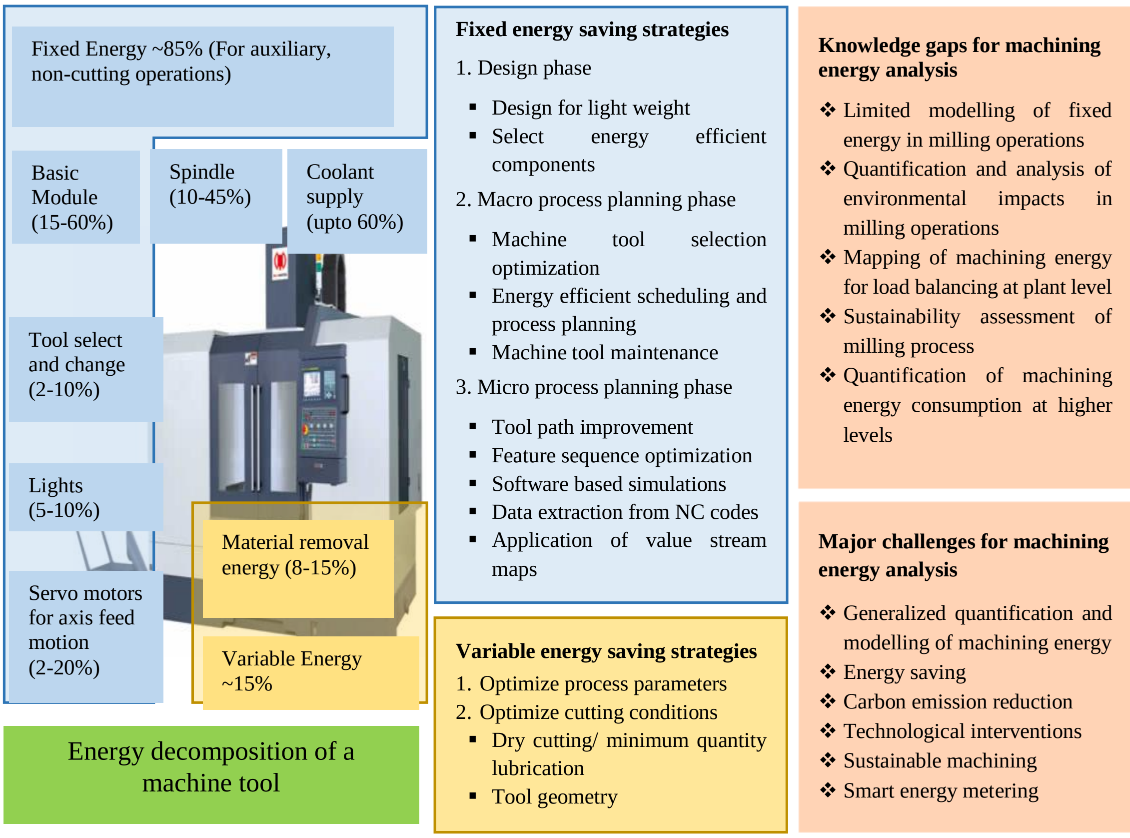

Figure 1.1 Summary of machining energy decomposition, saving strategies, knowledge gaps, and challenges

1.2 RESEARCH MOTIVATION

The Indian economy has experienced unprecedented economic growth over the last few decades. It was the seventh largest economy in the world in 2018 and is projected to move to fifth position by 2019 (International Monetary Fund, 2018). The increasing pace of sustained economic growth is placing enormous demand on energy resources. India was the third-largest energy consumer in the world in 2013, trailing only China and United States (EIA, 2016). The New Policies Scenario (NPS) projects that India’s share in world energy demand will increase from 5.5% in 2009 to 8.6% in 2035. The percentage increase in electricity consumption from 2015-16 (10,01,191 GWh) to 2016-17 (10,66,268 GWh) is 6.5%. The electricity demand of the country is expected to rise at an average rate of 5.5% over the next 20 years. The growth of demand has overtaken the power supply and India has been facing power shortage in spite of manifold growth over the years. India is primarily dependent on fossil fuels to meet its energy demand, which leads to threats like natural resource depletion, environmental pollution, global warming, climate change, etc.

Of the total electricity consumption in 2016-17, industry sector accounted for the largest share (40.01%). With a rise in economy and industrial activities during last few decades, the energy demand of Indian manufacturing industry has increased significantly. The manufacturing activities are expected to rise further in India in the coming years due to ‘Make in India’, the largest manufacturing initiative undertaken by the Government of India recently (PMINDIA, 2014). With the growth of manufacturing activities, the energy consumption and the associated environmental impacts are also expected to increase. On the other side, under Paris agreement, India has set a goal to reduce the emission intensity of its economy by 33-35% below the 2005 level by 2030 (ET Bureau, 2018).

Machining activities, as a key sub-sector of manufacturing industry, not only play an important role in the economy of the nation but also account for significant energy consumption and associated environmental emissions. Further, CNC machine tools are major energy consumers in the machining industry. According to a GIR (Global Info Research) study, the worldwide market for machine tools is 69200 million US$ in 2019 (Reuters, 2018). The machine tools mainly include machining centers (41.7%), turning machines (33.9%) and grinding machines (8.1%) (Reuters, 2018). Milling and turning are widely used machining activities. It is observed that the energy required for actual material removal is only 8-15% of the total energy required for the machining, and the efficiency of machine tools is very low. This requires the micro analysis of the machining activities to identify the basic non-value adding activities for possible elimination. Analysis and reduction of the machining energy consumption can lead to economic and environmental benefits to the industry and society. During last two decades, the increasing customer demand and growing environmental concerns have intensified the need to identify potential measures to use the machine tools more efficiently (Zein et al., 2011). It has been observed that the energy consumption by non-cutting operations varies with machine tools for a milling process whereas for a turning process it is almost independent of the machine tools (Lv et al., 2016). Therefore, analysis of milling process for energy efficiency is more important.

Estimation and real time monitoring of energy consumption for a milling process is a challenging issue due to complex structure of the machine tools and large number of energy consuming components. Understanding where and how the energy is consumed during the machining process lays a foundation for development of energy saving measures. This provides the motivation for this study to analyze the energy consumption and environmental emissions during cutting and non-cutting states for a milling process and develop energy saving measures. The sustainability performance of machining process from life cycle perspective is also analyzed to find the environmental hotspots throughout the lifecycle phases of a machined product.

1.3 OBJECTIVES OF THE STUDY

The objectives of this study are as follows:

- Development of an energy metering approach for monitoring and quantification of machining energy consumption.
- Analysis and optimization of cutting parameters to reduce the energy consumption and carbon emissions for milling process while achieving the required surface finish.
- Modelling of the energy consumption of a milling process up to the micro level and development of strategies to improve the machining energy efficiency.

- Modelling and assessment of environmental aspects of machining processes using life cycle assessment.
- Sustainability assessment of machining processes.

1.4 RESEARCH METHODOLOGY

The research methodology adopted for the present study, to achieve the above mentioned objectives, is presented in Figure 1.2. The different phases of the methodology are as follows:

- A systematic review of the literature focusing on the energy aspects of machining processes, including energy classification, modelling, saving strategies, and energy efficiency evaluation.
- Experimental modelling of the energy consumption by different components of a machine tool and development of a smart metering approach for machining energy monitoring and quantification.
- Experimental modelling of carbon emissions caused by various factors during milling process.
- Analysis and reduction of the cutting energy and carbon emissions using multi-objective optimization of cutting parameters, while maintaining the required surface finish.
- Analysis and reduction of the non-cutting energy and carbon emissions using Therblig based micro analysis.
- Development of a sustainability assessment index for milling process.
- Assessment and quantification of environmental performance of milling process by using life cycle assessment approach.

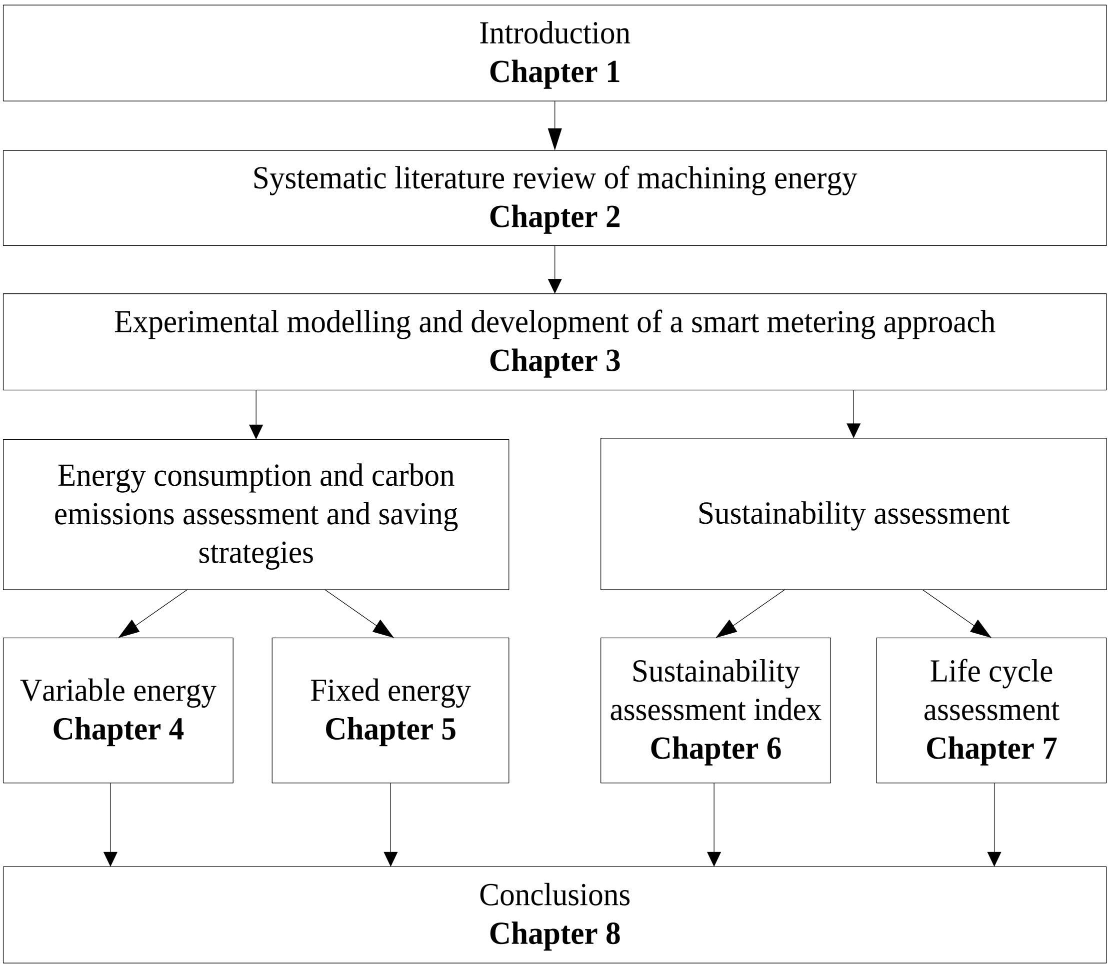

Figure 1.2 Research methodology to achieve the thesis objectives

1.5 SIGNIFICANCE OF THE STUDY

This study contributes to the existing body of knowledge on energy consumption and carbon emissions by the machining processes. It provides an extensive and systematic review of the literature encompassing the important research aspects relevant to energy consumption of the machining processes. It can be useful for the fellow researchers to understand the current state of knowledge in the area and derive the potential research gaps. The study can also be useful in explaining the machining energy characteristics during teaching practices.

The smart energy metering system developed in the study is a user-friendly, cost effective, and non-intrusive solution for efficient monitoring and quantification of energy consumption by machining processes. It can be extended for load monitoring at multi-machine and factory levels. The developed algorithm has potential to be adapted for industry 4.0 applications. This algorithm can also be used for condition monitoring of the machine tools.

The cutting parameter optimization study provides a practical approach to assign the optimization objectives to the process responses. The proposed Therblig based micro analysis provides a clear visualization of the energy and carbon hotspots, which can be used by the practitioners in improving the process planning for higher energy, time, and carbon efficiencies. The energy and carbon emissions of each activity provide better transparency of energy flow and carbon emissions information throughout the machining process. The sustainability assessment index presented in the study can provide decision support information to machine tool manufacturers and production managers to assess the machining sustainability performance of the machine tools. It can be used to develop sustainability performance labels for machine tools, which assists the decision makers regarding procurement of suitable machine tools. The life cycle assessment of milling process quantifies its environmental performance in terms of aggregate and comprehensive indices. These quantified results are useful for the machine tool designers and users to identify the high impact processes, materials and resources used during milling process and take the corrective actions to improve the environmental performance.

1.6 ORGANIZATION OF THE THESIS

The thesis is organized in eight chapters. Chapter 1 presents an introduction of the thesis. Chapter 2 presents a systematic literature review of 226 reference articles focusing on the energy aspects of the machining processes. Chapter 3 presents experimental modelling of the energy consumption by machine tool components and a smart metering approach for machining energy classification. The experimental modelling for carbon emissions during machining is also presented in this chapter. In chapter 4, multi-objective optimization of cutting parameters is done to minimize the specific energy consumptions and carbon emissions for milling process under dry and wet cutting conditions, while achieving the required surface finish. Chapter 5 presents a micro analysis based methodology for analysis of fixed machining energy and carbon emissions for a milling process. In chapter 6, the key performance indicators are identified for machining sustainability assessment and a sustainability assessment index is developed for the milling process. Chapter 7 presents assessment and quantification of the environmental impacts of the milling process using life cycle assessment (LCA) approach. Finally, the concluding remarks, limitations of the present study and future research scope are presented in chapter 8.