INVESTIGATION ON QUANTITATIVE ASSESSMENT OF ENERGY CONSUMPTION AND THE ASSOCIATED SUSTAINABILITY PERFORMANCE OF CNC MILLING MACHINES

A thesis submitted for the degree of Master of Philosophy

by

Behnood Afsharizand

School of Engineering and Design

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Abstract

The increasing trend of energy prices increment and more and tighter environmental legislation, has led to manufacturing industry and enterprises paying more attention to investigation of more prominent energy/resource efficient production methods, quantitative analysis on energy consumption in manufacturing systems and corresponding timely decision makings. This is further evidenced and supported by the development of latest ISO standards such as ISO 14000, ISO 20140, ISO/TC 39/SC 2, N1760 and ISO 14955 for this cause. Therefore, developing a comprehensive methodological approach for quantitative analysis of energy consumptions and the associated sustainability aspects of CNC machines and operations is the key driver for this research, albeit incorporating its implementation and application perspectives on shopfloor machining operations is the predominant goal as well.

The research presented consists of two inter-related parts. The first part discusses the development of the systematic integrated ERWC approach used for the modelling and simulation tenacities in CNC machines and machining operations by taking account of energy consumption (E), resource utilization (R) and waste resulted in production (W), and collectively the resultant carbon footprint (C). The ERWC modelling and analysis is explored in details with support of the MATLAB-based simulations developed and relevant case carried out. The second part of the research is focused on evaluation of the methodological approach by design of a special testing workpiece and the well-designed CNC machining experiments. The experiments are carried out on the Bridgeport 3-axis CNC milling machine, so the maximum output power of the machine can be determined using the designed testing workpiece and appropriate testing procedures. In the experiments, the milling machine is opted with the clamped power logger for power data-acquisition. The results are used to further validate the model, approach and simulations developed.

The contributions to knowledge are largely raised from developing the integrated ERWC modelling approach, innovative design of the testing workpiece, and their implementation perspectives on the 3-axis CNC milling machine, as supported with original research thoughts and exploration.

Acknowledgments

First and foremost, I wish to express my deepest gratitude and sincere appreciation to my supervisor Professor Kai Cheng for his invaluable and constructive suggestions throughout the period of this research. His keen interests in this research, constant encouragement, heartly motivation and timely help have made it possible to complete this research work successfully. I wish to thank my father who supported me financially and emotionally through out the period of my research.

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Nomenclature

Symbols

C	Carbon footprints
E	Energy consumption
fm	Feed rate
$f(x_e)$	Functional requirement related to energy
$f(x_r)$	Functional requirement related to resource
$f(x_w)$	Functional requirement related to waste
R	Resource utilization
t	Width of tool
w	The weight of machining parameters
W	Width of cut
W	Waste production
x_{ij}	Comparable sequence
X	Relation existed between FRs and DPs
y_{ij}	Machine tool parameters
$y(x_{0j},x_{ij})$	Grey relational coefficient
$\Gamma(x_{0j},x_{ij})$	Grey relational grade
ζ	Distinguishing coefficient

Abbreviations

AD	Axiomatic design

CAD	Computer aided design
CAM	Computer aided manufacturing
CAPP	Computer aided process planning
CES	Carbon emission signature
CNC	Computer numerical control
DP	Design parameters
ERWC	Energy, resource, waste and carbon footprints
FMS	Flexible manufacturing systems
FR	Functional requirements
GRA	Grey relational analysis
GUI	Graphical user interface
ISO	International Organization for Standardization
JIT	Just in time
KPI	Key performance indicator
LCA	Life cycle assessment
MADM	Multiple attribute decision making
MRR	Material removal rate

List of Figures

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A list of publications arising from this research

[1] Behnood Afsharizand and Kai Cheng, Design of a testing workpiece for energy efficiency assessment of the CNC milling machine, *Proceedings of the 10th International Conference of Manufacturing Research ICMR, 11-13 September*, 2012, pp 681-686.

[2] Behnood Afsharizand and Kai Cheng, Sustainable evaluation of the machine tools and associated machining operations with the case of milling operations, *Proceedings of the IMechE Part B: Journal of Engineering Manufacture* (under review).

[3] Behnood Afsharizand and Kai Cheng, An investigation on modeling and optimization of energy flow in automotive paint-shop operations and sustainable manufacturing, *15th Cambridge International Manufacturing Symposium, 23-24 September, 2010.*

Chapter 1 Introduction

1.1 Research background

1.1.1 Current issues in machining operations

Currently, increasing energy prices and environmental issues are driving industries to reduce their electricity consumption and Carbon emissions. According to the Kyoto protocol, the industrialized and developed countries have the most contribution on Carbon generation in the manufacturing sectors (Omer 2008). As the energy, which is used during machining operations, increases environmental pollution, the first step towards more sustainable manufacturing is to reduce energy consumption.

Along with energy considerations, there are many efforts for improving on resource utilization and waste production. In addition to sustainability problems, many companies have been suffering from the scarcity of the materials before and after the entity machined. Recently, the price of steel has doubled and demands have increased accordingly. So, the second step in sustainability is to optimize the resource utilization during material machining.

Looking at the machining as a whole system, many auxiliary device parameters also affect machining operations such as cutting tool, lubrication and fans and coolants. Those parameters also influence on the machining outputs and the cost of machining.

1.1.1.1 Definition of sustainability

According to the United Nation's commission, sustainability was defined as "meeting the needs of the present without compromising the ability of future generation to meet their own needs" (WBCD, 1987). Sustainability defined in this research as to optimize the organisational performance toward more environmental, economical and social viability. Sustainability criteria, which focused on previous literatures, have been presented in Fig. 1.1.

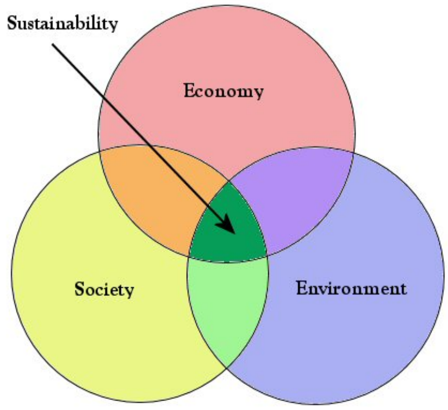


Fig. 1.1 Sustainability criteria (Rodrigo, 2008)

The scope of this research is more focused on the Environmental and Economical aspects of machining operations. The green highlighted area will be analysed during the development phase of sustainable manufacturing by well designed experiments and results.

1.1.1.2 Sustainability in manufacturing

Recently, many researches have been done towards more sustainable manufacturing operations in both quantitative and qualitative criteria. Sustainable manufacturing presented after the Lean concept which defined by Allwood (2009) as a method to "develop technologies to transform materials without emission of greenhouse gases, use of non-renewable or toxic materials or generation of waste". The wastes in lean manufacturing defined by Toyota (James et. al., 1990), which contributed in this research, are as follows:

- Unnecessary machining time
- Unnecessary axis movement
- Optimize feed rate
- Optimize cutting speed
- Optimize cutting number

Considering the above as the wastes during manufacturing, CO2 emission associated with machining also need to be analysed.

1.1.2 Challenges in sustainable manufacturing development

Developing sustainable manufacturing is always challenging because of the complexity of manufacturing systems. Fig. 1.2 shows some of the different aspect of sustainable manufacturing and complexity.

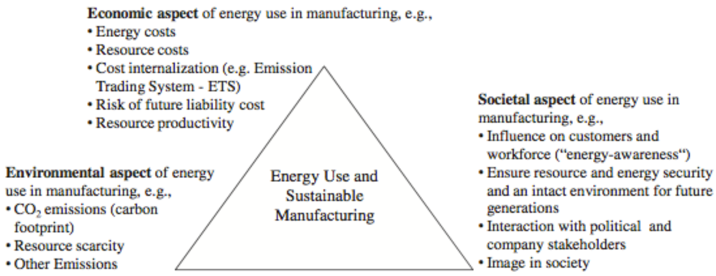


Fig. 1.2 Sustainable manufacturing aspects (Bunse et. al., 2011)

Specifically in machining operations, which is considered a highly complex system, methodology and boundary definition is highly important. Such complexity be raised when there is several parts that interacting with each other in the way that cannot measureable. In order to cope with the complexity in manufacturing there are several techniques presented:

- Deterministic modelling
- Stochastic modelling and simulation
- Object oriented modelling

A deterministic model is one in which every machining effects is uniquely determined by parameters in the model and by sets of previous states of these parameters. Conversely, in a stochastic model, randomness is present, and machining parameters are not described by unique values, but rather by probability distributions. In an object-oriented data model, the behaviour and effects of specific machining operations are merged into a single indivisible value.

1.2 Aim and objectives of the research

This research presents the systematically overview of the machining operations which has high impact in the sustainable development of the manufacturing processes. Energy consumption, resource utilization and waste production in machining operations has been mainly considered including the performance factor for Carbon emissions during machining. For obtaining the results which reasonable, the modelling and formulation of the cutting parameters has been produced and also the application of each has been described.

The distinct objectives of the research are to:

- Undertake the critical review on quantitative assessment of energy consumption on CNC machines and develop the corresponding ERWC modelling approach and its implementation prospective.
- Design a standardized test workpiece.
- Carry out experimental trials to further evaluate the models, simulation and the research development above.

1.3 Outline of the dissertation

The structure of this research has been presented in Fig. 1.3.

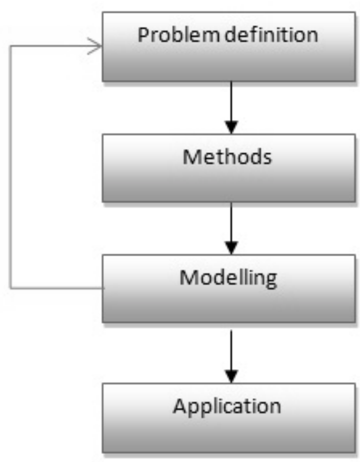


Fig. 1.3 Thesis structure

This thesis has been divided into two main parts. In the first part, the systematic overview of the machining operations has been explained. In the second part, the application of the assumed method has been validated by real experiments on the 3 axis milling machine.

The structure of the dissertation is as follows:

- Chapter 2 Reviewing the literature related to the research topic.
- Chapter 3 Modelling and simulation considering sustainability evaluation of the machining operations.
- Chapter 4 Developing the standard test procedures and workpiece for the energy analysis
- Chapter 5 Designing protocols for the experimental trials focused on energy consuming sources.

Chapter 2 Literature review

2.1 Introduction

Machine tools consumes high amount of energy during the machining operations (Park et al., 2009). The increase of the environmental awareness and electricity costs in industrial sectors put forces on the manufacturers and customers to reduce their operational energy consumption (Behrendt et al., 2012). The high environmental impact of the machine tools was also reported by the European Commission within it's ''Energy using products'' directive, which was produced for optimizing the environmental performance of products.

It was reported that machining operations contributed to 37% of the world's total energy consumption during 2006-2007 (Dang et al., 2007). The previous studies on the machine tools operations show that less than 30 % of energy consumed uses for the actual cutting operations and 70 % of the energy wastes for actuating the auxiliary devices such as coolant, fans and spindle (Liu et al, 1995). As it has shown in Fig. 2.1, only 40-60% of the energy entered into the machine tools perform the actual cutting operations. So, there is high potential for making the machining operations more efficient and environmentally friendlier.

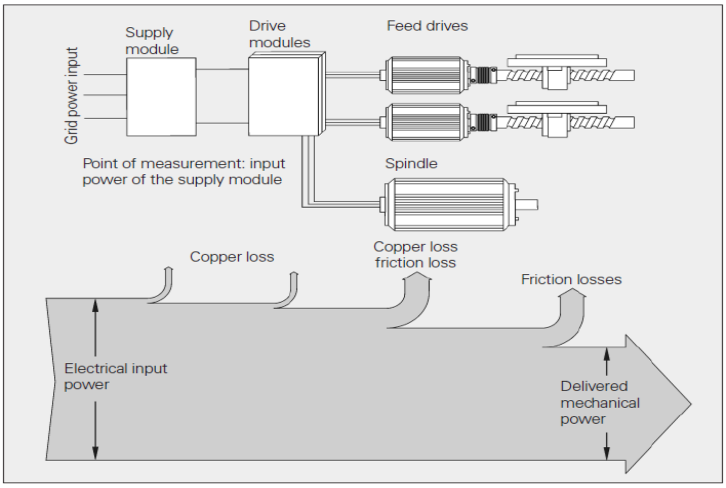


Fig. 2.1 Energy flow on the CNC milling machine.

2.2 Sustainable manufacturing development

The research on energy/resource efficient manufacturing has been being increasingly undertaken worldwide (Hermann et al, 2008; Jeswiet and Kara, 2008; Diaz et al, 2010; Vijayaraghavan and Dornfield, 2010), with research focuses mostly on:

- LCA based analysis of manufacturing systems and processes to fuse together energy/environmental and economic objectives;
- Approaches and technologies to developing innovative energy/resource efficient manufacturing;
- Exploiting manufacturing process science to address the complexity and integrity of energy modelling;
- Developing smart sensors and systems for monitoring and control of energy usage in manufacturing industries.

There has also been a number of following international standards/initiatives development for energy assessment in manufacturing, although some development is still at drafting stages, for instance:

- Japan based, ISO 20140 - "Automation systems and integration – Environmental and energy efficiency evaluation method for manufacturing systems";
- USA based, ISO/TC 39/SC 2, N1760, (2009) - "Test conditions for metal cutting machine tools",
- EU based, ISO 14955 - "Environmental evaluation of machine tools".

However, there is a critical but fundamental issue occurring in the research and development above, i.e. how to undertake stringent quantitative analysis and modelling of the energy consumption and the consequent carbon footprint of a manufacturing system. The issue is challenging because of the multiple factors and coupling effects involved in the system, and the complexity and diversity of the associated machine operations.

2.2.1 Machining operations optimization

Optimization of the machining operations has been done previously in three different levels. Process level has been investigated by Draganescu et al (2003) statistically developing empirical model and response surface methodology for specific energy consumption of the machine tools. He resulted that the energy consumption of the machine tool is a function of material removal rate. Sarwar et al (2009) measured the energy consumption of the machine tools based on the material variations of the workpiece. Avram and Xirouchakis (2011) has be evaluated the machining energy consumption by dividing the electricity usage into constant and variable power flow during the machining operations. The same research shows that machining has three main phases:

- Warm up time: when the machine is turned on and the controller of the CNC machine is on loading mode.
- Rapid movement: when the spindle arm finds the test workpiece on the table axes.
- Cutting: when the machine start the actual cutting operations out of the workpiece.

The components which have effect on the energy consumption of the machine tools and their interactions have been divided into direct and indirect parts by Neugebauer (2011). So, the direct and indirect devices which increase the energy efficiency of the machine tools have been identified.
Hermann and Thiede (2009) simulated the energy flow of the machine tools through the process chain in order to improve the energy efficiency of manufacturing processes. He and Liu (2010) also presented the systematic overview on the energy consumption of the machining operations considering the scheduling problem of the manufacturing systems.
Online monitoring system has been developed by Vijayaraghavan and Dornfeld (2010) for capturing the energy data during the machining operations. The benefit of this method is that the machinist can evaluate the real energy consumption when undertaking the actual cutting process.

2.2.2 Legislations and standards

Increasing the energy consumption in industry has considered by the government and the legislations. The governments tried to reduce the energy usage by increasing taxes and developing standards. Currently, there has been a number of following international standards/initiatives development for energy assessment in manufacturing, although some development is still at drafting stages, for instance:

- ISO 20140 - "Automation systems and integration – Environmental and energy efficiency evaluation method for manufacturing systems” (Japan based),
- ISO/TC 39/SC 2, N1760, (2009) - “Test conditions for metal cutting machine tools” (USA based),
- ISO 14955 - “Environmental evaluation of machine tools” (EU based).

Development of ISO 50001 was started in February 2008 by the International organization for standardization (ISO). The standard includes all the activities of industrial plants to manage the energy used for procurement and operations. The certified holders of ISO 50001 demonstrate that the plant or company has sustainable energy management system in place.

ISO 5001 is being written for having more compatibility with ISO 9001 and ISO 14001. The performance indicators have been developed in order to satisfy:

- Energy efficiency
- Energy performance
- Energy supply
- Procurement facilities
- Energy using equipment and system

In order to have more influence on the energy demands (up to 60%), the 150001 standard provides organizations and companies with technical and management strategies.

European energy policy also set up the new technology plan to bring new energy innovations and reduce greenhouse gases. The reduction of the 20% in greenhouse gases has been predicted by 2020. The short term objectives of the policy are as follow:

- Increasing energy efficiency
- Integrating renewable energy sources
- Developing alternative fuels

Development of a new generation low Carbon technologies has been considered in long term objectives. Recently, EU proposed specific rules for labelling products, services and infrastructure which shows the energy efficiency.

In July 2005, the Eco design Directive has been developed by the European parliament and the council as a prominent policy. The life cycle assessment of the initial stage of the product design has been done by the systematic integration of the environmental aspects. 34 product groups were selected for the environmental effects created by these product including the waste production and energy consumption in their manufacture and use.

Specifically, Machine Tools Company has been classified as the top three priorities for the product analysis as it’s shown in Table 2.1 So, energy efficiency in manufacturing systems and machining operations may be critical point of investigation as Eco design directive standard classified.

Table 2.1 Eco design direcive classification in terms of energy intensive products

Rank	Product group	Total energy (GER, PJ)	Priority
1	In-house networking (LAN) and data processing, storing and providing equipment	31227	A
2	Transformers	17695	A
3	Tool machines (manufacturing-industrial use)	17475	A
4	Electric and fossil fuel heating equipment	14383	A
5	Surgical, patient recovery and healing equipment	8395	A
6	Industrial and laboratory furnaces and ovens	5934	A
7	Domestic equipment for clothes caring and others	4206	A
8	Automatic and welding machines	3446	A
9	Electro-diagnostic apparatus	2621	A
10	Network equipment for all types of data processing (data, telecommunication, internet, mobile and radio network equipment)	2469	A
11	Power electronics products (inverters, static converters, inductors, soft starters)	1644	A
12	Sound and image processing machines and equipment	1575	A
13	Food preparing equipment, domestic and household use	1324	A
14	Refrigerating equipment	915	A
15	Air condition systems and heat pumps	813	A
16	Electromechanical hand tools	723	A
17	Measuring transformers	682	A
18	Aerials, antennas, radars, radio navigation and control systems	487	A
19	Lifting, moving and loading equipment	263	A
20	Cashiers and ticketing machines	254	A
21	Sound processing machines and equipment (including radio equipment)	242	A
22	Other motors or motor driven equipment not covered by lots and the above categories	140	A
23	High energy diagnostic and healing equipment	124	A
24	Lighting installations not covered by existing lots	121	A
25	Food production equipment	114	A
26	Vending machines for beverage and goods	104	B
27	Compressors	88	B
28	End equipment for data use and communication with option of net connection	77	B
29	Motor driven equipment for waste water process, hot water and chemical process	69	B
30	Machines for personal care	49	B
31	Ventilation equipment for underground infrastructures and special processes	18	B
32	Mowers	13	B
33	Boilers		B
34	Generating sets using fossil fuels		B

ISO14955 which presented by ISO Technical committee was assessed by 39 working group for environmental evaluation of machine tools.

This standard consists of 4 major parts as outlined below:-

i) ISO 14955-1: Eco-design methodology for machine tools (working draft available)

ii) ISO 14955-2: Methods of testing of energy consumption of machine tools and functional modules

iii) ISO 14955-3: Test pieces/test procedures and parameters for energy consumption on metal cutting machine tools

iv) ISO 14955-4: Test pieces/test procedures and parameters for energy consumption on metal forming machine tools

If successful this standard will provide a highly valuable basis to analyze and test existing and future machine tools.

2.2.3 Current strategies towards sustainable manufacturing

Currently, there is a challenge between the technological change, sustainable development and industrial competitiveness in manufacturing firms. Managers in company look for the win-win strategy to make competitive edge among the other companies, which is essential for the organization to survive (Faucheux, 1998). By developing the environmental objectives industry tries to increase its ROI using flexible methods (Porter, 1995). The strategies, which tie to the environmental aspect of the firm, should be investigated by appropriate methodology (Jovane et al, 2008).

2.2.3.1 Physical parameters in machining

As it has been shown in Fig. 2.2, there are so many machine tools components which consume energy and ties with the complexity in machining operations. In order to define the boundary of our work, machining parameters have been classified as follow.

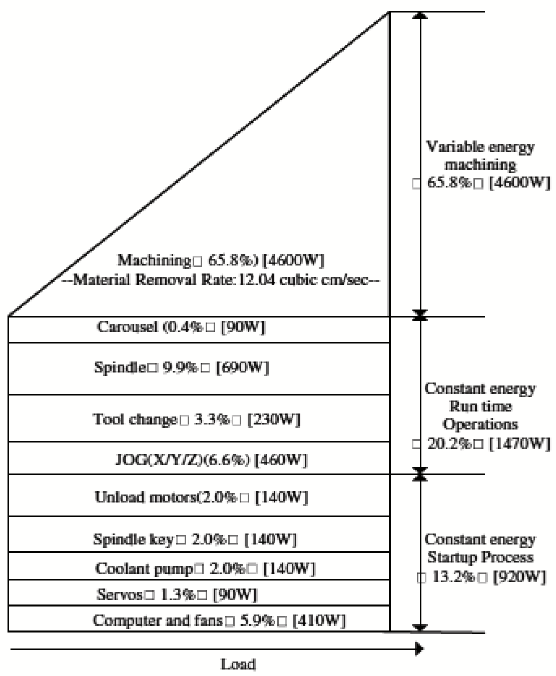


Fig. 2.2 Energy consumption models in machine tools (Kordonowy, 2003)

2.2.3.1.1 Materials used in machining

Materials used in the machining significantly effects on the energy consumption and resource utilization in the machine tools operations (Sarwar et al, 2009). The total material removal rates depend on the materials which used in the machining for instance, Steel which is tougher than Aluminium consumes more energy. The effects of the workpiece material has been investigated based on the energy formulation previously, and the results in Fig. 2.3 show that Steel is the most energy consuming material among Aluminium and Polycarbonate (Diaz, et al, 2011)

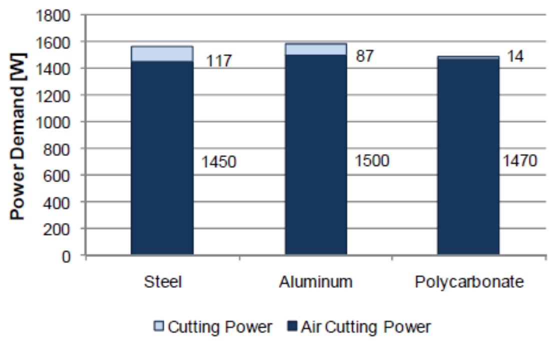


Fig. 2.3 Power demand of NV1500 DCG for Steel, Aluminium, and Polycarbonate

2.2.3.1.2 Lubrication used during machining

As it has shown in Fig. 2.4 electricity consumption of the machine tools is highly affected by the cooling system.

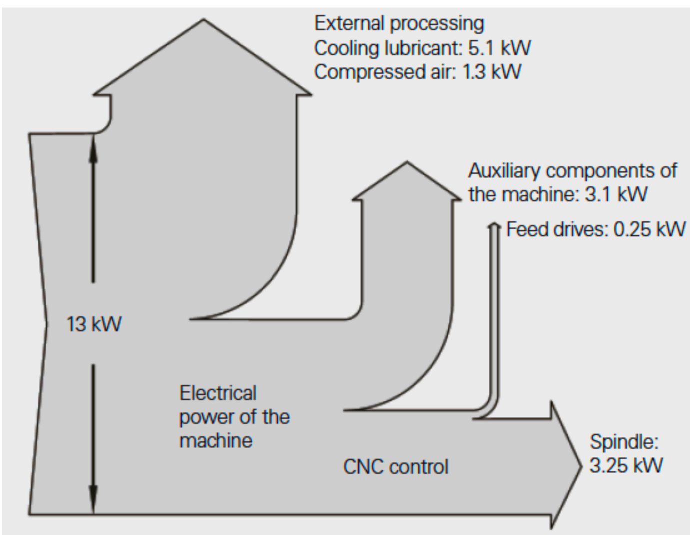


Fig. 2.4 Energy flow on the milling machine

The niche area of research has been allocated to the machining efficiency through optimization of the lubrication system. Currently, the focuses on dry machining show that omitting cooling from the machining significantly effect on the energy consumption of the machine tools operations.

2.2.3.1.3 Cutting tool selection

Material removal rate is the best key performance factor which can be applied for the energy efficiency comparisons. The material removal rate has been defined as follows:

$$MRR = \frac{Volume\ Removed}{CT} = \frac{L \times W \times t}{CT} = W \times t \times f_m$$

where

W - Width of cut
t - The width of tool
f_m - The table feed rate

So, material removal rate has been influenced by the size of cutter. Consequently, optimum cutting tool selection has too much effect on the energy efficient machining. Fig. 2.5 shows the change of material removal rate versus energy consumption on 3 axis milling machine.

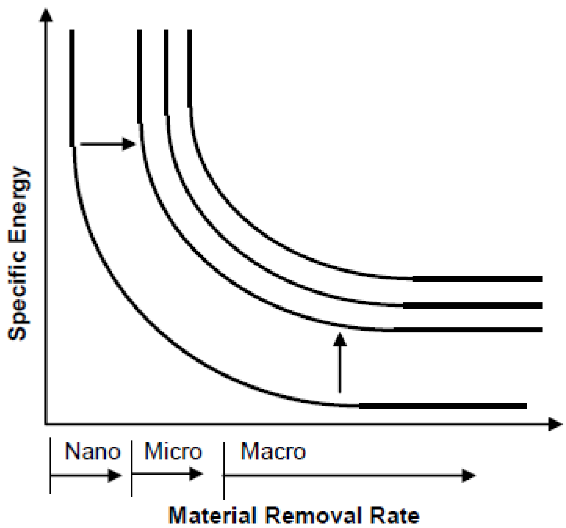


Fig. 2.5 Material removal rate vs. Energy consumption (Diaz et al, 2011)

2.2.3.2 Machining parameters

In addition to the machining parameters such as feed rate, cutting speed and depth of cut, which discussed earlier, there are also other potentials for more energy efficient manufacturing in process planning which will be discussed in this part.

2.2.3.2.1 Selection of machining processes

Computer aided process planning (CAPP) developed by Niebel on 1965 and It was used for the ease of process planning in CNC machines. Afterwards, in 1977 a pioneer named Wysk did his PhD focused on automated process planning and selection program. Later on the CAPP systems have been combined with CAD/CAM software. CAD/CAM software gives information to machinist about the number of tool paths and the machining strategies. Development of the CAPP has been investigated on the CNC machines for energy efficiency by Newman et al (2012).
The electricity consumption of the machine tools has been influenced by the number of tool paths. Increasing the number of tool paths and the machining time is not energy efficient since the auxiliary devices operate during the machining.

2.2.3.2.2 Selection of cutting parameters

Selecting the optimum cutting parameters is important decision making criteria for reducing energy consumption of the machine tools. Previous research for optimising the environmental issues of the machining operations shows lots of interest in this area. In the first stage the main focus was on the minimizing the production cost. The cutting parameters selection model has been formulated so as to minimize the cost of production for turning and milling operations (Chen et al, 1989 ;Hinduja and Sandiford, 2004). Similarly, Polynomial networks applied for increasing the production rate and minimizing the production cost (Lee and Tarng, 2000).
Second interest focused on the cutting parameters selection for minimizing the environmental emissions of the machining operations. Evaluation of the environmental burden of machining processes has been done, and the CO_2 equivalent was calculated based on the Carbon intensity factor of the machining parameters (Narita and Fujimoto, 2009).

As it has shown in Fig. 2.6, Jeswiet and Kara (2008) calculated the Carbon generated depends on the energy sources which received by the manufacturing processes.

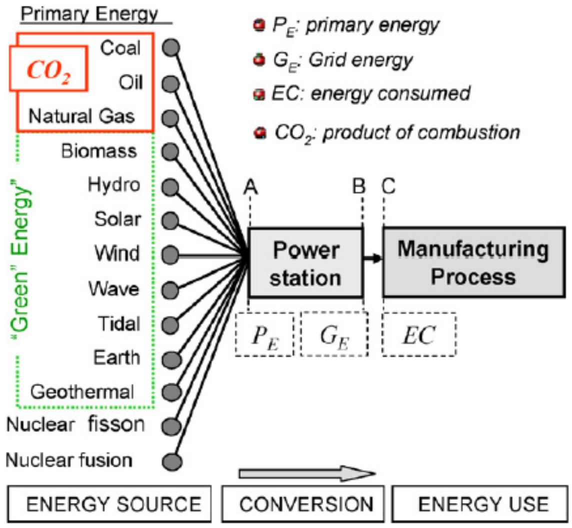


Fig. 2.6 Energy transmitted into manufacturing sector (Jeswiet and Kara, 2008)

There are also other researches on minimising the environmental issues of the manufacturing (Vijayaraghavan and Dornfeld, 2010; Devoldere et al, 2007).

2.3 Energy mapping

Energy mapping has been applied for gaining more knowledge over the machining operations (Dahmus and Gutowski, 2004). The presented diagrams in Fig. 2.7 used for the environmental analysis of the machining operations. It shows the inputs and outputs of the manufacturing systems presented the amount of the Carbon footprints released into the air.

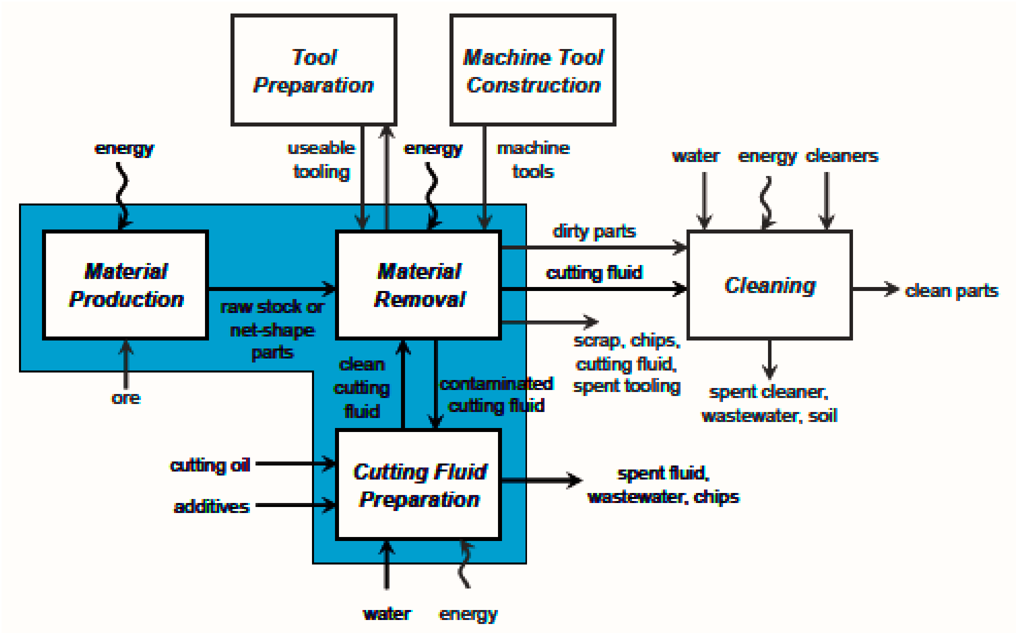


Fig. 2.7 Energy flow map developed by Dahmus and Gutowski (2004)

Basically, The transfer of the material into the product is highly energy consuming and carbon intensive. The energy which uses during manufacturing is converted to the Carbon footprints and the Carbon equivalent associated with the machining operation divided into direct and indirect. Direct generation happens when the energy consumed converted directly to the CO_2. However, the Carbon which generates during the recycling of the materials and the Carbon embodied in the inputs (e.g. Cutting tools, workpiece material) are considered as the indirect Carbon retrieved from the whole process.

Efficient manufacturing machines save energy while transferring the materials into the finished product. In fact, energy transformation can be applied as a value added process during the machining operations as the energy price contributed to the most expensive cost of the machining operations (Mani et al, 2009). Basically, the fixed energy consumed during machining such as (load/unload motors, coolant pumps, controllers, fans) is not measured during the energy analysis of the machining operations. However, these devices contributed to the high percentage of the electricity consumption during machining. In addition, production rate and the production cost are the most common key performances for the managers for checking the effectiveness of their industry. By introducing the CAD/CAM software, it is possible to simulate the tool path and the machining significant before even start to machine the part. So, there is no need for more inspection during the machining and the cost of manufactured the part reduces.

Using from the CAD/CAM software different scenarios tested on the machine tools and the feasibility of the approach presented here has been verified.

2.3.1 Energy mapping techniques and processes

In order to find a solution for reducing the energy consumption of the machine tools, the government has adopted the restricted environmental legislation. The effect of energy which consumes during the manufacturing operations on the environments has been studied (Jeswiet and Kara, 2008). The Carbon emission signature (CES) has been defined for estimating the energy converted to Carbon footprints during machining. After identifying the energy efficiency issues in machine tools, energy data has been collected from ten different machine tools involved in various operations (Filippi and Ippolito, 1981). The results show that less than 60% of the energy input in the machine tools used for the cutting operations. Qualitative research has been done on the alternative machining strategies which show the energy consumption relation with the machine tools auxiliary devices (Akbari et al, 2001; Fratila, 2009). According to Pusavec et al (2010) transition from conventional to new cooling systems improves the energy efficiency of the machine tools and reduces the waste and global warming potential. New cooling technologies such as Cryogenic or high pressurized lubrication method combined with the optimum lubrication strategies minimize the energy consumption of the machining systems.

In mass production environment 85 % of the energy which releases into the production line is used in non machining operations (Gutowski et al, 2006). Similarly, Kordonowy (2003) studied the energy consumption of the indirect machining devices such as (spindle, jog, coolant pump, NC unit, coolers and fans) during the operations. Results show that 30% of the machining power consumes by the no value adding devices. The calculations were based on the systematic overview of the machining operations.

Machining wastes and energy associated with manufacturing has been calculated through the modeling and software development by Dahmus and Gutowski (2004). The total energy consumption for the specific material removal rate has been compared to the power delivered into the machine tools. The results show that the electricity usage the material removed out of the workpiece is quite small compared to the power consumption of the other devices.

The cutting speed assigned for the material removal effects on the energy required for the machining significantly (Rajemi et al, 2010). So, the selection of the cutting parameters is important decision making for manufacturing a part.

Several literatures have been divided machining energy into three phases (Dahmus and Gutowski, 2004; Avram, O. and Xirouchakis, P., 2011).

- Warm up time: when the machine is turned on and the controller of the CNC machine is on loading mode. The energy consumption of this phase is constant.
- Rapid movement: when the spindle arm finds the test workpiece on the table axes. The machine is in the RUN TIME mode and the power consumption is not linear.
- Cutting: when the machine start the actual cutting operations out of the workpiece. The material removal operations are done in this phase.

The energy consumption of the machine tools have been investigated further in the next chapters with the well designed test workpiece and standards procedures.

The life cycle assessment (LCA) has been done in a systematic approach with the experiment which addresses the different machining phase by Delvodere et al (2007).

Grinding processes also considered as the machining operations which highly consumes energy and releases Carbon footprints. Herrmann et al (2009) modeled the dynamics between process parameters and specific processes in grinding operations.

Generic method for modeling the energy consumption has been produced by Dietmair and Verl (2009) based on the statistical data and curve fitting methods. However, the results are not fully confident since the change of machining parameters can effect on the whole machining systems. Environmental burden analysis of the machining operations has been done with formulating the specific amount of the CO_2 which generates during the machining (Narita et al, 2004). The auxiliary device effects on releasing emissions into the air have been considered as well as the main parts (e.g. spindle, controller and etc) during the machining operations.

2.3.2 Manufacturing techniques

In this section the manufacturing processes and techniques have been qualitatively analysed so as to define the boundary which project has to be done. There are 5 types of manufacturing systems (Hon, 2005):

- Single machine: is the most basic form of a manufacturing system in a single machine or work station. The model of single machine system has been shown in Fig. 2.8 (Peklenik, 1971).
- Manufacturing cell: requires several machines in order to achieve to desired geometrical features. The highly automated manufacturing cell was addressed as FMS (Burbidge, 1989).
- Flow line: is classified with pull and push systems for high volume manufacturing of identical or non identical products. JIT is the Toyota model which applied in this type of manufacturing (Ohno, 1988).
- Factory: consists of entire cycle from design, planning, programming, manufacturing, production control and dispatch (Merchant, 1961).
- Production network: The most recent production system with the increase of internet application through the supply chain was each node of the chain processes its own core manufacturing competence (Wiendahl and Lutz, 2002). The schematic presentation of a production system has been shown in Fig. 2.9.

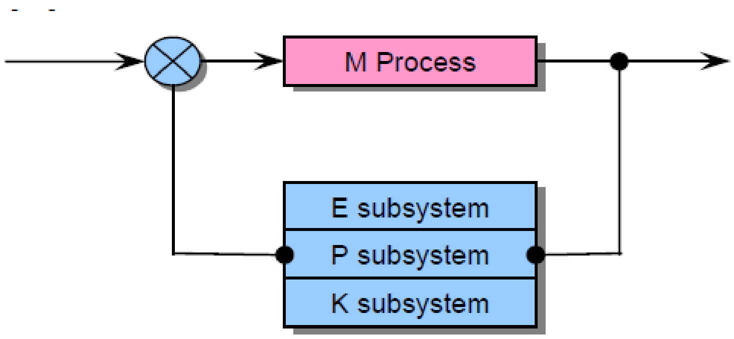


Fig. 2.8 The model of a manufacturing system (Peklenik, 1971).

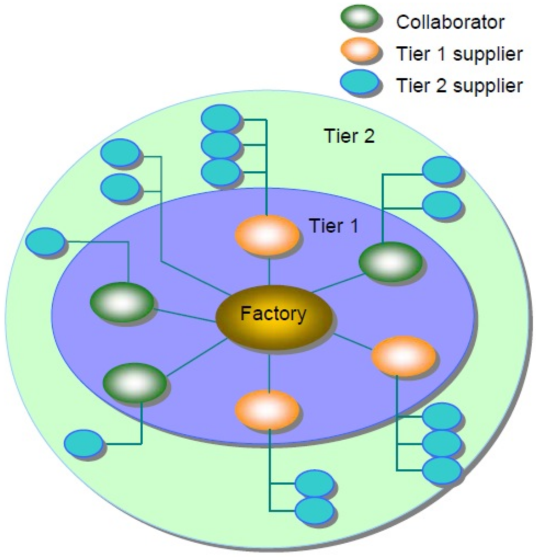


Fig. 2.9 Presentation of the production network

The performance measurement for each of those mentioned production systems were more cost based rather than environmental. Increasing the price of energy and also government regulations force the industries to develop the performance measurement for the amount of energy consumed and Carbon produced through the value chain. Currently, the firms which focused on the energy requirements and also environmental issues gain more profits from the final customers.

2.3.2.1 CNC technology

The computer numerical control (CNC) machines were built in 1940s and 1950s for developing highly automated machines for transferring the raw materials into the products. Also the surface roughness and high accuracy were the other performance which machinists were interested. Recently, The CNC machines are highly automated using Computer aided design (CAD) and computer aided manufacturing (CAM) program. After designing the geometry and defining the datum of the piece, CAM software generates the G codes which can be understood by the controller of the machine tools. By defining the cutting tools and the cutting strategies in CAM software there is high confidence that the proffered accuracy will be achieved.

The machining operations are taken for shaping or machining metal or rigid material, usually by cutting, boring, grinding, shearing and other forms of deformation. The machine tools attached with the cutting tool in order to taking out the material out of the workpiece. The movement between the workpiece and the cutting tool is addressed as tool path.

2.3.2.2 Machining strategies

Typical milling machine comes in two basic forms, horizontal and vertical which shows the orientation of the main spindle. In this research milling machine has been selected for analysing the energy efficiency during the milling operations. The milling strategies classified as follow:

- Profiling
- Pocketing
- End milling
- Slot drilling

Also, the machining is performed in two stages, roughing and finishing. Normally, in roughing operations more material removes from the workpiece. So, roughing consumes more energy than the finishing. Depends on the machining strategies, the tools and materials used as a workpiece, different energy requires during the operations.

2.4 Conclusions

Machining operations consumes energy and release Carbon emissions. In order to reduce the environmental issues associated with the machining operations internal investigations and external forces have been developed. The research focused on this area has been modelled the energy flow through the machining operations. The electricity consumption of the machine tools has been fully investigated on the different CNC machine. The methods used for the modelling approach was whether based on the statistical data obtained from the machining centres or deterministic models based on the cutting force calculated from the cutting tool parameters. However, the holistic/systematic approach to consider machining operation as a whole system has not been studied so far.

Chapter 3 Modelling and simulation of the machining energy consumption and sustainability aspects

3.1 Introduction

There are some dominant factors in a CNC machine tool and its associated machining operations, which have significant effect on energy consumption, resource utilization and waste production of the machine system and therefore its carbon footprint (E-R-W-C). However, the accurate quantitative analysis of the energy consumption and carbon footprint of a CNC machining system is a challenge because of the multiple factors involved and the complexity and diversity of the machining operations. Furthermore, the quantitative analysis and modelling of the energy consumption and carbon footprint of the machine system is fundamentally essential for optimal control of the machine and the associated CNC operations particularly for energy/resource efficient manufacturing purposes. In this section, a holistic integrated ERWC modelling approach is proposed on quantitative analysis of the energy consumption and carbon footprint of a CNC machine tool. The approach is based on modelling energy consumption with resource utilization and waste minimization in the machine system in an integrated manner, by using the axiomatic design and grey relational analysis. MATLAB-based programming is used as a tool for simulating the ERWC models and solutions, mathematical modelling and transformation of ERWC data matrices in particular. The modelling approach is evaluated and validated with empirical data and a case study on a Bridgeport CNC milling machine.

3.2 Modelling approach for the sustainability

The research on energy/resource efficient manufacturing has been increasingly undertaken worldwide (Hermann et al, 2007; Jeswiet and Kara, 2008; Diaz et al, 2010) with research focuses mostly on:

- LCA based analysis of manufacturing systems and processes to fuse together energy/environmental and economic objectives;
- Approaches and technologies to developing innovative energy/resource efficient manufacturing;

- Exploiting manufacturing process science to address the complexity and integrity of energy modelling;
- Developing smart sensors and systems for monitoring and control of energy usage in manufacturing industries.

There has also been a number of following international standards/initiatives development for energy assessment in manufacturing, although some development is still at drafting stages, for instance:

- Japan based, ISO 20140 **-** "Automation systems and integration – Environmental and energy efficiency evaluation method for manufacturing systems";
- USA based, ISO/TC 39/SC 2, N1760, (2009) - "Test conditions for metal cutting machine tools",
- EU based, ISO 14955 **-** "Environmental evaluation of machine tools".

However, there is a critical but fundamental issue occurring in the research and development above, i.e. how to undertake stringent quantitative analysis and modelling of the energy consumption and the consequent carbon footprint of a manufacturing system. The issue is challenging because of the multiple factors and coupling effects involved in the system, and the complexity and diversity of the associated machine operations.

In this section, a holistic integrated approach for modelling the energy consumption and carbon footprint of machine tools is presented by taking account of the energy, resources use and wastes produced in the machine system collectively. This part is organized firstly by introducing the integrated ERWC modelling approach. The computational analysis/ procedure, constraints and solutions, and implementation aspects are then discussed by using MATLAB programming environment. A case study supported with experimental data is followed on evaluating and validating the approach and models developed. Finally, the part concludes with discussions on the potential and application of the approach and modelling for sustainable manufacturing purposes.

3.2.1 Energy consumption

In this step, the machining parameters which have effect on the energy consumption of the machining have been classified. The parameters selected based on the literatures investigated the variations in cutting parameters versus to the power consumption of machining (Campatelli, 2009). The factors, which have selected for the energy analysis, are as follow:

- Cutting speed(m/min)
- Depth of cut(mm)
- Feed rate(mm/min)

In the last chapter, the effect of each factor has been tested with the well design procedure on the milling machine.

3.2.2 Resource utilization

The machining operations use resources to transfer the material into the product. Resources in machining operations have been identified as follow:

- Cutting tool
- Workpiece material
- Fans and Coolant
- Operator

Depends on the size of the machine tools and also the experience of the operator the machining utilize different amount of resources. Also, the study on the machining operations need a well defined boundary otherwise the relation between the resources in machining operation effects on the results.

3.2.3 Waste production

The wastes that derived from machining are divided into two categories.
First group is the wastes which produced from the nature of machining such as used oil/water, metal chips and extra spindle movement.
Second kind of wastes associated with the inappropriate setup of the machine tools, which causes the scrapped part, or useless movement of the spindle axis.
In this research first mentioned wastes are considered as the waste in machining.

3.2.4 Approach used for modelling machining operations

Previously, some models have been presented specifically on the energy consumption of the machining operations (Detmair and Verl, 2008; Gutowski et al, 2006), and also some modelling approaches tried to look at the machining operation holistically, but not systematically (Narita and Fujimoto, 2009; Avram and Xirouchakis, 2011). Basically, the approaches for modelling energy consumption of the machine tools presented so far, are whether Mechanistic (Rajemi et al, 2010; He et al, 2011) or based on the empirical data (Draganescu et al, 2003; Diaz et al, 2011). The modelling approach presented here is based on the empirical data which requires systematic overview on the machining/cutting parameters. However, the boundary of the system has not been specified in the ERWC model. Using artifacts designed for testing the energy consumption, resource utilization and waste production limited the ERWC model to the specific boundary defined as follow:

- Conditions dealing with material used in machining.
- Conditions dealing with tools applied in machining operations.
- Conditions dealing with machining strategies.
- Conditions dealing with CNC machine types.

The above definition has been shown in Fig. 3.1.

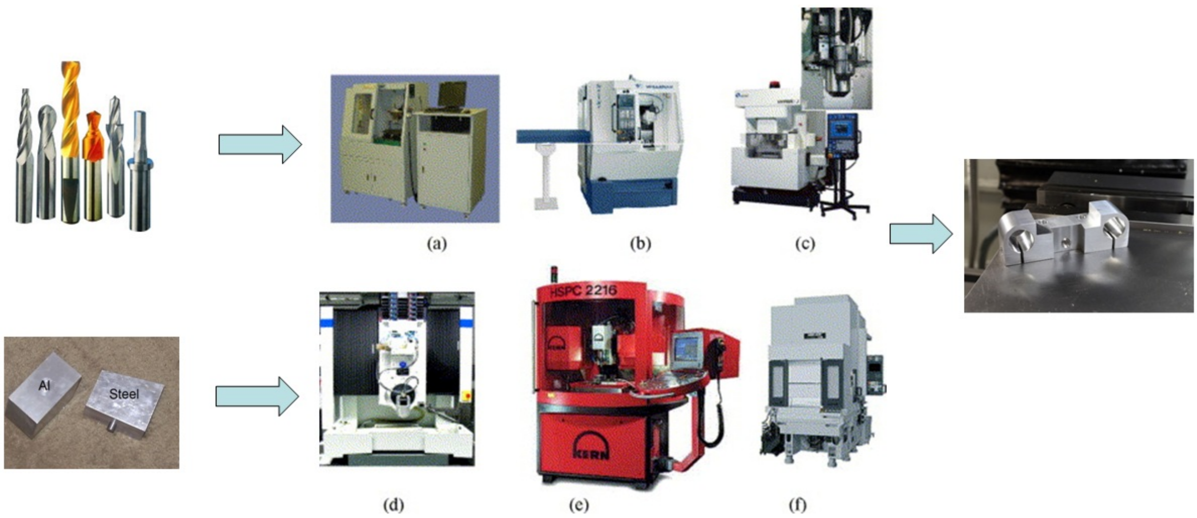


Fig. 3.1 Boundary definition for energy analyses

3.3 A framework developed for modelling

Characterizing the main features of the ERWC model is fundamentally important, as the modelling approach should be comprehensive, integral and accurate so as to cope with various CNC machine tools and systems. The main features include:

- Modularity
- Hierarchy
- Flexibility
- Multi-functionality

Modularity: In order to formulate the interrelations between the mechanical components of the machine tools it is necessary to classify each of the machine tools components into ERW group to use them as inputs to the Axiomatic design framework. This is the basis of modelling approach to quantitatively analyze the drive components (e.g. spindle axis, feed axis) and also the cooling system in machine tools.

For the energy consumption in the machine tools, the focuses are more on the mechanical parts which have the most contribution in the energy consumption, and here tried to model the contribution of each in the case of CNC milling. Calculation of the resource utilization is more based on the machine tool efficiency in using the appropriate machining time to deliver the finished parts. According to literatures, the highest energy efficiency achieved when the machine tools transfer the raw material to the finished work in the shortest machining time (Taha et al, 2010) Parameters like process sequencing, tool path and tool changing time are priorities for the resource modelling. Wastes in machining operations can be generalized as any sequence of actions which have no added value to our work piece. The wastes are produced when there are not appropriate machining conditions such as insufficient lubrication cooling and compressed air, long warm up time, irregular tool changing pattern. The wastes produce in the forms of heat or chip wastes that cause highly energy consumption.

Hierarchy: The hierarchical modelling structure has been approved efficiently on the energy consumption modelling of the machine tools operations (Neugebauer et al, 2011) With the machine tools parameters classification carried out in the first step the following hierarchical structure will be substantially defined. The model should be built by the integration of energy, resource and waste, so as the CO_2 value produce at the end. Signifying the relations between components and sub components of machine tools, we have to prove the following equation:

$$CO_2 = f\,(E, R, W)$$

To balance the left side of the equation with the right side, numerical value has been assigned to the sub components of the machine tools that construct the main model. The sub components effects must be investigated by decomposing the main model into the individual measureable performances for later evaluation.

Flexibility: To define energy, resource and waste options in the structure of the model, the boundary and flexibility of the model should be defined. Within the hierarchy of ERWC modelling, the machine tools including its components and sub components, works with the interactions between the mechanics joints that change during the machining operations. Also, there are tool and work piece changes during the machining actions which have to be fit into ERWC model. Thus, the flexibility of the model should be taken into consideration for building a reliable model for further uses, foremost by selecting individual machine tools parameters.

Multi-functionality: The complexity reflects when these three factors (ERW) being integrated together because, the energy consumption has the effect on resource utilization and both of the previous key performances effect on the waste production. For instance, deactivating the cooling system that is the major energy consumer reduces the energy usage during the machining, but removing cooling increases the scrap rate and therefore increase energy consumption. Also, the sub components and sub assemblies in the machine tools should be considered in order to build a generic and reliable ERW model which increases the complexity in the modelling. To cope with the complexity issues of integrating those parameters, ERW is formulated while maintaining the natural interrelations (information contents) between energy consumption, resource utilization and waste production during the machining operations.

Selection of the specific sets of machine tools parameters for modelling the ERWC is preformed implicitly and intuitively by experienced machine tools worker who have well understandings about the effects of the machine tools setup parameters on ERW. After building a conceptual model based on the machine tools variables with the proper sequence, we must formulized a solution by postulating the fact that *"There are values assigned for the physical domains of the machine tools operations which address the contribution of each machine tools parameters with the energy, resource and waste."*

The systematically ERWC modelling approach presented here, albeit hypothetical, may be an ideal and practical approach for analysing every machine tools parameter which has contribution in carbon foot prints which generated during the machining operations. Each methods has been used for ERWC modelling has been described in the following sections in details. Fig. 3.2 shows the formulation of ERWC model based on the approaches presented.

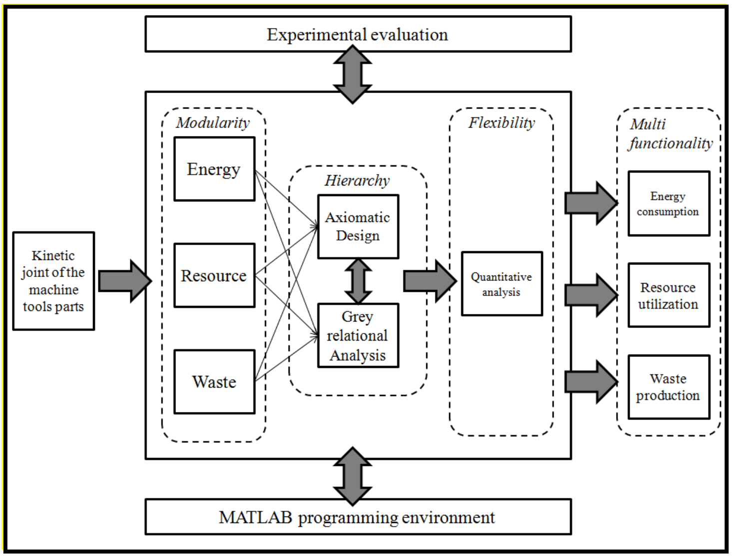


Fig. 3.2 Concept of the ERWC modelling approach

The mechanical relationship between machining parameters considered while cutting operations undertake on assumed workpiece. Each machining parameter contribution on the model development presented on Fig. 3.2.Finally, The ERWC has been modelled based on the heuristic integration of AD and GRA. The contribution of each has been described at below.

3.3.1 Axiomatic design approach

The study of energy consumption in systems is usually done by breaking down the systems into smaller systems and subsystems which make it possible to compare different energy consuming subsystems (Imani et al, 2009) To apply the same methodology for our case, axiomatic design (AD) study has been conducted. The AD has been applied to manufacturing operations successfully through the systematic approach of multi attribute decision making (Kulak and Kahraman, 2005;Suh, 2001;Suh, 1997; Suh et al, 1998). The AD theory is for the first time proposed by Suh (2001) for determining the best design among many alternatives. The main objective of AD is to satisfy functional requirements (FR) of the problem, by identifying plausible design parameters (DP). Specially, it can be applied to the optimization problems in which the DPs are vaguely defined. Dealing with the complexity of manufacturing systems, we have to break down the problems to sub-problems. To find a logical and rational relation between FRs and DPs, AD creates their hierarchies through decomposition process. In fact, the design which has the coupled design should be uncoupled to be processed. Fig. 3.3 illustrates the general scheme of the FRs and DPs contribution in axiomatic study.

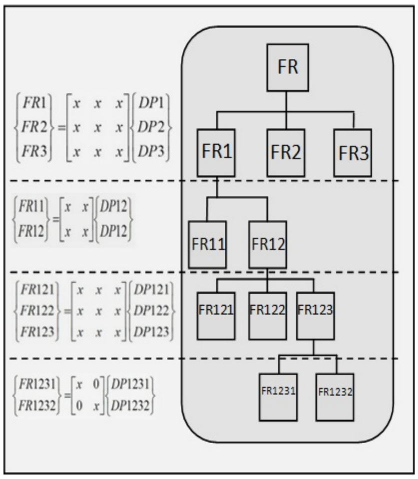


Fig. 3.3 Schematic presentation of FRs and DPs hierarchies (Suh, 2001)

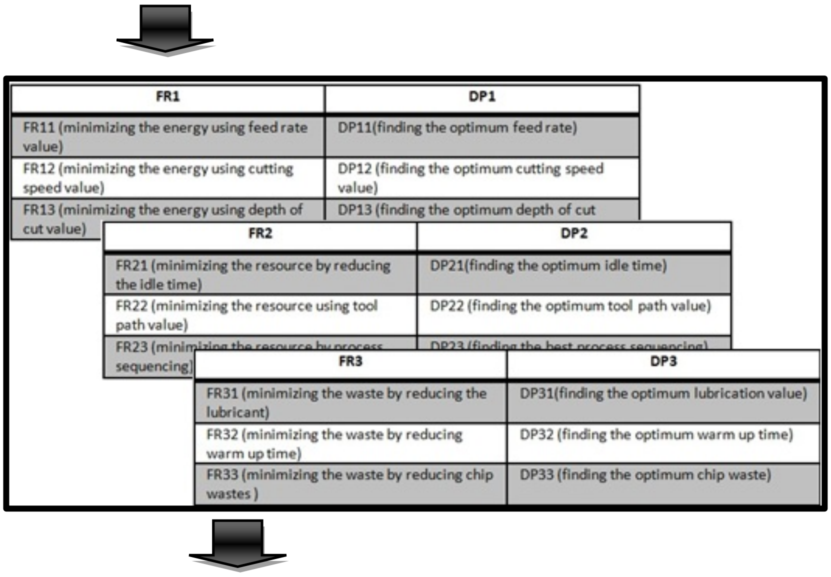
The parameters definition which used for ERWC modelling has been shown in Table 3.1.

Table 3.1 Axiomatic parameters for modelling ERWC (First level)

FRs		DPs	
FR1	Minimizing the energy consumption	DP1	Optimization of the energy
FR2	Minimizing the resource utilization	DP2	Optimization of resources
FR3	Minimizing the waste production	DP3	Optimization of wastes

The model formulation performed by breaking down the FRs and DPs parameters in Table 3.1. Procedure of modelling ERWC has been shown in Fig. 3.4 Defining such limited machine tools parameters leads to simplicity of the ERWC model and its verification process, but restricts the ERWC model to a very limited extent of applications. However, the methodology used in this section can be extended to construct a more general model including different cutting processes and also to the carbon measurement of a machine tool at the times when it is not actually cutting, without any problems. The *'X'* value signifies a strong relationship between the FRs and DPs. As the decomposition is developed, there are less FRs parameters which have strong relationship with DPs. In fact, at each level, the physical realization should be shown. At higher level, the physical embodiments do not have all the details. As the decomposition proceeds, the details are added to the physical embodiment.

FRs	DPs
FR1 (minimizing the energy usage)	DP1 (optimizing the energy)
FR2 (minimizing the resource utilization)	DP2 (optimizing the resource utilization)
FR3 (minimizing the waste production)	DP3 (optimizing the waste production)



$$[Carbon\ Footprints] = \begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & X & X \\ X & X & X \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix}$$

Fig. 3.4 FRs-DPs decomposition hierarchy

The hierarchy framework of AD provides the information needed for modelling the ERWC. However, to meet the FRs by DPs the relation matrix should be either triangular or diagonal (Imani et al, 2009**).** Fig. 3.5 shows the uncoupling process for modelling ERWC. The lowest level FRs and DPs do not need to be decomposed because the DPs can be implemented.

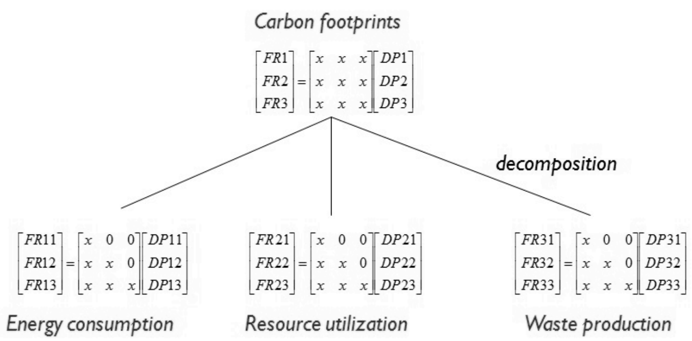


Fig. 3.5 Matrix decomposition in ERWC modelling (The FR-DPs hierarchy tree)

Grey relational analysis has been used as systematic and logical mathematic tools to lead decision making in considering a number of selection alternatives and their interrelations.

For the case study will be presented in the section, Carbon intensity factor has been selected from the database based on the measurement from that particular machining operation. For instance, Carbon intensity factor for electricity is 0.381 (kg-CO_2/kWh) or Carbon intensity factor for lubrication waste is 2.612(kg-CO_2/litre). Carbon intensity makes possible the direct diversion from the cutting parameters to the Carbon released into the air. The model structure has been shown in Fig. 3.6.

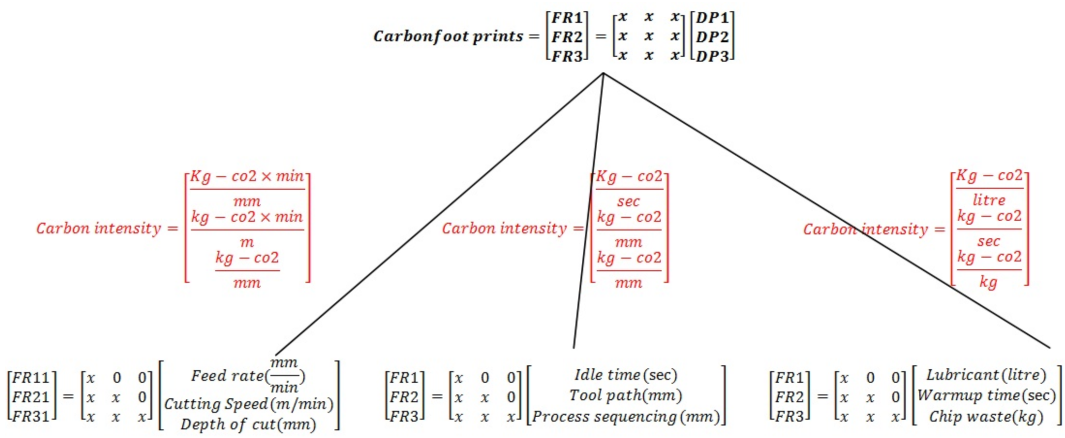


Fig. 3.6 Carbon diversion from the cutting parameters

Machining operations inherits the data from developed model, so that the time of machining has direct relationships with the energy used and Carbon released. Optimization on the machining time and process planning shorten the idle time and suppresses energy wastes.

3.3.2 Grey relational analysis

Grey relational analysis (GRA) is the efficient way for solving multiple attribute decision making (MADM) when the “attributes” or “goals” have complicated relationships between them especially when the problem solving deals with the poor, incomplete, and uncertain information (Moran et al, 2006).GRA has been applied to the machining operation approved to be an appropriate method for optimizing or evaluating the machining operations (Lu et al, 2009; Balasubramanian and Ganapathy, 2011). Based on the predefined factors affected on the machining operation using Taguchi method, GRA optimized the cutting performance, and the results showed the significant improvements in setting up the machining parameters (Tzeng et al, 2009; Cabera et al, 2011). GRA solves problems by integrating the entire range of attribute values being assigned for every alternative into one single value. This reduces the original problem to a single attribute decision making problem (Kue et al, 2008). Fig. 3.7 illustrates the procedures used for the grey relational analysis of the model built by AD**.**

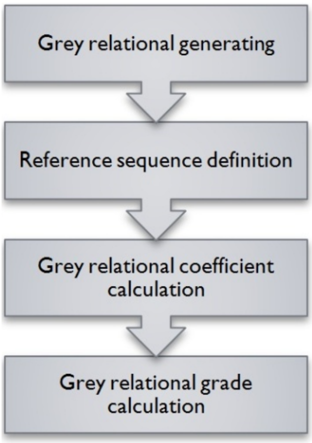


Fig 3.7 Procedure of the GRA

Each process shown in Fig. 3.7 has been described, and empirical illustration will be presented at the end of this chapter.

Data pre-processing

When the units in which performance is observed are different for various parameters, the effects of some attributes may be deserted. This may also happen if some performance parameters have a wide range. In addition, if the goals of those attributes have conflict with each other, it will lead us to unreliable results in the analysis (Huang and Liao, 2003)**.** In order to determine the performance of each attributes, parameters should be transferred to a comparable sequence.

For our case, if there are *m* machine tool parameters, and *n* experimental observations of the machine tool operations, the *i*th alternative can be expressed as $Y_i = (y_{i1}, y_{i2},..., y_{ij},..., y_{in})$, where y_{ij} is the machine tool performance value of parameter *j* of alternative *i*. The machine tools parameters (Y_i) has been transferred into the comparability sequence $X_i = (x_{i1}, x_{i2,} ... x_{ij}, ..., x_{in})$ by use of Equation (3.1).

$$x_{ij} = \frac{Max\{y_{ij}, i=1,2,...,m\} - y_{ij}}{Max\{y_{ij}, i=1,2,...,m\} - Min\{y_{ij}, i=1,2,...,m\}} \quad \text{for } i=1,2,...,m \quad j=1,2,...,n \qquad (3.1)$$

After generating the grey relational numbers of the machine tools performance values, the scaling procedures applied for limiting the data range between [0,1] . By defining a reference sequence X_0 as (x_{01}, x_{02}, ..., x_{0j},..., x_{0n})=(1,1,...,1,...,1) the aims will be searching for the machine tool parameter which comparability sequence is the closest to the reference sequence.

GRA coefficient measurement

To build a scientific and logical comparison between our machine tool parameters and our reference sequence, grey relational coefficient has been evaluated according to Equation (3.2).

$$y(x_{0j}, x_{ij}) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{ij} + \zeta\Delta_{\max}} \qquad \text{for } i=1,2,...,m \quad j=1,2,...,n \qquad (3.2)$$

Where:

$$\Delta_{ij} = \left| x_{0j} - x_{ij} \right|$$
$$\Delta_{\min} = Min\{\Delta_{ij}, i = 1,2,\ldots,m; j = 1,2,\ldots,n\}$$
$$\Delta_{\max} = Max\{\Delta_{ij}, i = 1,2,\ldots,m; j = 1,2,\ldots,n\}$$

ζ Is the distinguishing coefficient, between [0, 1]. We used 0.5 as distinguishing coefficient for machine tools operations.

Grey relational grade calculation

Equation (3.3) generates the Grey relational grade. The purpose of calculating grey relational grade is to address the level of correlation between reference sequence and the comparability sequence (Kuo et al, 2008). The Grey relational grade Rating is based on the weighted values assigned to the columns of each alternative.

$$\Gamma(X_0, X_i) = \sum_{j=1}^{n} w_j \times y(x_{0j}, x_{ij}) \qquad \text{for } i=1,2,...,m \quad j=1,2,...,n \qquad (3.3)$$

Where:

Wj - the weight of machine tool parameter j

$$\sum_{j=1}^{n} Wj = 1$$

3.3.3 Software development on MATLAB

Since MATLAB software has built with advanced matrix operations, MATLAB based modelling and simulation applied for analysing machine tools operations. In order to indicate the AD/GRA modelling approach more clearly, some numerical examples have been illustrated in this part. The Fig. 3.8 shows the MATLAB software which has been developed and the related MATLAB codes have been attached to the Appendix A.

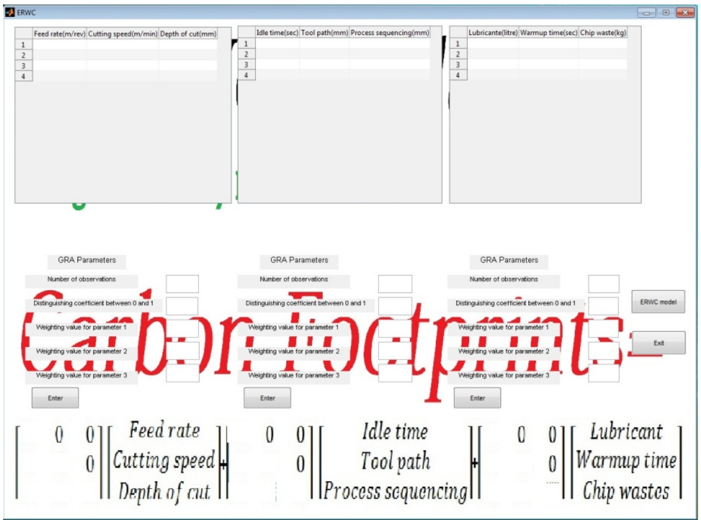


Fig. 3.8 MATLAB programming and developments on the ERWC modelling

Based on the axiomatic study of the machine tools, the main model has been broken down to lower levels for having more details about machine tools setup parameters. GRA applied successfully to ERWC model based on the well-designed scenarios for machine tools operations. The weighted average values for alternative *a*, *b* and *c* are respectively 0.2, 0.5 and 0.3. The data in *'mat5'* is produced in Grey basis for the ease of comparison between machine tool parameters.

For reference sequencing using MATLAB software, we defined a new function named *'insertrows'* which appends the generated data matrix to reference sequence matrix. The closer grey relational numbers to the reference sequence, the better results would be.

After determining the distinguishing coefficient equals to 0.5, the Grey relational coefficient values have been computed by MATLAB software. Finally, Grey relational grade calculated using the weighted average values for each alternative. The final values reflect the contribution of each factor to the success of the FR.

The Grey relational grade has been calculated for each alternative, but still there is a need for weighting the machine tool parameters which effect on the ERWC model. Equation (3.4) provides a holistic systematic approach for modelling the parameters of machine tools operations. In the next chapter, a case study based on the real data collection from the machine tool parameters illustrates the empirical application of the ERWC model presented.

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} 0.4940 & 0 & 0 \\ 0.4940 & 1.2868 & 0 \\ 0.4940 & 1.2868 & 0.7834 \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \end{bmatrix} \tag{3.4}$$

To create a user-friendly environment on MATLAB software, the ERWC software with graphical user interface of MATLAB software has been developed.

3.3.4 Carbon intensity database

Emission intensity data used for calculating the environmental burden and it's referred to categories such as global warming, eutrophication and human toxicity (Narita and Fujimoto, 2009). The database uses from previous data and it's transformed the cutting process into the Carbon equivalent. The benefit of using from the database is in the evaluation phase when you need exact amount of the emissions released into the air, unlike the conventional method.

The database is well fitted into the modelling approach presented.

3.3.5 Assumptions

The linearity assumption has been made between the cutting parameters which considered as strong assumption. The boundary has defined so as to the power consumption variations can be estimated by the linearity. Fig. 3.9 shows the fact that with the change of spindle speed power consumption changes at the linear rate. Similarly, the assumption has been made for other cutting parameters like feed rate.

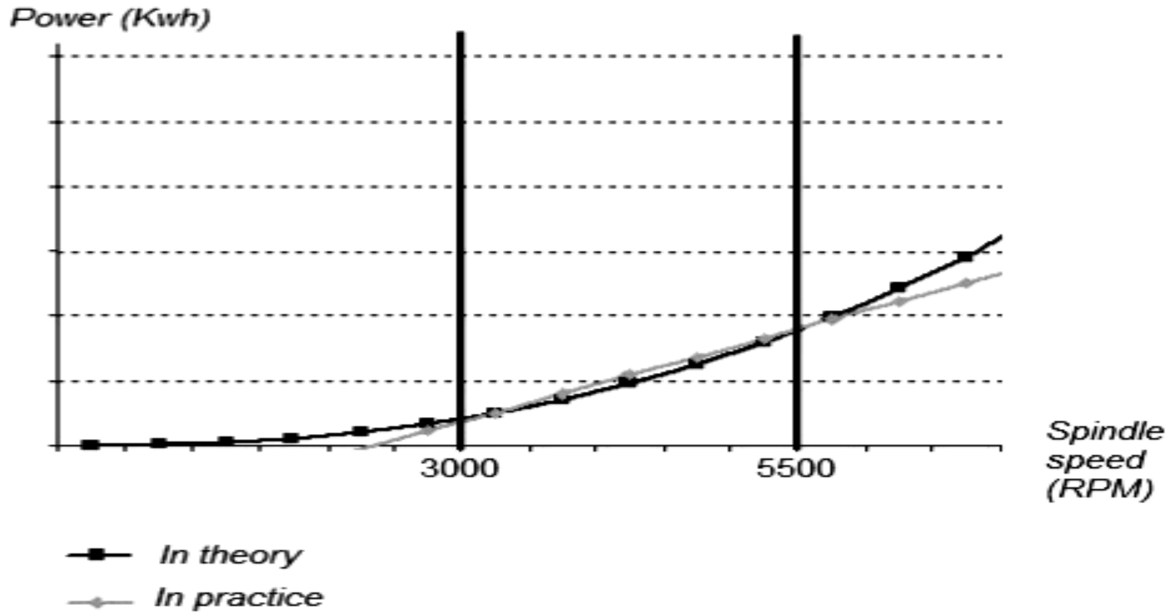


Fig. 3.9 Power consumption vs. spindle speed

3.4 Application of the presented model with case study

The case study presented here is based on the actual data collection from a Bridgeport VMC 500x milling machine while performing a process of cutting a straight slot of various depths out of a work piece. Since there are different factors effect on the energy consumption, resource utilization and waste production and the limitation on the degree of freedom, it is rarely feasible to find deterministic mathematical relations between the cutting factors. However, with fictive input data which can be based on the experiments or simulation studies or testing artifacts several cases or scenarios can be evaluated in terms of Carbon generation. The example will illustrate what kind of analyses that could be performed and what decision-making bases you can get. Slot machining has been undertaken on the aluminium block so that, 3 axis of the milling machine involved in the machining operation. The motion of the X, Y and Z axis should be integrated as to reflect the maximum energy usage of the machine tool which is under the survey. The slotting operation has been performed on the vertical axis of the Bridgeport CNC machine with the cutter size of 8 mm diameters having two teeth. An aluminium block has been cut in 150 mm width and 300 mm length as a work piece. Water-based soluble oils have been used as lubrication and coolant system. Basically, energy consumption of the machine tools will be changed by the tool size and machining setup parameters. To consider the machining operations as a dynamic system which changes all the time, we defined a boundary with 9 machining parameter inputs based on the contribution they have on the energy consumption, resource utilization and waste production of the machine tools (Campatelli, 2009) (e.g. feed rate, cutting speed, depth of cut, idle time, tool path, process sequencing, lubrication, warm up time and chip wastes).

Grey relational analysis integrated with the model in order to estimate the contribution of each cutting parameters to energy consumption, resource utilization and waste production. Cutting speed which is the major energy consumer during the machining operations has directly related to the electricity usage, but it might have effect on the resource utilization. Based on the GRA the major factors which significantly affecting to the energy, resource and waste has been signified. The applicability of the approach has been validated through a test case; the results obtained using fictive input data.

Fig. 3.10 shows how the case study has been conducted. Effective data collection and analysis is essential for ERWC modelling based on the approach presented in this section.

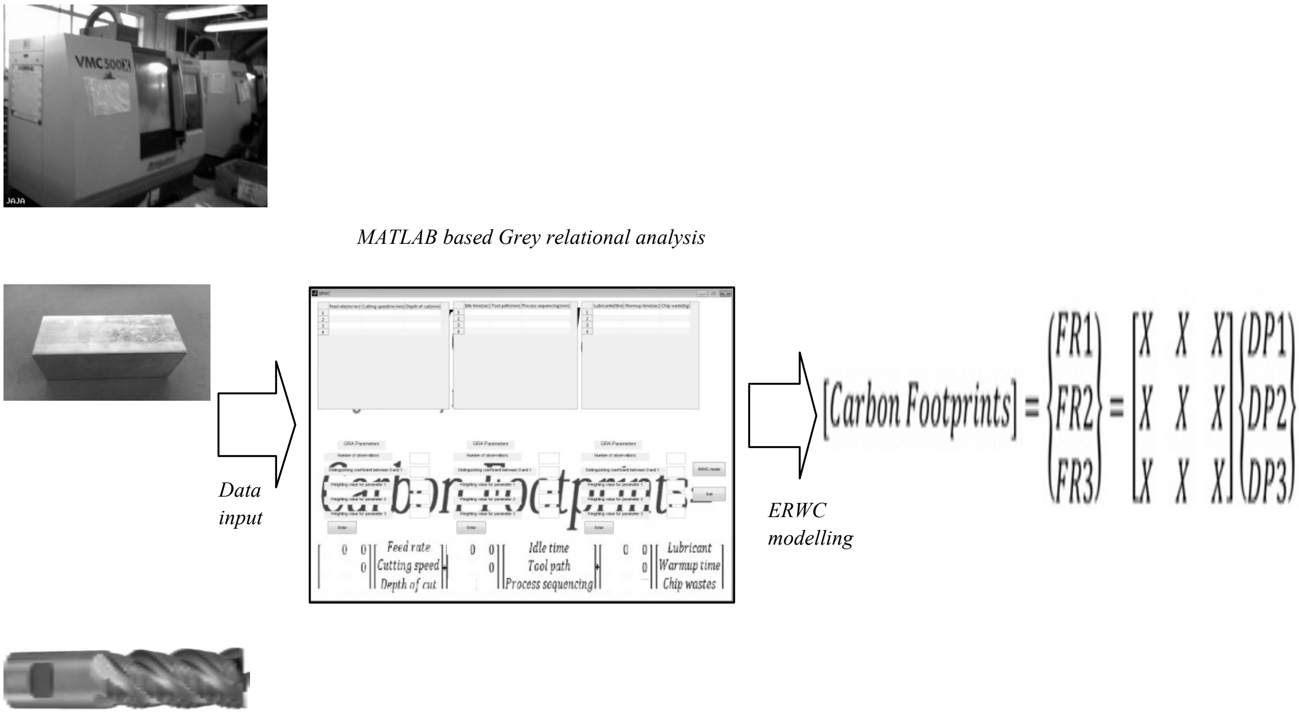


Fig. 3.10 A case study designed for ERWC model evaluation

3.4.1 Data collection

Because of the diversity of machine tool parameters which have contribution on the energy consumption, resource utilization and waste generation, slotting operations have been performed in 9 separate times for data collection. Table 3.2 shows the data collected from the slotting operation designed for modelling the ERWC of the Bridgeport milling machine operations.

Table 3.2 Data sheet for milling operations on the Bridgeport CNC machine.

	Feed rate (mm/min)	Cutting speed (m/min)	Depth of cut (mm)	Idle time (sec)	Tool path (mm)	Process sequencing (mm)	Lubricant (litre)	Warm up time (sec)	Chip wastes (gr)
1	0.66	105	4	23	301.2	801.4	4.3	21	129.6
2	0.56	76	2	13	152.1	652.3	2.3	25	64.8
3	0.62	102	4	13	303.3	803.4	4.2	30	130.1
4	0.46	78	2	16	151.4	651.3	2.2	34	63.8
5	0.64	101	3	29	301.5	801.4	4.1	22	97.2
6	0.75	92	3	19	300.6	800.4	3.5	26	98
7	0.53	91	2	27	152.2	652.4	3.2	24	64.5
8	0.55	78	1	13	151.5	651.3	2.8	27	32.4
9	0.71	84	2	19	151.4	651.4	3.1	20	64.7

Table 3.3 shows the values used for Grey relational analysis of the cutting parameters.

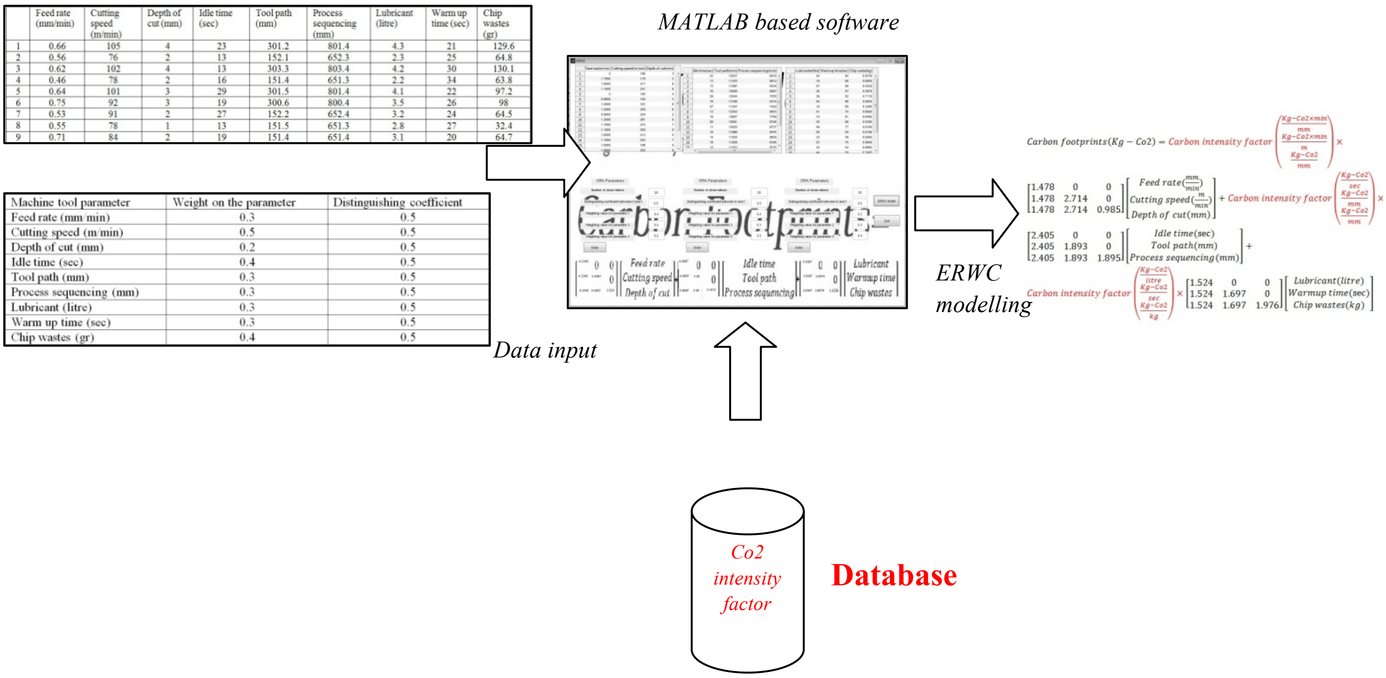
Table 3.3 GRA parameters needed for formulating ERWC

Machine tool parameter	Weight on the parameter	Distinguishing coefficient
Feed rate (mm/min)	0.3	0.5
Cutting speed (m/min)	0.5	0.5
Depth of cut (mm)	0.2	0.5
Idle time (sec)	0.4	0.5
Tool path (mm)	0.3	0.5
Process sequencing (mm)	0.3	0.5
Lubricant (litre)	0.3	0.5
Warm up time (sec)	0.3	0.5
Chip wastes (gr)	0.4	0.5

3.4.2 Model validation

The data has been transferred to ERWC model by MATLAB GUI and the final model displayed in the MATLAB figure as shown in Equation (3.5). Fig. 3.11 shows the data input and processes for ERWC modelling.

$$
\begin{aligned}
&Carbon\ footprints(Kg-Co2) = Carbon\ intensity\ factor \begin{pmatrix} \frac{Kg-Co2\times min}{mm} \\ \frac{Kg-Co2\times min}{m} \\ \frac{Kg-Co2}{mm} \end{pmatrix} \times \\
&\begin{bmatrix} 1.478 & 0 & 0 \\ 1.478 & 2.714 & 0 \\ 1.478 & 2.714 & 0.985 \end{bmatrix} \begin{bmatrix} Feed\ rate(\frac{mm}{min}) \\ Cutting\ speed(\frac{m}{min}) \\ Depth\ of\ cut(mm) \end{bmatrix} + \\
&Carbon\ intensity\ factor \begin{pmatrix} \frac{Kg-Co2}{sec} \\ \frac{Kg-Co2}{mm} \\ \frac{Kg-Co2}{mm} \end{pmatrix} \times \\
&\begin{bmatrix} 2.405 & 0 & 0 \\ 2.405 & 1.893 & 0 \\ 2.405 & 1.893 & 1.895 \end{bmatrix} \begin{bmatrix} Idle\ time(\mathrm{sec}) \\ Tool\ path(mm) \\ Process\ sequencing(mm) \end{bmatrix} + \\
&Carbon\ intensity\ factor \begin{pmatrix} \frac{Kg-Co2}{litre} \\ \frac{Kg-Co2}{sec} \\ \frac{Kg-Co2}{kg} \end{pmatrix} \times \\
&\begin{bmatrix} 1.524 & 0 & 0 \\ 1.524 & 1.697 & 0 \\ 1.524 & 1.697 & 1.976 \end{bmatrix} \begin{bmatrix} Lubricant(litre) \\ Warmup\ time(\mathrm{sec}) \\ Chip\ wastes(kg) \end{bmatrix}
\end{aligned}
\tag{3.5}
$$



	Feed rate (mm/min)	Cutting speed (m/min)	Depth of cut (mm)	Idle time (sec)	Tool path (mm)	Process sequencing (mm)	Lubricant (litre)	Warm up time (sec)	Chip wastes (gr)
1	0.66	105	4	23	301.2	801.4	4.3	21	129.6
2	0.56	76	2	13	152.1	652.3	2.3	25	64.8
3	0.62	102	4	13	303.3	803.4	4.2	30	130.1
4	0.46	78	2	16	151.4	651.3	2.2	34	63.8
5	0.64	101	3	29	301.5	801.4	4.1	22	97.2
6	0.75	92	3	19	300.6	800.4	3.5	26	98
7	0.53	91	2	27	152.2	652.4	3.2	24	64.5
8	0.55	78	1	13	151.5	651.3	2.8	27	32.4
9	0.71	84	2	19	151.4	651.4	3.1	20	64.7

Machine tool parameter	Weight on the parameter	Distinguishing coefficient
Feed rate (mm/min)	0.3	0.5
Cutting speed (m/min)	0.5	0.5
Depth of cut (mm)	0.2	0.5
Idle time (sec)	0.4	0.5
Tool path (mm)	0.3	0.5
Process sequencing (mm)	0.3	0.5
Lubricant (litre)	0.3	0.5
Warm up time (sec)	0.3	0.5
Chip wastes (gr)	0.4	0.5

Fig. 3.11 Analytical calculation of the Bridgeport CNC machine parameters for ERWC modelling

3.4 Conclusions

Machining operations are highly energy consuming and harmful for the environment. Developing a systematic/holistic model that encompasses energy consumption, resource utilization and waste production of the machine tool operations has been disputed widely. Building specific international standards for the same purposes mentioned earlier can be a proof of the severity, which needs to undertake on the machining operations. Based on the European commission framework released in July 2012, the energy measurement of the CNC machines operations should be defined by specific and quantitatively measurable key performance indicators (KPI). Also, formulating multi objective ERWC model, for better analyzing the CNC machines operations became dominant these days. The most cumbersome for modelling the ERWC exists in the complexity between the machine tools parameters. Thus, the approach for finding an appropriate ERWC model integration which estimates all the dynamic behaviour of the CNC machines presented. The presented approach for ERWC modelling has been illustrated with a case study on the Bridgeport milling machine at the end. We replicated 9^{th} individual slotting operations for designing the case study. MATLAB based software has been designed for the analytical calculation purposes. The outcomes from the case study verified the AD/GRA approach for formulating the ERWC model based on the prepared scenarios.

Chapter 4 Energy consumption measurement of CNC machines using a standardized test workpiece

4.1 Introduction

Development of ISO standards for assessing the energy efficiency of machine tools shows significant efforts for minimizing the environmental impact of machine tools and the associated operations. For proper and accurate assessment of machine tools' performance on energy consumption, resource utilization, waste in operations and the consequent carbon generation (ERWC), a well designed test workpiece is essential and much needed so as to test and assess the machine tool in a calibrated comparable manner. The test workpiece should be utilized as an index to provide comparable and quantitative results. The designed workpiece as an artifact has been machined and trialed out on a 3-axis CNC milling machine to test the appropriateness of the artifact and thus assess the energy consumption of the machine in a quantitative and comprehensive manner.

4.2 Design of the standard test piece for energy measurement

Energy consumption of machine tools in operations has been discussed extensively from both economic and environmental aspects of sustainable manufacturing. Since machine tools have substantial contribution to energy consumption in manufacturing processes, several standards are being developed for assessing the energy consumption of machine tools so as to improve in environmental performance of the machines and associated operations. For instance, Japanese standards coded JIS TS B 0024-1:2010 is published by the Japanese Standards Association and presented a standard procedure for measuring the energy consumption of CNC machines (JSA, 2010). The designed test workpiece is evaluated within the standard cycle of 4 hours to achieve empirically significant data. A 3-axis milling machine is selected for energy analysis since milling operations are more energy sensitive. The machine drives are evaluated by moving the spindle along a cubic motion pattern. The proposed test workpiece has 2 main features (i.e. holes and grooves), and is incorporated with face milling, end milling and drilling operations on this 3- axis milling machine. In the mean time, the Fraunhofer institute has published several documents focusing on industrial standards policy and impact

analysis of machine tools and related operations (Fraunhofer, 2012). They developed standard definitions and procedures for reducing the energy consumption and carbon emissions through test workpieces designed by NC Gesselschaft e.V. A test workpiece has been designed for 5-axis milling operations with 9 different features machined with face milling strategy.
In this section, the design of a ‘standard’ test workpiece is presented by taking account of the complexity of machine tools operations. The design attempts to address multiple factors and coupling effects involved in the machine system, the complexity and diversity of associated machining operations. The proposed design approach and testing protocols aim to standardize the energy consumption assessment of machine tools, which are carried out in a holistic, comprehensive and quantitative assessment manner.

The CAD model has been developed for designing the artifact followed by simulation with Powermill to select the best cutting strategies and cutting tools. The standard test piece design parameters which correlate with the energy consumption of the machine tools were considered as follows:

- Machine Tool Drives(X, Y and Z axis): The motion of the X, Y and Z axis should be integrated as to reflect the maximum energy usage of the machine tool which is under the survey. Also, the drives movement during the warm up period and following the tool path were studied as well as the time when tool cut the surface of the workpiece .

- Machining Strategies: The methods of machining the workpiece have been well evaluated. Roughing and profiling have more contribution to the energy consumption rather than other machining methods as they have longer machining time and larger material removal rate. The machining strategies have been integrated so that the all possible machining methods investigated on the designed test workpiece as it shown in Fig. 4.1.

- Dimensions: Scaling the dimensions of the workpiece should be matched to the capabilities of the machine under study. Three main groups of machine tool sizes are subsequently classified: small (working area<0.1 m2), medium (0.1

m2<working area<1 m2), and large (working area>1 m2). Selection of the cutting tool is also linked to the dimension setting (some cutting tools may cause less energy consumption if there is no need for step by step reworking on the feature). Bridgeport VMC 500X milling machine has been selected for the experiment.

- Workpiece Materials: The material used in the standard test piece should highlight the energy usage side of the machining operations. A plastic work piece for example is expected to produce a smaller load on the spindle motor than a Aluminum work piece and therefore consumes a lower cutting power. Even though the cutting speed of Aluminum is the highest between all metals, it does not necessarily deliver the highest amount of energy consumption. Neglecting the machinability of the material, Steel has been selected as the workpiece material.

- Cutting Tool: Coated tools generally produce lower friction at the tool chip interface which leads to lower cutting energy, contact temperature and tool wear.(Grzesik 2003) Thus, we used coated tools for the machining operations. 6 mm and 5 mm end mill tools have been used for surfacing and 3 mm ball nosed tool has been used for shaping the dome.

- Other Features: There are also some other factors for designing the test piece which has been considered such as: easy and fast to manufacture and measure, give comparable and quantitative results, producible in different types of 3 axis milling machines.
- The procedure of developing test workpiece correlated with integrating the above features has shown in Fig. 4.1. The CAD drawing of the designed test piece has been attached to this thesis (Appendix B).

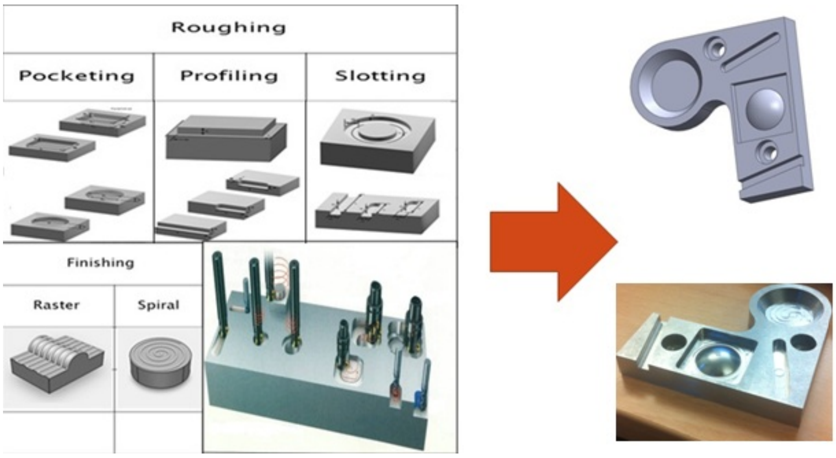


Fig. 4.1 The procedures of designing the test workpiece for energy assessment of a CNC milling machine

4.2.1 Previous testing workpiece designs for energy consumption

Previous designs of the test work piece for energy measuring purposes have been shown in Fig. 4.2 Behrendt et. al (2012) designed a test workpiece based on the JIS TS B 0024-1:2010, which consists of 17 different features and is machined with face milling, grooving , pocketing and drilling operations. The designed workpiece can be fitted to any size of machine tools by scaling the dimensions of the workpiece matching the capabilities of the machine assessed. Berkley sustainable manufacturing research group has also designed a test piece for standardizing the energy measuring procedures. The Japanese test piece has 3 closed slots and 6 open slots.

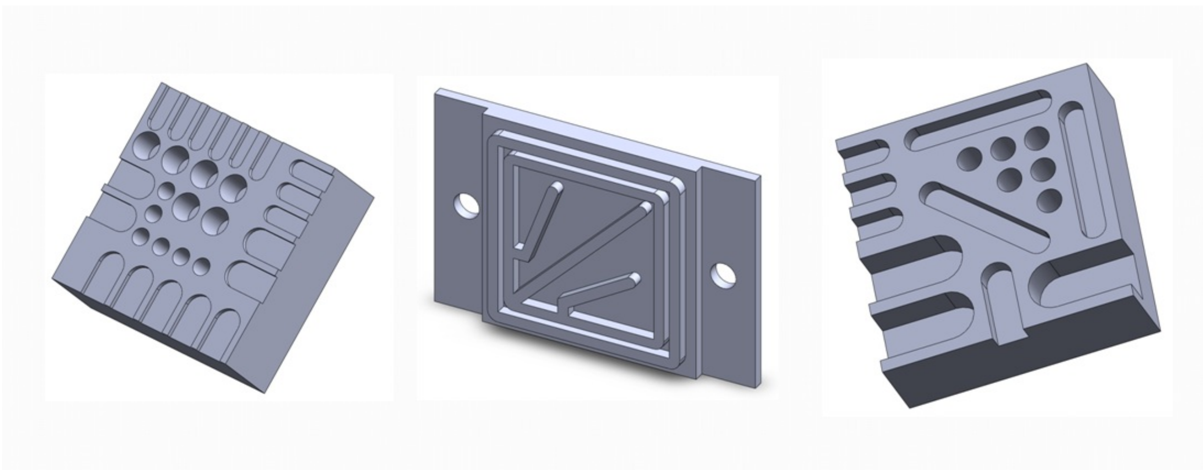


Fig. 4.2 Previous designed test workpieces for energy consumption measurement (Behrendt et. al, 2012; Berkley sustainability group; Japanese standard)

4.2.2 Quantitative analysis of the shapes machined on the test piece

In order to achieve to the best design for the energy measuring purposes, we have combined the above designs as well as quantitative analysis of different shapes and features. The energy consumption of different shapes has been investigated with respect to the cutting directions and the cutting strategies. The parameters are weighted based on the effect they each has on the energy consumption of the machining operations. Finally, we selected the ratios which indicate the highest energy consumption for the machining as its highlighted in Fig. 4.3 So, the combination of these shapes reflects the highest power consumption of the milling machine under the study.

Machining direction / *Machining strategies*	Profiling	Pocketing	End milling	Slot drilling
X and Y	0.5	0.6	0.3	0.3
X, Y and Z	0.7	0.7	0.4	0.6
Circular	0.8	0.8	0.4	0.6
Angle	0.7	0.9	0.4	0.6

Fig. 4.3 Quantitative analysis on the test workpiece design

4.3 Testing procedures

According to the cutting conditions shown in Fig. 4.3, the machining procedures are as follows:

- Profiling in X and Y should be done (roughing and finishing)
- Pocketing with 123° angle (roughing and finishing)
- Pocketing with dome (roughing and finishing)
- End milling to make open slot
- Slot drilling for make close slot

The test piece has been designed in Solidworks 2012, and input to the PowerMILL 2011 to generate the G-codes for the CNC machine input. The design and the tool path generation have been shown in Fig. 4.4.

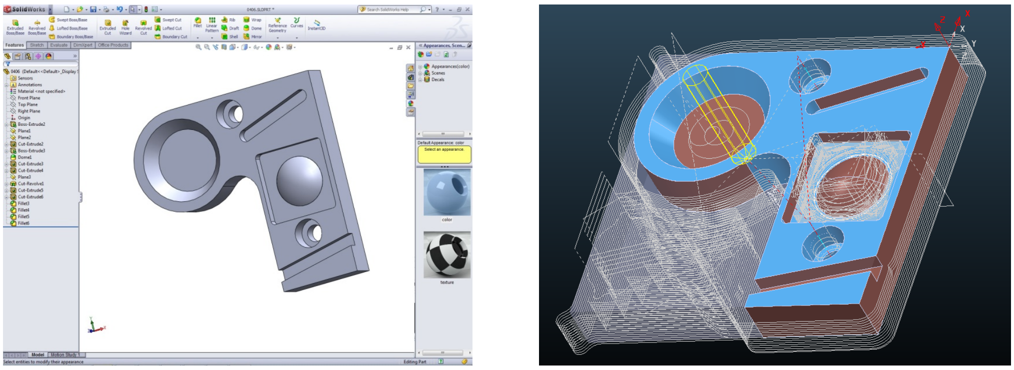


Fig. 4.4 Design and tool path generation of the test workpiece

4.3.1 The experimental setup

The test workpiece shown in Fig. 4.4 has been machined with a 3-axis Bridgeport machine, and the cutting condition was assigned by the values suggested by Sandvik tools handbook. Table 4.1 summarizes the cutting parameters used for machining the test piece.

Fixed values has been tried out on the cutting speed and feed rates, however, the material used and also tool wear are reasons for the changes.

Table 4.1 Cutting parameters for machining the designed test workpiece

Cutting conditions	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5
Feed rate (mm/min)	400	400	500	400	400
Cutting speed (RPM)	4000	4000	5000	4000	4000

4.3.2 Data collection methods

The Power logger has been attached to the Power bus of the milling machine. The specific test box has been design for clamping into the channels of 3 phases motor so as to reduce the danger of electricity shock. The Delta connection has been considered for measuring the 3 phases motor. So, the current probes have been connected to the machine directly, but for measuring the voltage flexible nodes surrounded the current probes. Fig. 4.5 and 4.6 shows the connections and the experimental setups. Fig. 4.7 shows the machine test workepiece. The process of measuring the machine tools energy has been displayed in Appendix C.

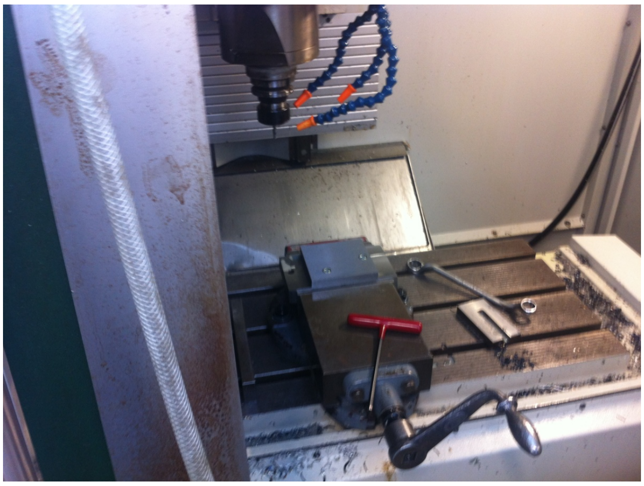


Fig. 4.5 Steel block clamped into the 3 axis milling machine

Fig. 4.6 The power logger connected to the 3 phases motor

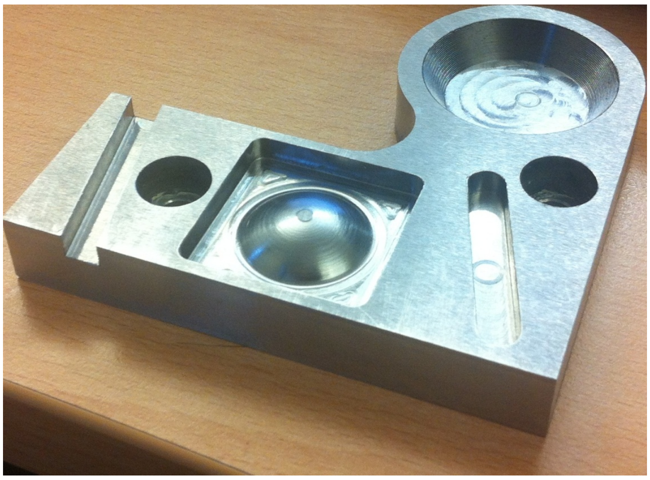


Fig. 4.7 The standard test workpiece machined

4.4 Results and discussions

For measuring the energy consumption of the 3 axis Bridgeport machine, the power logger has been clamped to the 3 phases motor. Generally, CNC machines consume energy in three following phases :(Avram and Xirouchakis 2011)

4.4.1 Warm up Time

In this phase the energy which used by the auxiliary devices such as lighting, coolant pump, chip conveyer, mist collector and numerical control unit has been measured in a specific cycle time (75 sec) as it shown in Fig. 4.8.

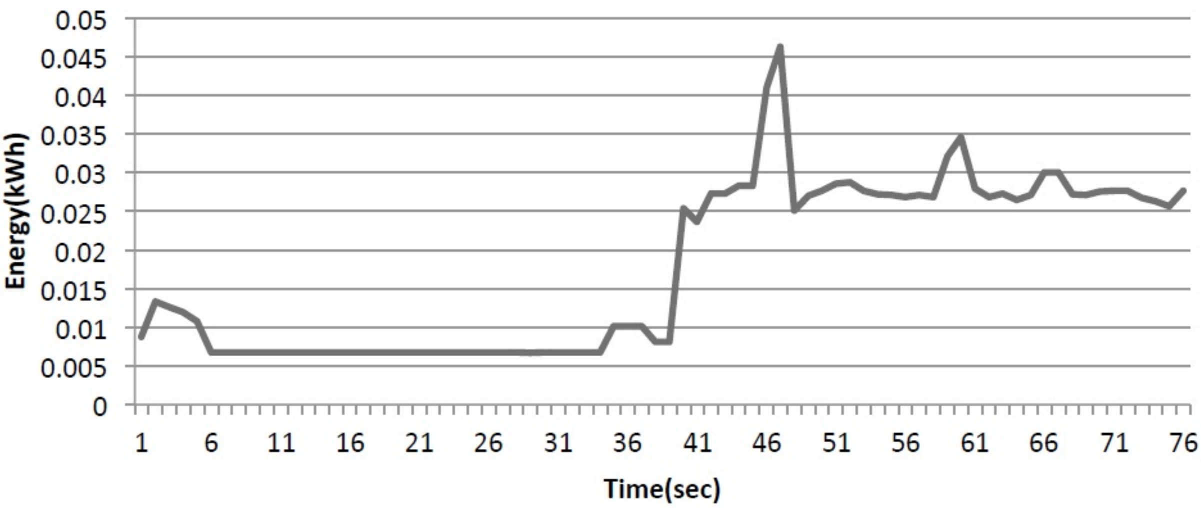


Fig. 4.8 Energy consumption during the CNC machine warm up

Where the total energy used for warming up the CNC machine is equal to 1.35 kWh The electricity picks caused by the turning on the auxiliary devices such as lighting, fans, coolants and controller.

4.4.2 Rapid Movement of Axis

For measuring the power consumption of the spindle axis units, the cubic movements of the mechanic arms have been considered. The highlighted lines in Fig. 4.9 show the routes of the experiment (a-h-f-d-a- g-b-c-d-a), and Fig. 4.10 shows the energy consumption of the air cutting test.

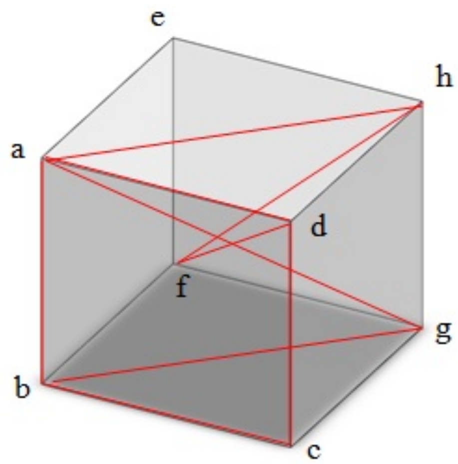


Fig. 4.9 Spindle movement for measuring the power in air cutting

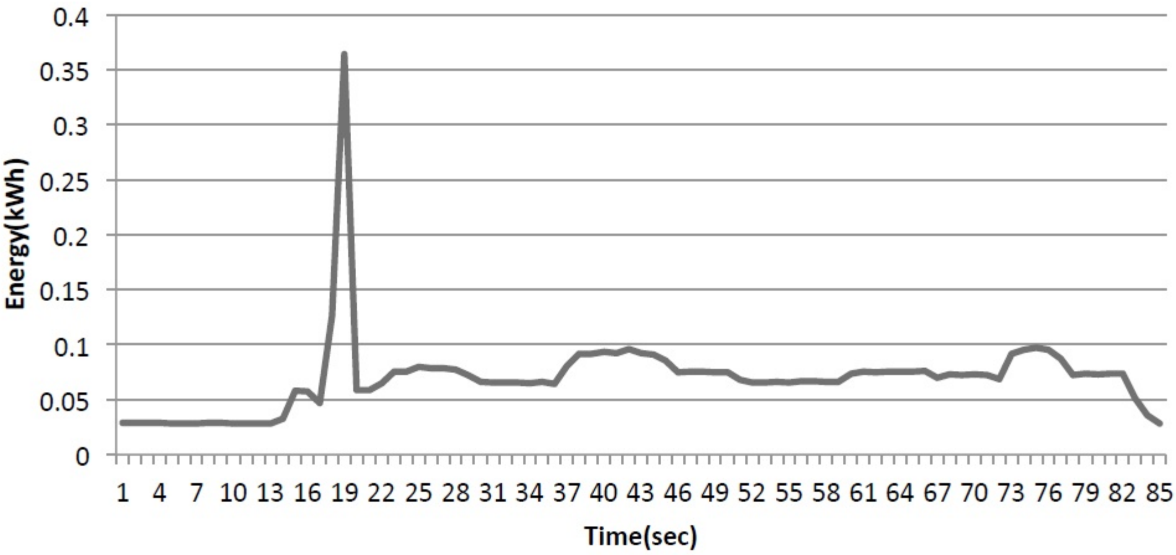


Fig. 4.10 Energy consumption during air cutting of the CNC machine.

Where the energy consumption for air cutting is equal to 5.92 kWh.

4.4.3 Actual Cutting

The specific artifacts have been designed for measuring the machining power of the machine tools. The design of the test workpiece features derived from the test piece suggested by JSA and TU Braunschweig (JSA, 2010; Behrendt et al., 2012). The cutting parameters setup was based on Table 1 data. The energy consumed during the machining has been plotted in Fig. 4.11.

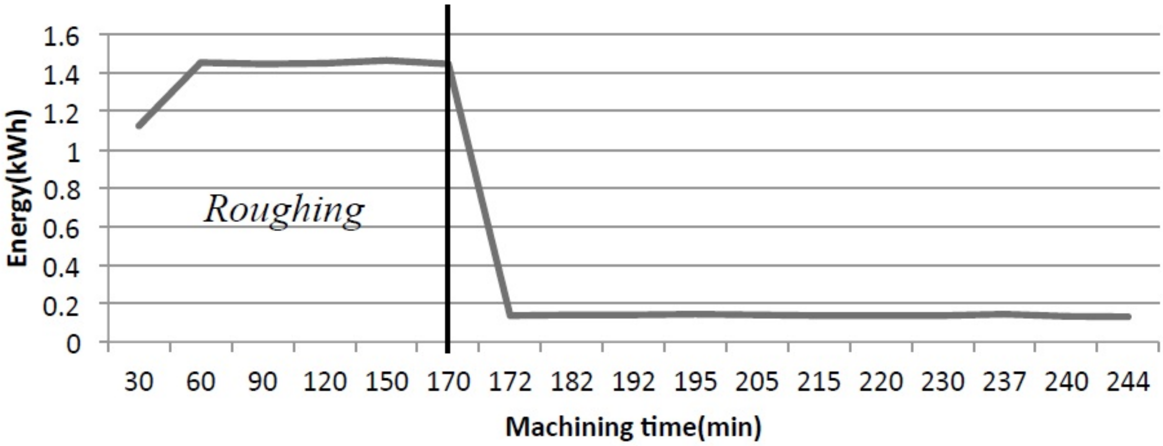


Fig. 4.11 Average energy usage of the CNC milling machine

The average energy used for the actual cutting operations is 10 kWh.
The roughing operation contributed to the most energy consumption of the total cutting operations. With the increase of the material removal rate (MRR) the energy consumed per volume increased. However, increasing the material removal rate reduce the machining time and minimize the total cutting power consumed from the start to end of operations. The electricity measurement of the machine tools per machining time has been plotted in Appendix D.

4.4.4 Further discussion

Improvement on the energy consumption during machining needs quantitative and accurate testing procedure with the well designed artefact. The test workpiece designed with specific features correlated with the energy consumption in the 3 axis milling machine so as to reflect the maximum energy of the machine tool under study. The electricity consumption has been measured in 3 steps after turning on the CNC machine in order to show the exact amount of electricity usage in each step. Fig. 4.12 shows the entire procedures for measuring the cutting power. Roughing the steel out of the block consumed the most energy in comparison with the other machining strategies. So, the energy usage affected by the cutting time as it's presented. The results show that further improvements can be done in the energy consumption of the machining operations as follow:

- Reschedule the machining of the testing features, so that the spindle and axes movement time reduces during one cycle of machining.
- Optimization of the cutting parameters for delivering more energy efficient product.

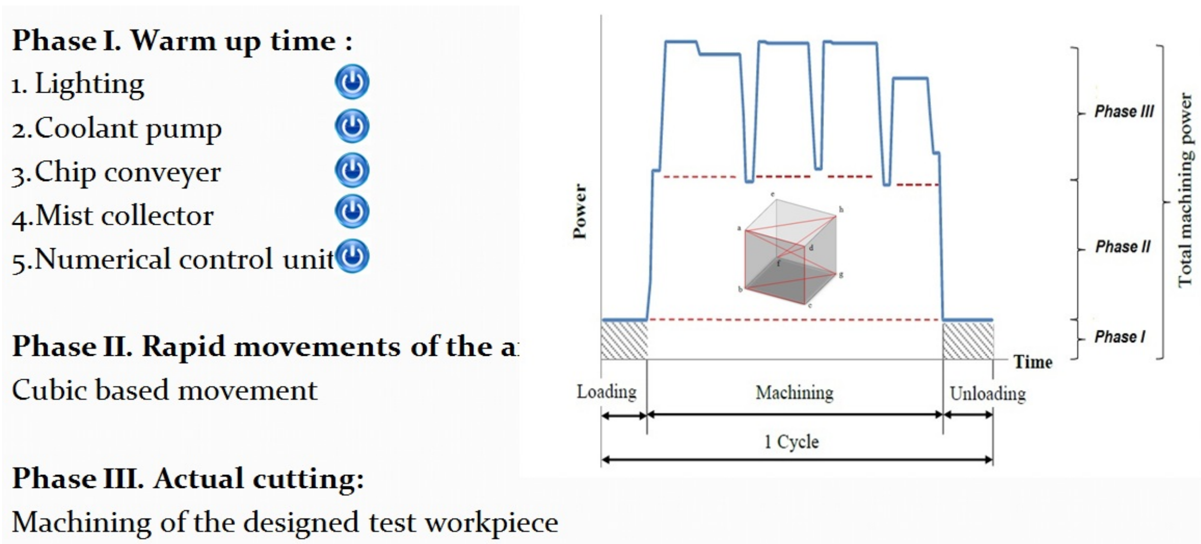


Fig. 4.12 Testing procedures used for energy consumption measurement (Behrendt e. al., 2012)

Chapter 5 Testing protocols of machining parameters for the machine energy consumption

5.1 Introduction

The testing procedure presented in the previous chapter was based on the indirect cutting parameters effect such as auxiliary devices, tools, materials on energy consumption as we assigned cutting parameters (e.g. Cutting speed, feed rate and depth of cut) to fixed values. However, in this chapter the standard proposal for measuring the direct cutting parameters such as cutting speed, feed rate and depth of cut has been developed.

Also the effects of the spindle axis have been evaluated versus to the table axes.

5.2 Testing protocols for energy measurement

Basically, the energy experiments on the machine tools have to be pre defined in order to lead to the reasonable results at the end. In this section, each machining parameters effect on the energy consuming during the operations has been investigated. The cutting parameters which have the most contribution in the energy consumption are considered as follow:

- Cutting speed(RPM)
- Feed rate(mm/min)
- Depth of cut(mm)

In next section, each of the above parameter's influences has been studied on the 3 axis milling machine.

5.2.1 Depth of cut in the experiment setup

Three open slots in a block have been designed for measuring the energy of the machining, as it has shown in Fig. 5.1. The fixed values for cutting speed and feed rate has been assumed while the depth of cut is increasing 2 mm in each experiment.

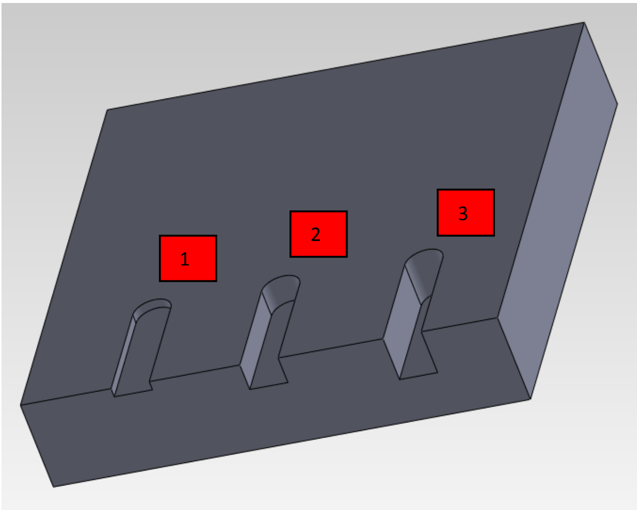


Fig. 5.1 Depth of cut in the experiment design

Table 5.1 Machining experiment setup on the effect of depth of cut

Slot number	Depth of cut (mm)	Feed rate (mm/min)	Number of cuts	Cutting speed (RPM)
1	1	1,800	1	10,000
2	3	1,800	1	10,000
3	5	1,800	1	10,000

The cutter size is important in this experiment because the slots should be machined in one go. Also the energy monitoring has to be done in a fixed cycle time so as to retrieve reasonable energy data of machining the slots.

5.2.2 Feed rate in the experiment setup

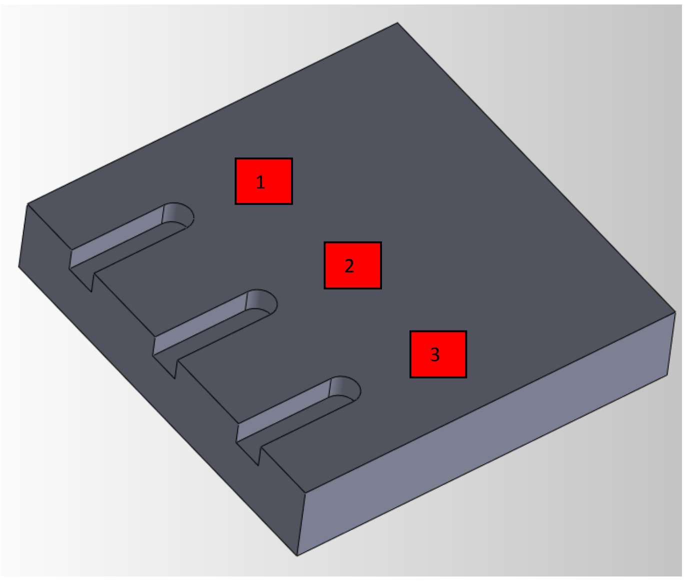


Fig. 5.2 Feed rate in the experiment design

Table 5.2 Machining experiment setup on the effect of feed rate

Slot number	Depth of cut (mm)	Feed rate (mm/min)	Number of cuts	Cutting speed (RPM)
1	3	1,800	1	10,000
2	3	1,200	1	10,000
3	3	800	1	10,000

This experiment has been adapted for experiencing the energy usage of the feed rate changes during specific cycle time. (Fig. 5.2) The depths of cut and cutting speed have been set to be fixed during machining, but the feed rate is reduced from 1,800 mm/min to 800 mm/min.

In this experiment, the workpiece which are being machined should be well tested so that, during the machining there is no cutter breakage or tool wear. Aluminium has the desired flexibility to be machined with different feed rates and cutting speed. So, Aluminium has been selected for the proposed experiment. Of course, the surface roughnesses which will be gained are different for the three slots.

5.2.3 Cutting speed in the experiment

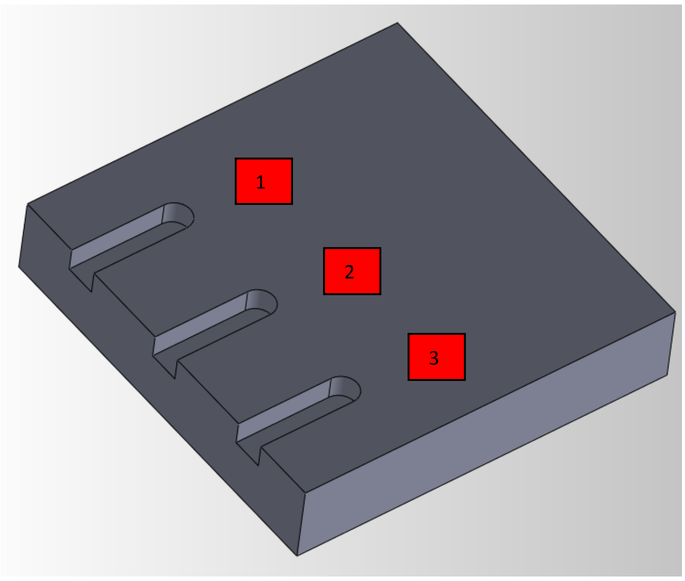


Fig. 5.3 Cutting speed in the experiment design

Table 5.3 Machining experiment setup on the effect of spindle speed

Slot number	Depth of cut (mm)	Feed rate (mm/min)	Number of cuts	Cutting speed (RPM)
1	3	1,800	1	10,000
2	3	1,800	1	9,000
3	3	1,800	1	8,000

Energy data should be collected during the machining of three slots with three different intervals. (Fig. 5.3)The first slot should be machined with the 1000 RPM and reduce gradually for the entire of experiment. The machining power between machining intervals is decreased significantly so that it is easy to distinguish between the cutting power and air cutting power.

5.2.4 Spindle axis experiment

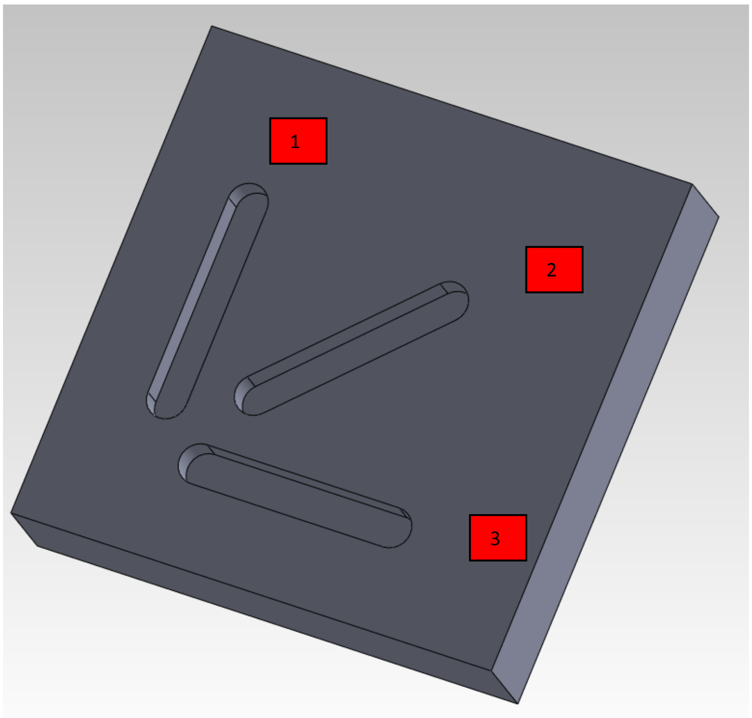


Fig. 5.4 Spindle axis experiment design

Table 5.4 Cutting parameters for Spindle axis experiment

Slot number	Depth of cut (mm)	Feed rate (mm/min)	Number of cuts	Cutting speed (RPM)
1	3	1800	1	10000
2	3	1800	1	10000
3	3	1800	1	10000

Spindle axis in milling machine has to be analysed for the energy efficiency since it uses most of the time during milling operations.

Machining in the XY planes has been investigated so far neglecting the fact that machining uses more energy with the direction changes to XY and Z. The changes of the power consumption have been investigated for three identical close slots. (Fig. 5.4) The angle between the horizontal slot and vertical slot is 90 degree, and the middle slot divides the space between them by the equal degrees (45 degree).

The energy requirement for the slot 1 and 3 should be similar while the 2nd slot consumes higher energy (estimate to be double). The drawings of the CAD model have been attached to this thesis for all the experiments (Appendix E).

5.2.5 The experimental setup

The setup parameters for evaluating the cutting parameters with respect to the energy usage of each have been shown in Table 5.1.

Table 5.5 Machining setup for the energy effects

Elements of experiment set up	Description
Block size	50 mm X 50 mm X 10 mm
Material	Aluminium
Machine	Bridgeport VMC
Tool	4 mm high speed steel
Slot length	14.5 mm

5.2.6 Data collection methods

The data should be collected with the 3 phase power logger device. The saved data plots in the graph later with the power logger software. During the machining intervals the picks and drops show the cutting and air cutting periods.
The power connection should be fully understood since there is no neural channel in delta connection. However, the start connection needs neural channel for the exact measurement.

5.3 Conclusions

In order to investigate the effects of the main cutting parameters 4 cases have been studied in the fixed cycle time. The experiments designed so that it reflects the energy consumption of the cutting parameters not the tools or workpiece material. However, the energy used during machining be effected by other auxiliary devices such as machining table, tool changed, tool magazine. The results gained from these experiments present valuable information for the machinist or machine tool companies. However, the effect of the cutting tools and workpiece material compromises the results of these sets of experiments. The dominant factors in machining should be focused in the energy intensive industries more than the indirect devices.

Chapter 6 Conclusions and recommendations for future work

6.1 Conclusions

Increasing the energy prices and legislation from the government forces the machine tool companies to save more energy on the machining related operations. There is 40-60% potential for increasing the energy efficiency of the machine tools operations. The modelling and simulation approach applied for optimizing the machining operations. The different modelling approach has been analyzed in order to achieve the best systematic structures model. Energy consumption, resource utilization and waste production have been integrated in order to get the quantitative results on the Carbon generated during the machining. Model formulation has been computerized with the MATLAB GUI software development. The modelling approach has been processes and tested on the well designed test workpiece retrieved from previous designs for energy measuring purposes. The standard procedure has been developed in order to test the workpiece in a fixed cycle time. 3 phases of the machining status has been considered for measuring the effective power consumption. During the machining, the machining time and machining power has been logged in the power measurement device. The schematic overview of the presented thesis has been displayed in Fig. 6.1.

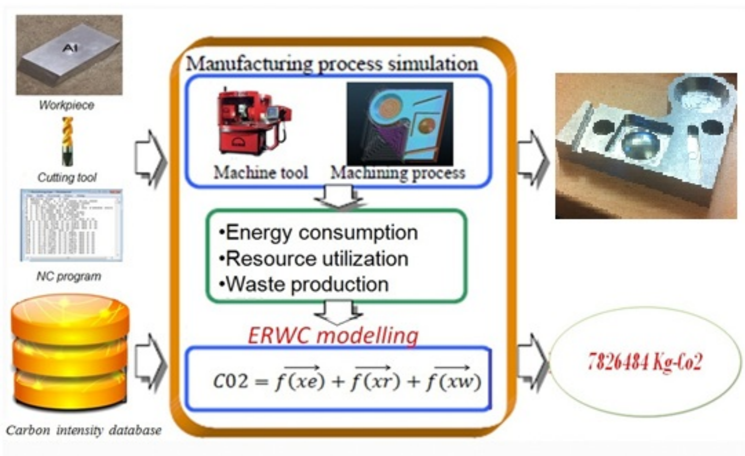


Fig. 6.1 Energy-resource efficient sustainable manufacturing and development

Similarly, the proposal for the cutting parameters effect on the energy consumption has been developed to find the dominant factors in machining operations. The experimental setup and machining intervals has been presented based on the literatures and the previous experiences. The results show that further improvements can be done in the energy consumption of the machining operations as follow:

- Process optimization so that the auxiliary and main machining devices integrated in the efficient way.
- Efficient cutting parameters set up in order to save more energy, and Carbon emissions.

The knowledge contributions from this research are mostly lied in:

- Modelling and simulation approach for evaluating the sustainability analysis of the machining energy consumption and associated operations.
- Design of the test workpiece for smoothing the energy measurement procedures.
- developing protocols on effects of machining parameters for the machine energy consumption

6.2 Recommendations for future work

The research presented here for the energy efficiency of the manufacturing process considering the machining parameters optimization and the associated machining devices. Development of the green manufacturing research has been classified as follow:

- Restructuring the design of CNC machines
- Online and Offline monitoring of the machining operations
- External devices improvement for energy efficient machining

Potentials for improvements of the above statements have been detailed in the next section.

6.2.1 Restructuring the design of CNC machines

Currently, the designed CNC machines have too much complexities for energy saving. Consequently, studies showed that the less machining time gained, the more energy saved during the manufacturing a part. Redesigning the machine tools by improving the hydraulics and physical devices may lead to greener manufacturing. Currently, the project has been developed by seventh framework programme titled DEMAT is working in the same topic.

6.2.2 Online and offline monitoring of the machining operations

The exact amount of energy used during the machining operations inform the machinist from the potential of the energy saving. The offline monitoring of the G codes which estimates the power consumption associated with machining optimizes the cutting operations. Currently, there are no features on the CAM software for the energy estimation of the machining simulation. Linking the electricity usage and the exact tool path generation may be interested area of research.

6.2.3 External devices for improving energy efficient machining

The external devices attached to the machine tools harmonises the electricity flow which cause more electricity savings. Turning off the machine tool devices during the idle time also cut the wastes and energy consumption. Currently, the German company called DMG is focused on building the box which resist to the electricity noises and harmonise the 3 phases of CNC machine motors during machining. The box developed by DMG has been shown in Fig. 6.2.

Fig. 6.2 An external device for improving energy efficient machining and operations

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Appendices

Appendix A

MATLAB Codes for the EWRC modelling approach

```
function varargout = ERWC(varargin)
% ERWC M-file for ERWC.fig
%      ERWC, by itself, creates a new ERWC or raises the existing
%      singleton*.
%
%      H = ERWC returns the handle to a new ERWC or the handle to
%      the existing singleton*.
%
%      ERWC('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in ERWC.M with the given input
arguments.
%
%      ERWC('Property','Value',...) creates a new ERWC or raises the
%      existing singleton*.  Starting from the left, property value
pairs are
%      applied to the GUI before ERWC_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property
application
%      stop.  All inputs are passed to ERWC_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows
only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help ERWC

% Last Modified by GUIDE v2.5 24-Nov-2011 02:33:59

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @ERWC_OpeningFcn, ...
                   'gui_OutputFcn',  @ERWC_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before ERWC is made visible.
```

```
function ERWC_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to ERWC (see VARARGIN)

% Choose default command line output for ERWC
handles.output = hObject;


ha=axes('units','normalized',...
    'position',[0 0 1 1]);
uistack(ha,'bottom');
I=imread('h:\desktop\erwc1.jpg');
hi=imagesc(I);
set(ha,'handlevisibility','off',...
    'visible','off');


% Update handles structure
guidata(hObject, handles);

% UIWAIT makes ERWC wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.



function varargout = ERWC_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)






% Get default command line output from handles structure
varargout{1} = handles.output;


% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)




x=get(handles.edit1,'string');
x=str2double(x);
```

```
w1=get(handles.edit3,'string');
w1=str2double(w1);
w2=get(handles.edit4,'string');
w2=str2double(w2);
w3=get(handles.edit5,'string');
w3=str2double(w3);

y=get(handles.edit6,'string');
y=str2double(y);

w11=get(handles.edit8,'string');
w11=str2double(w11);
w22=get(handles.edit9,'string');
w22=str2double(w22);
w33=get(handles.edit10,'string');
w33=str2double(w33);

z=get(handles.edit11,'string');
z=str2double(z);

w111=get(handles.edit13,'string');
w111=str2double(w111);
w222=get(handles.edit14,'string');
w222=str2double(w222);
w333=get(handles.edit15,'string');
w333=str2double(w333);




mat1 = get(handles.uitable1,'data');


mat3=ones(1,3);



mat2(:,1)=((max(mat1(:,1))-mat1(:,1)))/(max(mat1(:,1))-
min(mat1(:,1)));
mat2(:,2)=((max(mat1(:,2))-mat1(:,2)))/(max(mat1(:,2))-
min(mat1(:,2)));
mat2(:,3)=((max(mat1(:,3))-mat1(:,3)))/(max(mat1(:,3))-
min(mat1(:,3)));

mat4=insertrows(mat2,mat3,0);

for i=1:x
    for j=1
        mat5(i,j)=(0.5)/(abs((mat4(i+1,j)-mat4(i,j)))+0.5);
    end
end


for i=1:x
    for j=2
        mat5(i,j)=(0.5)/(abs((mat4(i+1,j)-mat4(i,j)))+0.5);
    end
```

```
end

for i=1:x
    for j=3
        mat5(i,j)=(0.5)/(abs((mat4(i+1,j)-mat4(i,j)))+0.5);
    end
end


sum1=sum(mat5(:,1));
gra1=sum1*w1;

sum2=sum(mat5(:,2));
gra2=sum2*w2;

sum3=sum(mat5(:,3));
gra3=sum3*w3;



%Second table

mat11 = get(handles.uitable2,'data');
mat33=ones(1,3);



mat22(:,1)=((max(mat11(:,1))-mat11(:,1)))/(max(mat11(:,1))-
min(mat11(:,1)));
mat22(:,2)=((max(mat11(:,2))-mat11(:,2)))/(max(mat11(:,2))-
min(mat11(:,2)));
mat22(:,3)=((max(mat11(:,3))-mat11(:,3)))/(max(mat11(:,3))-
min(mat11(:,3)));

mat44=insertrows(mat22,mat33,0);

for i=1:y
    for j=1
        mat55(i,j)=(0.5)/(abs((mat44(i+1,j)-mat44(i,j)))+0.5);
    end
end


for i=1:y
    for j=2
        mat55(i,j)=(0.5)/(abs((mat44(i+1,j)-mat44(i,j)))+0.5);
    end
end

for i=1:y
    for j=3
        mat55(i,j)=(0.5)/(abs((mat44(i+1,j)-mat44(i,j)))+0.5);
    end
end


sum11=sum(mat55(:,1));
```

```
gra11=sum11*w11;

sum22=sum(mat55(:,2));
gra22=sum22*w22;

sum33=sum(mat55(:,3));
gra33=sum33*w33;


%Third table

mat111 = get(handles.uitable3,'data');
mat333=ones(1,3);



mat222(:,1)=((max(mat111(:,1))-mat111(:,1)))/(max(mat111(:,1))-
min(mat111(:,1)));
mat222(:,2)=((max(mat111(:,2))-mat111(:,2)))/(max(mat111(:,2))-
min(mat111(:,2)));
mat222(:,3)=((max(mat111(:,3))-mat111(:,3)))/(max(mat111(:,3))-
min(mat111(:,3)));

mat444=insertrows(mat222,mat333,0);

for i=1:z
    for j=1
        mat555(i,j)=(0.5)/(abs((mat444(i+1,j)-mat444(i,j)))+0.5);
    end
end


for i=1:z
    for j=2
        mat555(i,j)=(0.5)/(abs((mat444(i+1,j)-mat444(i,j)))+0.5);
    end
end

for i=1:z
    for j=3
        mat555(i,j)=(0.5)/(abs((mat444(i+1,j)-mat444(i,j)))+0.5);
    end
end


sum111=sum(mat555(:,1));
gra111=sum111*w111;

sum222=sum(mat555(:,2));
gra222=sum222*w222;

sum333=sum(mat555(:,3));
gra333=sum333*w333;


gra1=num2str(gra1);
gra2=num2str(gra2);
```

```
gra3=num2str(gra3);
gra11=num2str(gra11);
gra22=num2str(gra22);
gra33=num2str(gra33);
gra111=num2str(gra111);
gra222=num2str(gra222);
gra333=num2str(gra333);

set(handles.text19,'string',gra1);
set(handles.text20,'string',gra2);
set(handles.text21,'string',gra3);
set(handles.text32,'string',gra11);
set(handles.text33,'string',gra22);
set(handles.text34,'string',gra33);
set(handles.text38,'string',gra111);
set(handles.text39,'string',gra222);
set(handles.text40,'string',gra333);
set(handles.text28,'string',gra1);
set(handles.text30,'string',gra1);
set(handles.text31,'string',gra2);
set(handles.text35,'string',gra11);
set(handles.text36,'string',gra11);
set(handles.text37,'string',gra22);
set(handles.text41,'string',gra111);
set(handles.text42,'string',gra111);
set(handles.text43,'string',gra222);




% --- Executes on button press in pushbutton2.
function pushbutton2_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)


close(gcbf);


function edit1_Callback(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit1 as text
%        str2double(get(hObject,'String')) returns contents of edit1
as a double


% --- Executes during object creation, after setting all properties.
function edit1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
```

```
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in pushbutton3.
function pushbutton3_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
x=get(handles.edit1,'string');
x=str2double(x);

for i=1:x
    for j=1:3
        mat1(i,j)=0;
    end
end


%e=get(handles.edit2,'string');
%e=str2num(e);

%w1=get(handles.edit3,'string');
%w1=str2num(w1);
%w2=get(handles.edit4,'string');
%w2=str2num(w2);
%w3=get(handles.edit5,'string');
%w3=str2num(w3);



set(handles.uitable1,'data',mat1);

function edit2_Callback(hObject, eventdata, handles)
% hObject    handle to edit2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit2 as text
%        str2double(get(hObject,'String')) returns contents of edit2
as a double


% --- Executes during object creation, after setting all properties.
function edit2_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
```

```
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit3_Callback(hObject, eventdata, handles)
% hObject    handle to edit3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit3 as text
%        str2double(get(hObject,'String')) returns contents of edit3
as a double


% --- Executes during object creation, after setting all properties.
function edit3_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit4_Callback(hObject, eventdata, handles)
% hObject    handle to edit4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit4 as text
%        str2double(get(hObject,'String')) returns contents of edit4
as a double


% --- Executes during object creation, after setting all properties.
function edit4_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

```
function edit5_Callback(hObject, eventdata, handles)
% hObject    handle to edit5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit5 as text
%        str2double(get(hObject,'String')) returns contents of edit5
as a double


% --- Executes during object creation, after setting all properties.
function edit5_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit6_Callback(hObject, eventdata, handles)
% hObject    handle to edit6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit6 as text
%        str2double(get(hObject,'String')) returns contents of edit6
as a double


% --- Executes during object creation, after setting all properties.
function edit6_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in pushbutton4.
function pushbutton4_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

```
y=get(handles.edit6,'string');
y=str2double(y);

for i=1:y
    for j=1:3
        mat11(i,j)=0;
    end
end


%e=get(handles.edit2,'string');
%e=str2num(e);

%w11=get(handles.edit8,'string');
%w11=str2num(w11);
%w22=get(handles.edit9,'string');
%w22=str2num(w22);
%w33=get(handles.edit10,'string');
%w33=str2num(w33);



set(handles.uitable2,'data',mat11);


function edit7_Callback(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit7 as text
%        str2double(get(hObject,'String')) returns contents of edit7
as a double


% --- Executes during object creation, after setting all properties.
function edit7_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit8_Callback(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit8 as text
```

```
%         str2double(get(hObject,'String')) returns contents of edit8
as a double


% --- Executes during object creation, after setting all properties.
function edit8_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit9_Callback(hObject, eventdata, handles)
% hObject    handle to edit9 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit9 as text
%        str2double(get(hObject,'String')) returns contents of edit9
as a double


% --- Executes during object creation, after setting all properties.
function edit9_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit9 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit10_Callback(hObject, eventdata, handles)
% hObject    handle to edit10 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit10 as text
%        str2double(get(hObject,'String')) returns contents of edit10
as a double


% --- Executes during object creation, after setting all properties.
function edit10_CreateFcn(hObject, eventdata, handles)
```

```
% hObject    handle to edit10 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit11_Callback(hObject, eventdata, handles)
% hObject    handle to edit11 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit11 as text
%        str2double(get(hObject,'String')) returns contents of edit11
as a double


% --- Executes during object creation, after setting all properties.
function edit11_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit11 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in pushbutton5.
function pushbutton5_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
z=get(handles.edit11,'string');
z=str2double(z);

for i=1:z
    for j=1:3
        mat111(i,j)=0;
    end
end


%e=get(handles.edit2,'string');
%e=str2num(e);

%w111=get(handles.edit13,'string');
```

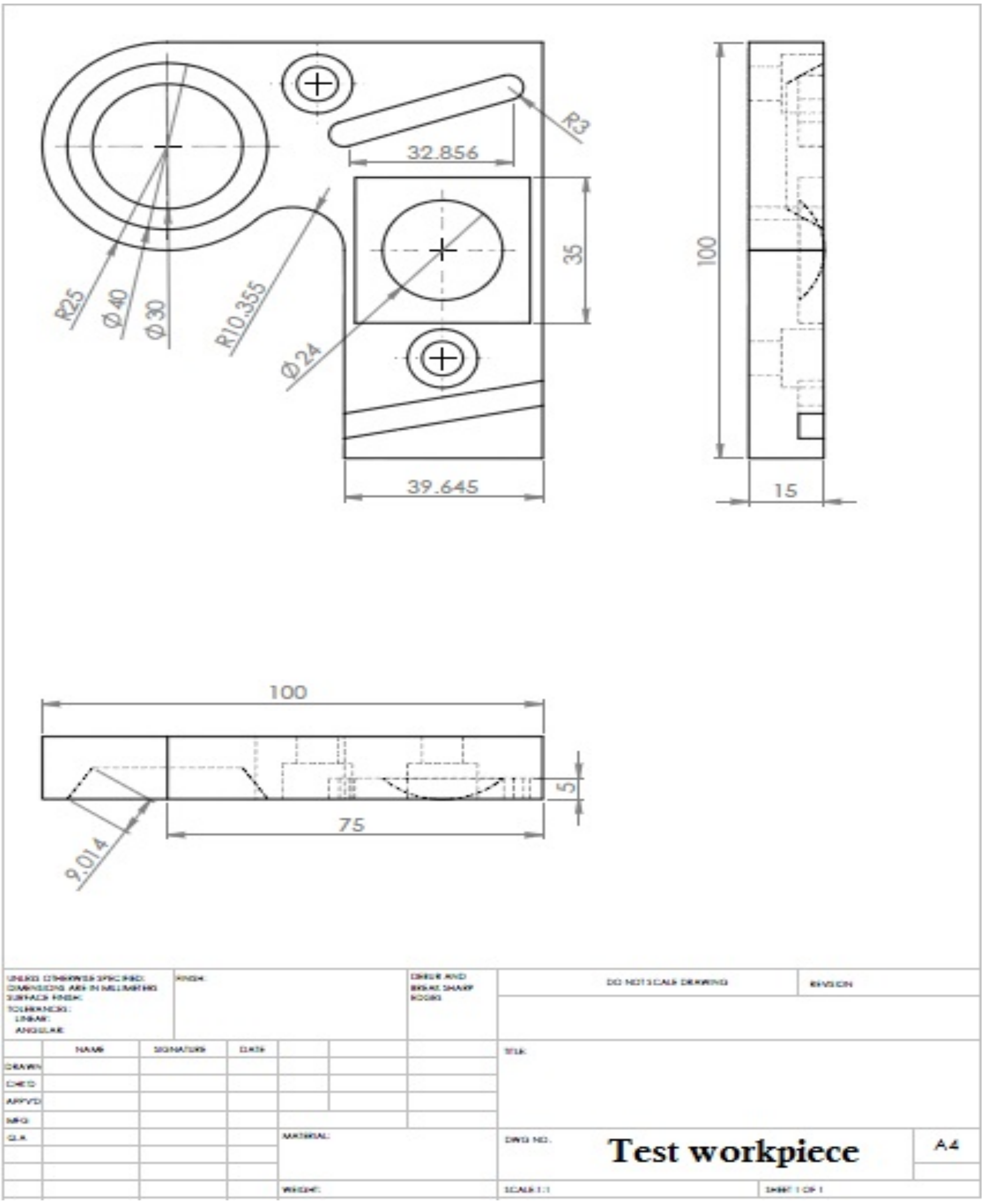
```
%w111=str2num(w111);
%w222=get(handles.edit14,'string');
%w222=str2num(w222);
%w333=get(handles.edit15,'string');
%w333=str2num(w333);



set(handles.uitable3,'data',mat111);


function edit12_Callback(hObject, eventdata, handles)
% hObject    handle to edit12 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit12 as text
%        str2double(get(hObject,'String')) returns contents of edit12
as a double


% --- Executes during object creation, after setting all properties.
function edit12_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit12 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit13_Callback(hObject, eventdata, handles)
% hObject    handle to edit13 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit13 as text
%        str2double(get(hObject,'String')) returns contents of edit13
as a double


% --- Executes during object creation, after setting all properties.
function edit13_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit13 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
```

```
    set(hObject,'BackgroundColor','white');
end



function edit14_Callback(hObject, eventdata, handles)
% hObject    handle to edit14 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit14 as text
%        str2double(get(hObject,'String')) returns contents of edit14
as a double


% --- Executes during object creation, after setting all properties.
function edit14_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit14 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function edit15_Callback(hObject, eventdata, handles)
% hObject    handle to edit15 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit15 as text
%        str2double(get(hObject,'String')) returns contents of edit15
as a double


% --- Executes during object creation, after setting all properties.
function edit15_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit15 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes during object creation, after setting all properties.
function figure1_CreateFcn(hObject, eventdata, handles)
```

```
% hObject    handle to figure1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called


% --- Executes during object creation, after setting all properties.
function axes1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to axes1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: place code in OpeningFcn to populate axes1


% --- Executes on mouse press over axes background.
function axes1_ButtonDownFcn(hObject, eventdata, handles)
% hObject    handle to axes1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)


% --- Executes during object deletion, before destroying properties.
function axes1_DeleteFcn(hObject, eventdata, handles)
% hObject    handle to axes1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

Appendix B

Testing workpiece design for energy consumption measurement on the 3 axis milling machine



Appendix C

Experimental setup and procedures

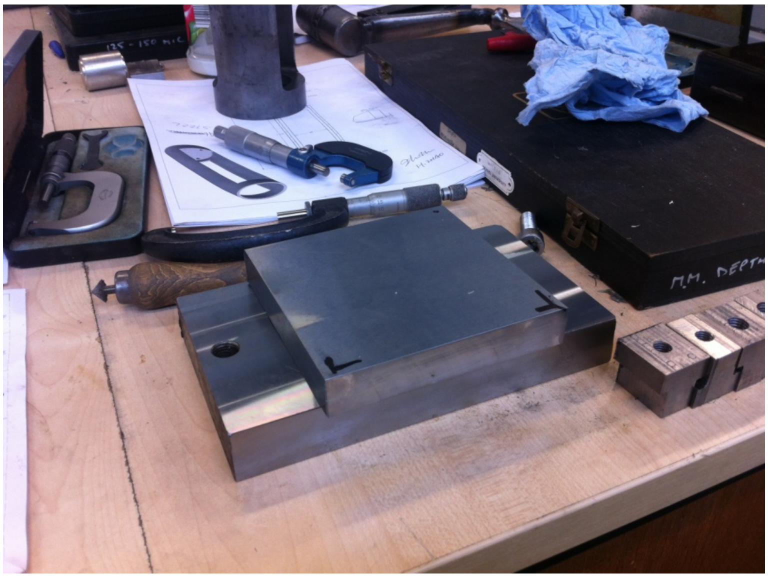


Fig. C.1 Fixture design

Fig. C.2 Clamping the test piece into the machine

Fig. C.3 Power logger connections

Fig. C.4 logging during the machining

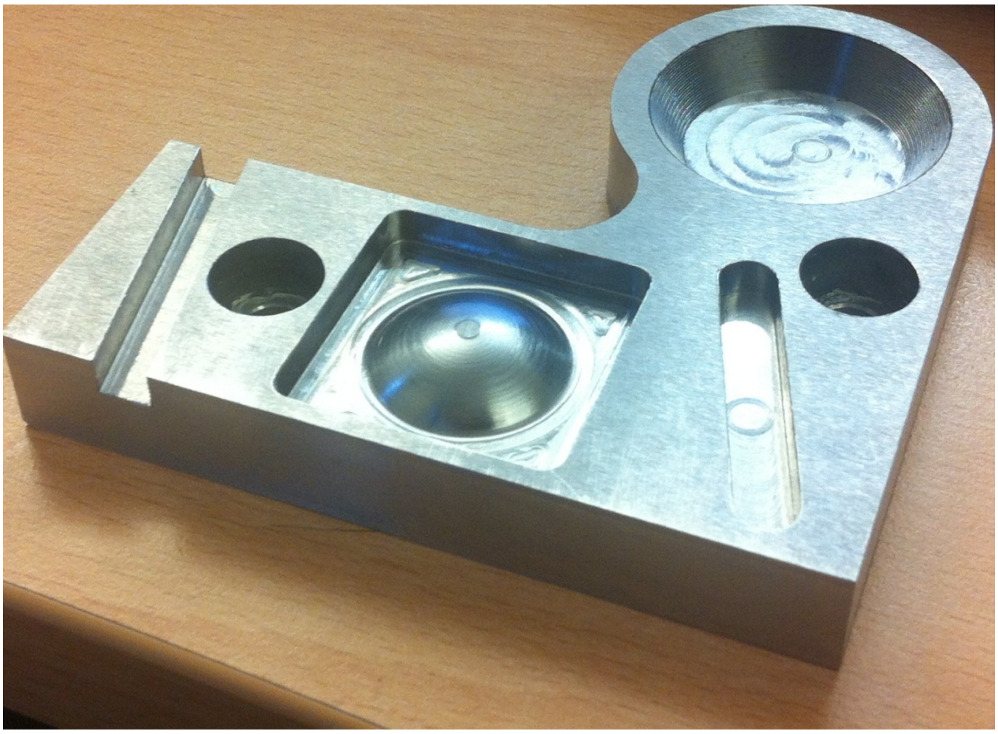


Fig. C.5 Machine test workpiece

Appendix D

Power measurement results

Table D.1 Warm up time energy consumption

Time(sec)	Energy(Kwh)	Energy(Wh)
1	0.00001	0.008785
2	0.00001	0.013293
3	0.00001	0.01262
4	0.00001	0.01196
5	0.00001	0.010766
6	0.00001	0.006725
7	0.00001	0.006725
8	0.00001	0.006723
9	0.00001	0.006725
10	0.00001	0.006727
11	0.00001	0.006725
12	0.00001	0.006726
13	0.00001	0.006724
14	0.00001	0.00672
15	0.00001	0.006722
16	0.00001	0.006724
17	0.00001	0.006725
18	0.00001	0.006726
19	0.00001	0.006724
20	0.00001	0.006723
21	0.00001	0.006723
22	0.00001	0.006724
23	0.00001	0.006724
24	0.00001	0.006726
25	0.00001	0.006725
26	0.00001	0.006724
27	0.00001	0.006726
28	0.00001	0.006727
29	0.00001	0.006691
30	0.00001	0.006725
31	0.00001	0.006724
32	0.00001	0.006724
33	0.00001	0.006724
34	0.00001	0.006726
35	0.00001	0.010086
36	0.00001	0.010088
37	0.00001	0.010086
38	0.00001	0.008073

39	0.00001	0.008073
40	0.00003	0.025407
41	0.00002	0.023661
42	0.00003	0.027327
43	0.00003	0.027314
44	0.00003	0.028271
45	0.00003	0.028263
46	0.00004	0.041063
47	0.00005	0.046281
48	0.00003	0.025128
49	0.00003	0.027032
50	0.00003	0.027676
51	0.00003	0.028562
52	0.00003	0.028716
53	0.00003	0.027676
54	0.00003	0.027169
55	0.00003	0.027071
56	0.00003	0.026807
57	0.00003	0.027059
58	0.00003	0.026807
59	0.00003	0.032083
60	0.00003	0.034572
61	0.00003	0.027953
62	0.00003	0.026797
63	0.00003	0.027277
64	0.00003	0.026467
65	0.00003	0.027069
66	0.00003	0.030036
67	0.00003	0.030036
68	0.00003	0.027172
69	0.00003	0.027069
70	0.00003	0.027572
71	0.00003	0.027673
72	0.00003	0.027673
73	0.00003	0.02676
74	0.00003	0.026275
75	0.00003	0.025602

Table D.2 Rapid movement of axis energy consumption

Time	Energy(kWh)	Energy(Wh)
0.5	0.00003	0.02904171
1	0.00003	0.02890416
1.5	0.00003	0.02889871
2	0.00003	0.02889599
2.5	0.00003	0.02856575
3	0.00003	0.02839795
3.5	0.00003	0.0284712
4	0.00003	0.02889054
4.5	0.00003	0.02888509
5	0.00003	0.02851863
5.5	0.00003	0.02856306
6	0.00003	0.02819423
6.5	0.00003	0.02824349
7	0.00003	0.03232951
7.5	0.00006	0.05817212
8	0.00006	0.05733502
8.5	0.00005	0.04687324
9	0.00013	0.12648216
9.5	0.00036	0.3639593
10	0.00006	0.05839684
10.5	0.00006	0.05847876
11	0.00006	0.06469196
11.5	0.00008	0.07545973
12	0.00008	0.07572094
12.5	0.00008	0.07973374
13	0.00008	0.07883196
13.5	0.00008	0.07882453
14	0.00008	0.07740777
14.5	0.00007	0.07263797
15	0.00007	0.0660794
15.5	0.00007	0.06546655
16	0.00007	0.0653548
16.5	0.00007	0.06567247
17	0.00006	0.06462791
17.5	0.00007	0.06598556
18	0.00006	0.06441671
18.5	0.00008	0.08044549
19	0.00009	0.0917143
19.5	0.00009	0.09139894
20	0.00009	0.09350876
20.5	0.00009	0.09210612
21	0.00010	0.09571331

21.5	0.00009	0.09192559
22	0.00009	0.09126087
22.5	0.00009	0.08534185
23	0.00007	0.07483718
23.5	0.00008	0.07534603
24	0.00008	0.07531392
24.5	0.00008	0.07510238
25	0.00007	0.0749617
25.5	0.00007	0.06794861
26	0.00007	0.06551437
26.5	0.00007	0.06555651
27	0.00007	0.0663461
27.5	0.00007	0.06582753
28	0.00007	0.06671741
28.5	0.00007	0.06690105
29	0.00007	0.0663461
29.5	0.00007	0.06597606
30	0.00007	0.07334566
30.5	0.00008	0.07533182
31	0.00007	0.07480892
31.5	0.00008	0.07541703
32	0.00008	0.07520648
32.5	0.00008	0.07528551
33	0.00008	0.07604214
33.5	0.00007	0.06962466
34	0.00007	0.07318298
34.5	0.00007	0.07255166
35	0.00007	0.07303983
35.5	0.00007	0.07265258
36	0.00007	0.0688374
36.5	0.00009	0.09139296
37	0.00010	0.09509635
37.5	0.00010	0.09748171
38	0.00010	0.09504723
38.5	0.00009	0.08748909
39	0.00007	0.07261829
39.5	0.00007	0.07375484
40	0.00007	0.07301915
40.5	0.00007	0.07372699
41	0.00007	0.07376094
41.5	0.00005	0.05104947
42	0.00004	0.03571824
42.5	0.00003	0.02826547

Table D.3 Actual cutting energy consumption

Time(min)	Energy(Wh)
30	1.122554
60	1.451212753
90	1.446631429
120	1.448116269
150	1.462943498
170	1.443895527
172	0.138566
182	0.139113
192	0.142531
195	0.142968
205	0.140146
215	0.137002
220	0.138749
230	0.138368
237	0.144887
240	0.131812
244	0.131002

Appendix E

CAD drawings used for the energy testing proposal

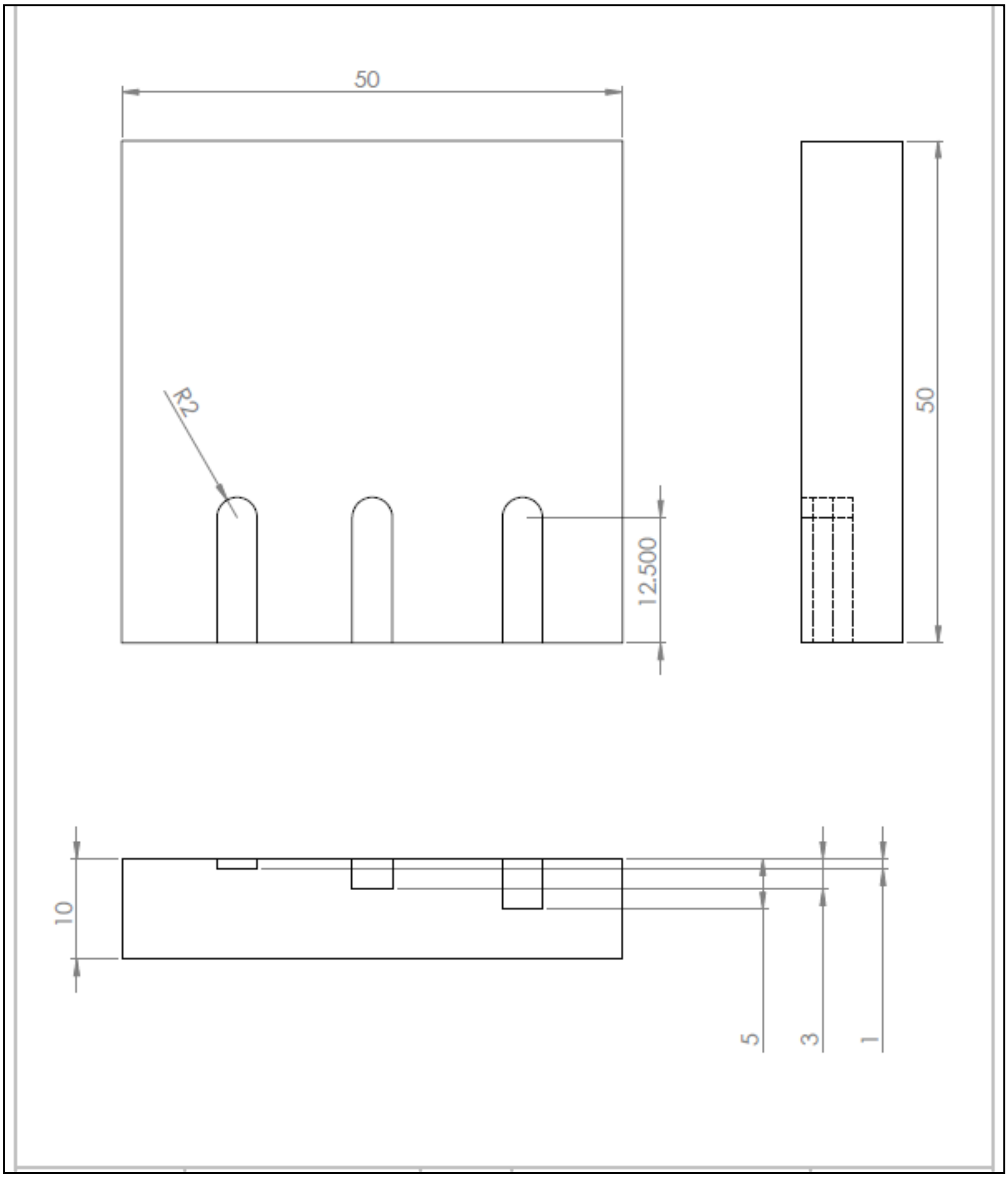


Fig E.1 Depth of cut experiment

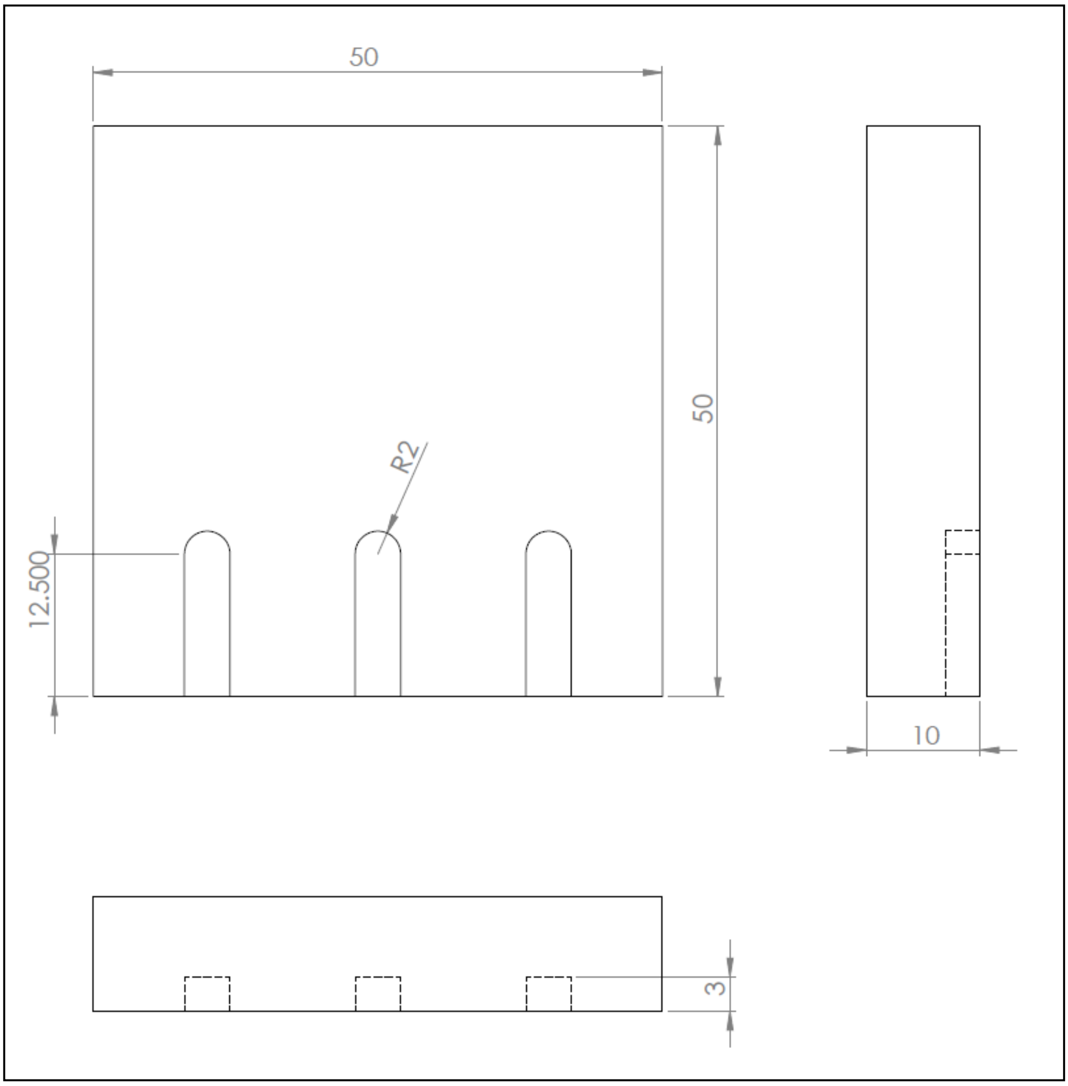


Fig. E.2 Cutting speed experiment

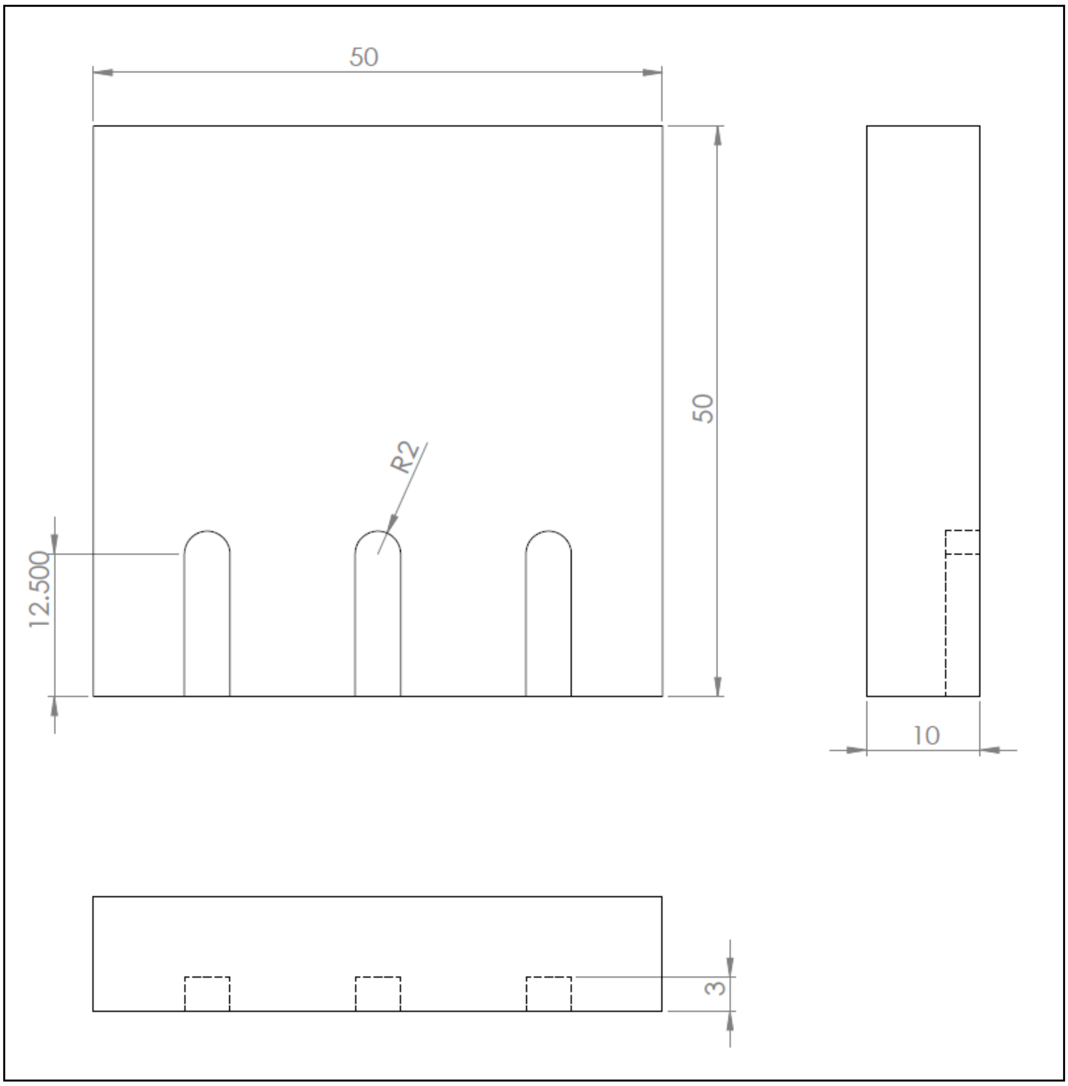


Fig. E.3 Feed rate experiment

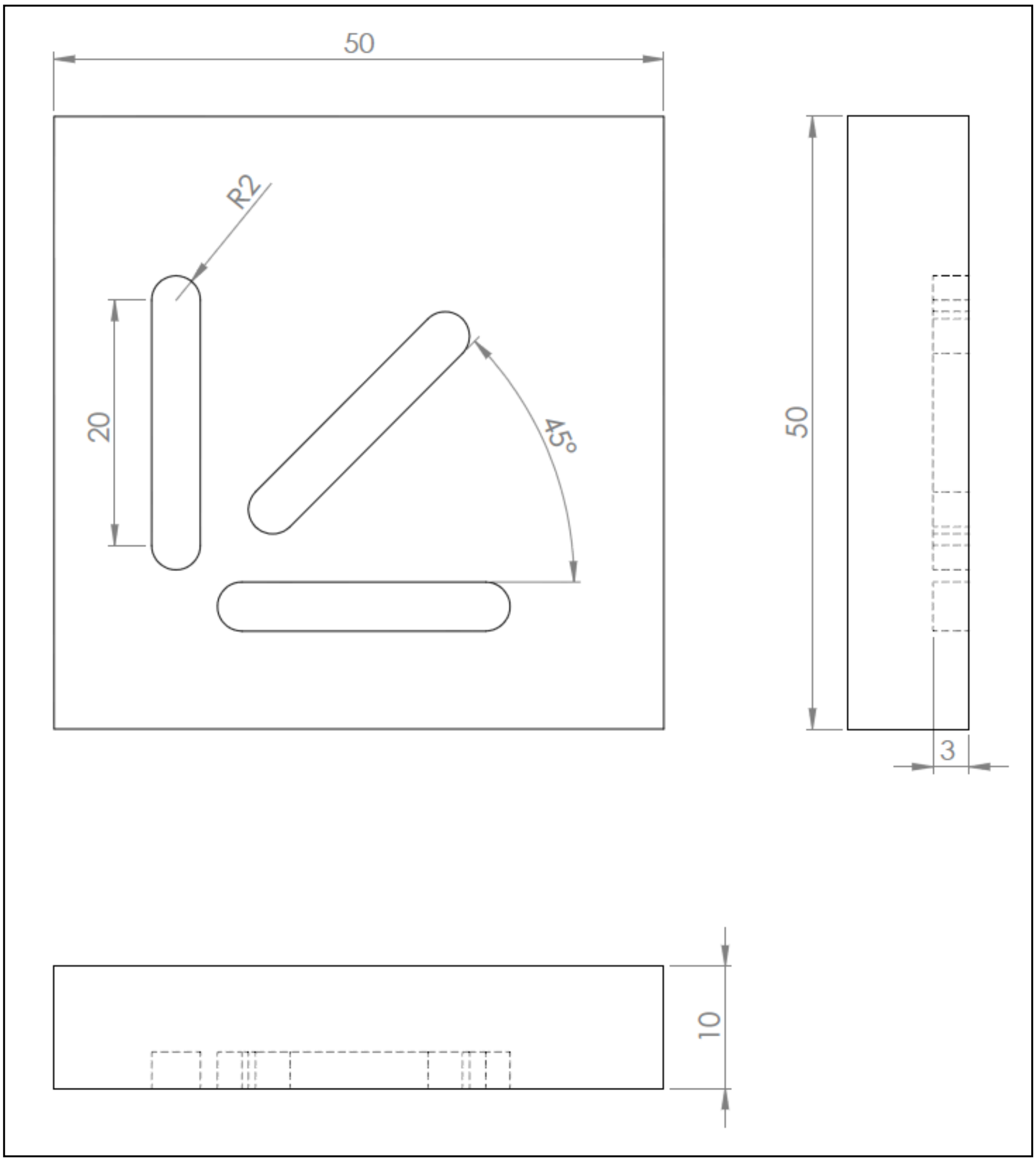


Fig. E.4 Spindle axis experiment

Appendix F

Two research papers published from this research

Proceedings of the 10th International Conference on Manufacturing Research ICMR 2012

DESIGN OF A TESTING WORKPIECE FOR ENERGY EFFICIENCY ASSESSMENT OF CNC MILLING MACHINES

Behnood Afsharizand
School of Engineering and Design
Brunel University
Kingston Lane London UB8 3PH, UK
Behnood.Afsharizand@brunel.ac.uk

Kai Cheng
School of Engineering and Design
Brunel University
Kingston Lane, London UB8 3PH, UK
Kai.Cheng@brunel.ac.uk

ABSTRACT

Development of ISO standards for assessing the energy efficiency of machine tools shows significant efforts for minimizing the environmental impact of machine tools and the associated operations. For proper and accurate assessment of machine tools' performance on energy consumption, resource utilization, waste in operations and the consequent carbon generation (ERWC), a well designed test workpiece is essential and much needed so as to test and assess the machine tool in a calibrated comparable manner. The test workpiece should be utilized as an index to provide comparable and quantitative results. The designed workpiece as an artifact has been machined and trialed out on a 3-axis CNC milling machine to test the appropriateness of the artifact and thus assess the energy consumption of the machine in a quantitative and comprehensive manner.

Keywords: Test workpiece, Artifact design, Energy efficiency assessment, CNC milling machines

1 INTRODUCTION

Energy consumption of machine tools in operations has been discussed extensively from both economic and environmental aspects of sustainable manufacturing. Since machine tools have substantial contribution to energy consumption in manufacturing processes, several standards are being developed for assessing the energy consumption of machine tools so as to improve in environmental performance of the machines and associated operations. For instance, Japanese standards coded *JIS TS B 0024-1:2010* is published by the Japanese Standards Association and presented a standard procedure for measuring the energy consumption of CNC machines (JSA 2010). The designed test workpiece is evaluated within the standard cycle of 4 hours to achieve empirically significant data. A 3-axis milling machine is selected for energy analysis since milling operations are more energy sensitive. The machine drives are evaluated by moving the spindle along a cubic motion pattern. The proposed test workpiece has 2 main features (i.e. holes and grooves), and is incorporated with face milling, end milling and drilling operations on this 3-axis milling machine. In the mean time, the Fraunhofer institute has published several documents focusing on industrial standards policy and impact analysis of machine tools and related operations (Fraunhofer 2012). They developed standard definitions and procedures for reducing the energy consumption and carbon emissions through test workpieces designed by *NC Gesselschaft e.V.* A test workpiece has been designed for 5-axis milling operations with 9 different features machined with face milling strategy. Behrendt *et. al* (2012) designed a test workpiece based on the *JIS TS B 0024-1:2010*, which consists of 17 different features and is machined with face milling, grooving , pocketing and drilling operations. The designed workpiece can be fitted to any size of machine tools by scaling the dimensions of the workpiece matching the capabilities of the machine assessed.

In this paper, the design of a 'standard' test workpiece is presented by taking account of the complexity of machine tools operations. The design attempts to address multiple factors and coupling effects involved in the machine system, the complexity and diversity of associated machining operations. The proposed design approach and testing protocols aim to standardize the energy consumption assessment of machine tools, which are carried out in a holistic, comprehensive and quantitative assessment manner.

2 DESIGN OF THE TESTING WORKPIECE

The CAD model has been developed for designing the artifact followed by simulation with Powermill to select the best cutting strategies and cutting tools. The standard test piece design parameters which correlate with the energy consumption of the machine tools were considered as follow:

2.1 Machine Tool Drives(X,Y and Z axis)

The motion of the X, Y and Z axis should be integrated as to reflect the maximum energy usage of the machine tool which is under the survey. Also, the drives movement during the warm up period and following the tool path were studied as well as the time when tool cut the surface of the workpiece .

2.2 Machining Strategies

The methods of machining the workpiece has been well evaluated. Roughing and profiling have more contribution to the energy consumption rather than other machining methods as they have longer machining time and larger material removal rate. The machining strategies has been integrated so that the all possible machining methods investigated on the designed test workpiece as it shown in Figure 1.

2.3 Dimensions

Scaling the dimensions of the workpiece should be matched to the capabilities of the machine under study. Three main groups of machine tool sizes are subsequently classified: small (working area<0.1 m^2), medium (0.1 m^2<working area<1 m^2), and large (working area>1 m^2). Selection of the cutting tool is also linked to the dimension setting (some cutting tools may cause less energy consumption if there is no need for step by step reworking on the feature). Bridgeport VMC 500X milling machine has been selected for the experiment.

2.4 Workpiece Material

The material used in the standard test piece should highlight the energy usage side of the machining operations. A plastic work piece for example is expected to produce a smaller load on the spindle motor than a Aluminum work piece and therefore consumes a lower cutting power. Even though the cutting speed of Aluminum is the highest between all metals, it does not necessarily deliver the highest amount of energy consumption. Neglecting the machinability of the material, Steel has been selected as the workpiece material.

2.5 Cutting Tool

Coated tools generally produces lower friction at the tool chip interface which leads to lower cutting energy, contact temperature and tool wear.(Grzesik 2003) Thus, we used coated tools for the machining operations. 6 mm and 5 mm end mill tools have been used for surfacing and 3 mm ball nosed tool has been used for shaping the dome.

2.6 Other Features

There are also some other factors for designing the test piece which has been considered such as: easy and fast to manufacture and measure, give comparable and quantitative results, producible in different types of 3 axis milling machines.

The procedure of developing test workpiece correlated with integrating the above features has shown in Figure 1.

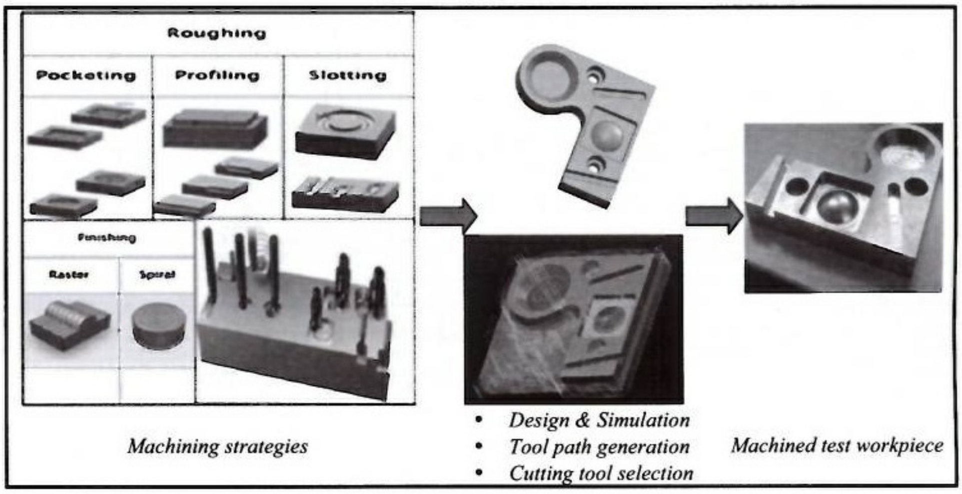


Figure 1: The procedures of designing test workpiece for energy assessment of CNC machine.

3 TESTING PROTOCLS AND AN APPLICATION CASE STUDY

According to the cutting conditions shown in Table 1, The machining procedures are as follows:

- Profiling in X and Y should be done (roughing and finishing)
- Pocketing with 123° angle (roughing and finishing)
- Pocketing with dome (roughing and finishing)
- End milling to make open slot
- Slot drilling for make close slot

The test workpiece shown in Figure 1 has been machined with a 3-axis Bridgeport machine, and the cutting condition was assigned by the values suggested by Sandvik tools handbook. Table 1 summarizes the cutting parameters used for machining the test piece.

Table 1: Cutting parameters for machining the designed test workpiece.

Cutting conditions	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5
Feed rate(mm/min)	400	400	500	400	400
Cutting speed(rpm)	4000	4000	5000	4000	4000

4 RESULTS ANALYSIS AND DISCUSSIONS

For measuring the energy consumption of the 3 axis Bridgeport machine, the power logger has been clamped to the 3 phases motor. Generally, CNC machines consume energy in three following phases: (Avram and Xirouchakis 2011)

4.1 Warm up Time

In this phase the energy which used by the auxiliary devices such as lighting, coolant pump, chip conveyer, mist collector and numerical control unit has been measured in a specific cycle time (75 sec) as it shown in Figure 2.

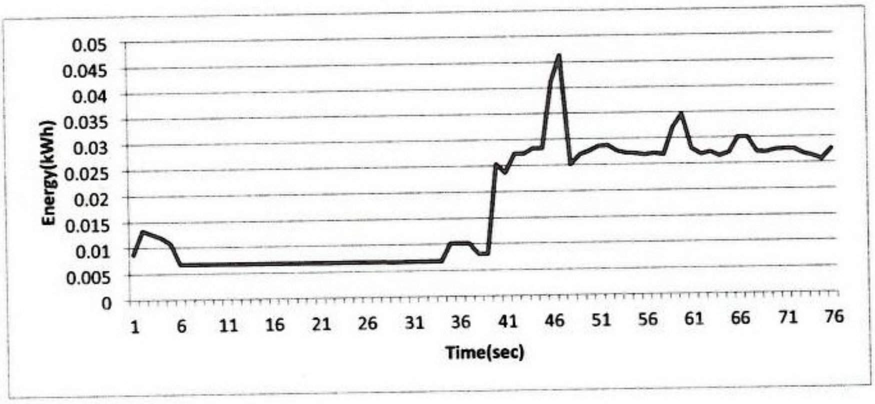


Figure 2: Energy consumption during CNC machine warm up.

Where the total energy used for warming up the CNC machine is equal to 1.35 kWh.

4.2 Rapid Movements of Axis

For measuring the power consumption of the spindle axis units, the cubic movements of the mechanic arms have been considered. The highlighted lines in Figure 3 show the routes of the experiment (a-h-f-d-a-g-b-c-d-a), and Figure 4 shows the energy consumption of the air cutting test.

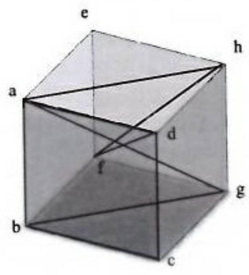


Figure 3: Spindle movement for measuring power in air cutting.

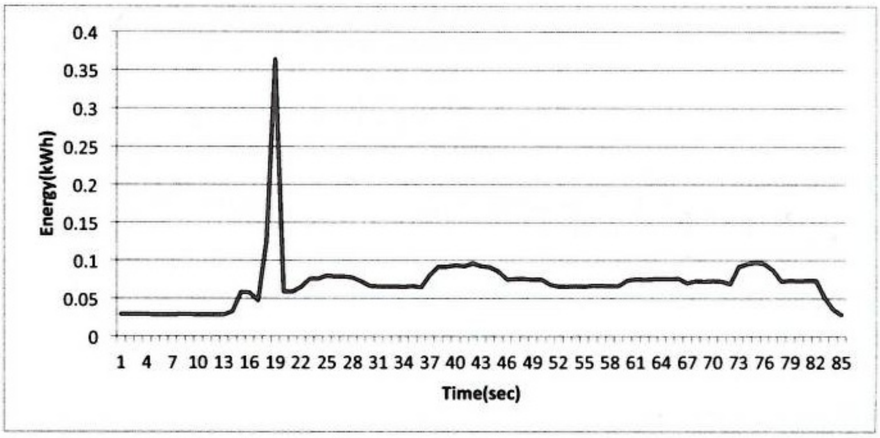


Figure 4: Energy consumption during air cutting of the CNC machine.

Where the energy consumption for air cutting is equal to 5.92 kWh.

4.3 Actual Cutting

The specific artifacts have been designed for measuring the machining power of the machine tools. The design of the test workpiece features derived from the test piece suggested by JSA and TU Braunschweig (JSA, 2010; Behrendt *et al.*, 2012). The cutting parameters setup was based on Table 1 data. The energy consumed during the machining has been plotted in Figure 5.

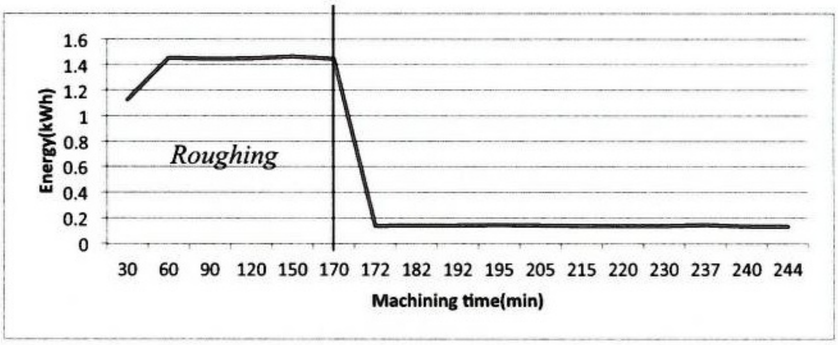


Figure 5: Average energy usage of CNC milling machine.

The average energy used for the actual cutting operations is 10 kWh.

5 CONCLUSION

Improvement on the energy consumption during machining needs quantitative and accurate testing procedure with the well designed artefact. The test workpiece designed with specific features correlated with the energy consumption in the 3 axis milling machine so as to reflects the maximum energy of the machine tool under study. The electricity consumption has been measured in 3 steps after turning on the CNC machine in order to show the exact amount of electricity usage in each step. Roughing the steel out of the block consumed the most energy in comparison with the other machining strategies. So, The energy usage effected by the cutting time as its presented. The results show that further improvements can be done in the energy consumption of the machining operations as follow:

- Reschedule the machining of the testing features, so that the spindle and axes movement time reduces during one cycle of machining.
- Optimization of the cutting parameters for delivering more energy efficient product.

ACKNOWLEDGMENTS

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An investigation on modeling and optimization of energy flow in automotive paint-shop operations and sustainable manufacturing

Behnood Afsharizand and Kai Cheng
Advanced Manufacturing & Enterprise Engineering (AMEE) Department
School of Engineering and Design, Brunel University
Uxbridge, West London UB8 3PH, UK
Emails: im09bba@brunel.ac.uk; kai.cheng@brunel.ac.uk

Abstract

Automotive paint-shop and its operations are significant value added compared with the other sections in the automotive assembly plant. Up to 60% of the energy needed by automobile assembly plants is consumed by the paint shop, and this causes both economic and environmental impacts.

The investigation presented in this paper is focused on developing the modeling and optimization approach applied to quantitative analysis of energy flow in automotive paint shop operations. The model is created based on computing the energy consumption of painting facilities in the automobile paint-shop. The model and simulation are trying to virtually agree with the facility layout in a typical contempory automotive paint shop. Several application scenarios have been investigated as case studies such as the process automation, facility layout optimization and equipment refurbishment, etc. The results show that there is significant potential in energy saving and better resource utilization. Arena 12 software is used to simulate the model and analyze the results of application case studies above. The paper concludes with further discussions on the potential and application of the approach for energy and resource efficient and effective sustainable manufacturing in automotive industry.

1. Introduction

Painting an automobile adds considerable value because many consumers rank paint color and quality as one of the most important purchase decision criteria. On the other hand, automobile painting consumes approximately 60% of the energy required for an automobile assembly plant (Kolta, 1992). There are two major issues for high energy consumption in an automotive paint shop, i.e. the high need of ventilation in primer and top coat, and the long process time consuming more energy than usual.

For major automobile manufacturers, the energy consumed during automobile painting is in the range of 10% to 20% of total corporate energy use, according to Kolta's study. Decreasing the amount of energy consumed can reduce the operation cost of the painting process and also make progress toward achieving environmental goals (for example, energy and carbon footprint reductions from automobile manufacturing). (Roelant, Kemppainen and Shonnard , 2004). Three types of paint used in automotive manufacturing are water-based, solvent-based and powder. Powder is the most environmental friendly since it does not have any carrier in it but, solvent-based paints produce VOCs (Volatile organic compounds) which are too harmful for the environment. Regarding the materials used in the automotive paint shop, we should expect some changes in the energy consumed by the operations.

In order to reduce the amount of carbon emissions we should also optimize the facility layout of the paint shop. According to a survey by Howard (2000), 40% of all cars in the production are held in paint shop and a further 22% held in the painted body store. The high amount of cars which come through the painting operations will cause high rate of energy utilization and high amount of emissions. Thus, we have investigated the optimum layout of the paint shop floor which included the ideal rate of automation and the relocation of the equipments and facilities. Because of complexity of the manufacturing systems, usually analytical methods are not enough. Although some analytical methods have been developed to analyze energy utilization, most of them do not address the unreliable nature of a production system.

Simulation can emulate the real and complicated processes with the good rate of individualization, and link the simulation models to different simulation software. (Venkateswaran et al., 2001; McLean and Riddick, 2000; Gan et al., 2000; Taylor et al., 2001). According to Shah (2000), Modeling reduces the cost and time that would be wasted due to wrong execution of the process. Models also reduce the complexity and help in communication with better understanding of processes. IDEF (Integrated Definition) diagrams have been used to structure the paint process model and Arena 12 software package used to implement the model which has been built with IDEF.

In this paper an innovative method to measure energy with those changes is presented, and an optimum solution is proposed towards sustainability. We have used the modeling and simulation methods to analyze the processes. Using simulation results, we have planned automotive paint shop so as to reduce the energy utilization. Arena software has been developed for simulating the real paint shop operations against the requirements from the industrial partner.

2. Typical automotive paint shop operations and energy flow

Normally, automotive painting consists of the following main sections:

- Precleaning
- Pretreatment
- Electro coating
- Sealer application
- Primer coat
- Top coat
- Wax application

Figure 1 shows the painting process before the final assembly and the conventional layout usage in the automotive paint shop. The old paint shop layout has less flexibility to the new model cars, and it is environmentally harmful due to the VOCs (Volatile organic compounds) which it releases to the air. Turning the old automotive layout to the new one can make the opportunity to increase the quality and cut costs by better use of space and facilities. Powder paints are more interested in new paint shop layout since it has fewer emissions in comparison with solvent and water based paints. The energy used during these processes is the combination of electricity and gas. Ovens are the most energy consuming part of the automotive painting process. Figure 2 shows the energy flow in the automotive paint process and highlights the significant parts in the process.

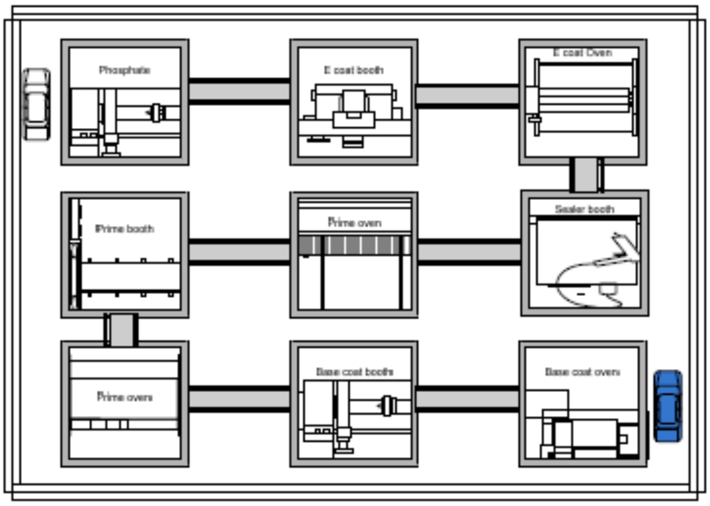

Figure 1. Typical automotive paint shop lay out

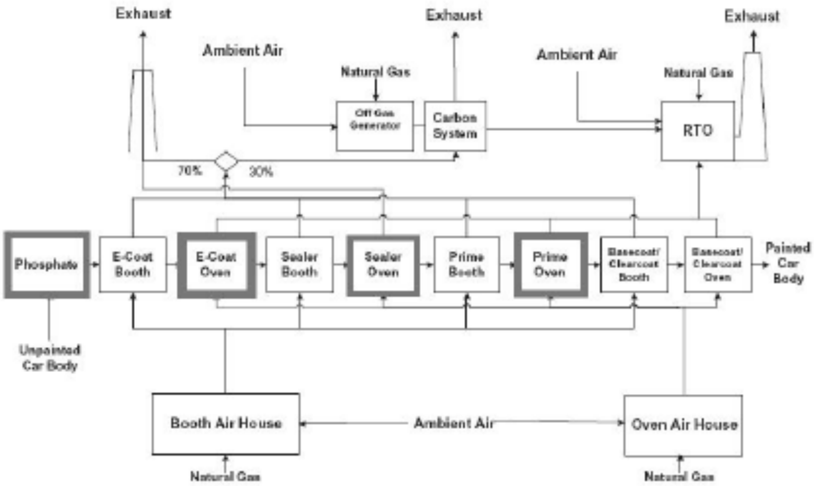

Figure 2. Process Flow in Typical Paint Shops (Roelant et al, 2004)

There is not typical facility layout for automotive paint floor because of diversity in paint methods (powder coating, solvent based, water based), but we tried to show the inputs and outputs in solvent-based paint shop in Figure 2 according to Roelant et al (2004) literature.

As reported by Ryan (2002) on Ford Motor Company, Solvent based paints release significant amount of VOCs in the air, which consume too much energy needed for retreat them. Based on the literature by Roelant et al (2004) we have classified the type of energy which uses in each step in Table 1.

Table 1. Energy sources in automotive paint shop

Operation	Energy Source
Phosphate	Electric
	Natural Gas
Airflow booths	Electric
Airflow ovens	Electric
Heat booth air	Natural Gas
E-coat booth	Electric
E-coat oven	Natural Gas
Prime oven	Natural Gas
Sealer oven	Natural Gas
Basecoat oven	Natural Gas
RTO	Natural Gas
	Electric
Carbon wheel	Natural Gas
	Electric

3. Energy flow modeling, simulation and operations

According to a literature by Ryan and Heavey (2007) prior to simulation phase we have to look at some tasks such as problem definition, project planning, system definition, conceptual model formulation, preliminary experiment design and input data preparation. According to Wang and Brooks (2006) conceptual modeling section of every simulation project adds considerable value to the results. Balci(1986) states that formulating the conceptual model is often time consuming because of the information needed for processes is rarely can be find easily. In the following sections we have modeled the energy flow of the automotive paint shop, and then we have simulated the model by Arena software.

3.1. Modeling

To build a conceptual model, we have used from IDEF (Integrated Definition) diagrams which show the inputs, and outputs of each section. Basically, IDEF diagrams are simple and easy to use in terms of comprehending the whole system with a glance.

Generally, IDEF diagrams build with boxes and arrows. Boxes represent actions and arrows represent interfaces between those actions. According to the several literatures (Hill 1995, Mayer 1993, US Air Force 1981) it is easy to understand and document the IDEF diagrams. IDEF diagrams also can apply to any organization without looking to their size and complexity (Godwin et al, 1989).

According to Harrel and Tumay (1995), similarity between IDEF diagrams and manufacturing systems like entities (inputs and outputs), activities, resources and controls, make it even easier for modeling purposes. With the help of IDEF0 diagrams which focus on functional modeling and, IDEF3 diagrams which present the process description we can generate the model to discrete event simulation (Mayer et al. 1998).
The purpose of this study is to evaluate the energy consumption by simulation study. Therefore, we can use from the model which has been built by IDEF diagrams to simulate the real operation. Figure 5 shows the IDEF0 diagram for the two levels of automotive paint shop which prepared by AI0 WIN software.
To have a closer look at automotive painting process we may have interest to draw the next level of IDEF0.

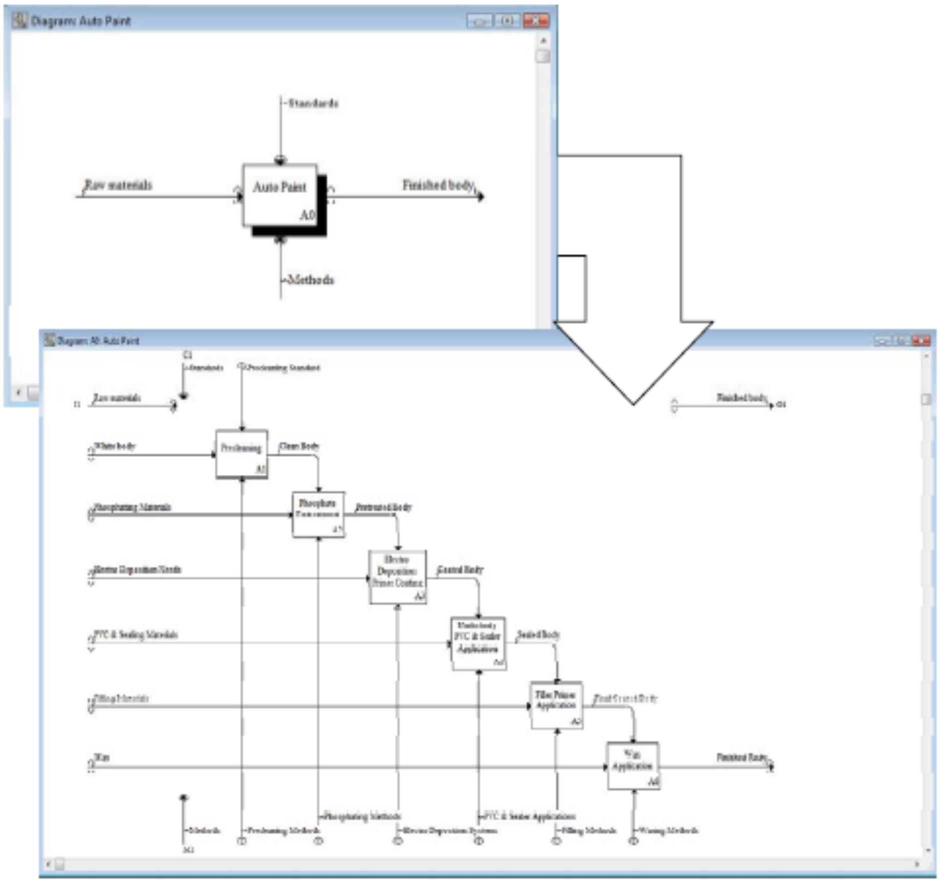

Figure 5. IDEF0 for the first and second level of automotive paint shop

Although IDEF0 diagrams provide complete description about "what" the system does, but we still need more information about the logic or the timing associated with the activities. IDEF3 is another modeling diagram which represents further information about the system behavior.

Basically, IDEF diagrams present an understandably scheme of the system, but to take the dynamic characteristics of systems into considerations we have to use from computer aided simulation.

3.2. Simulation

Simulation studies can reduce the costs of experiencing one operation in real, and in our case simulation will provide us with some information which is not measurable in reality. According to Choi et al (2002) simulation modeling is useful management tool which visualize the automotive manufacturing plant for further analysis.

Altinkilinc (2004) investigated the application of simulation in layout planning. Arena software has been used to simulate the automotive paint process. We have used from car bodies as our entities, and energy as our resources.

In order to clarify which energy uses in each station we used from Table 1.
Basically, to simulate the energy consumption of automotive paint shop floor we used from these steps: (Maria , 1997)

- Define the problem.
- Collect system data by available literature.
- Develop a model by IDEF diagrams.
- Validate the model.
- Establish experimental conditions for runs.
- Perform simulation runs.
- Interpret and present results.
- Recommend further course of action.

There are particular assumptions for simulating automotive paint shop process which presented in Table 2.

Table 2. Time estimation for each section (days time unit)

Station	Time required
Phosphate booth	TRIA(0.1,0.3,0.5)
Booth airflow	TRIA(0.1,0.2,0.3)
Oven airflow	TRIA(0.1,0.15,0.2)
Heating the booth air	TRIA(0.1,0.2,0.3)
E-coat booth	TRIA(0.1,0.3,0.5)
Sealer oven	TRIA(0.1,0.2,0.3)
Prime oven	TRIA(0.1,0.15,0.2)
Base coat	TRIA(0.1,0.2,0.3)
Carbon wheel	TRIA(0.1,0.3,0.5)
RTO	TRIA(0.1,0.3,0.5)

Car body's arrivals also follow exponential distribution with the mean of 2 hours.
We have run this model for 30 days and 7 hours per day with 2 hours warm up time and 1 replication. We assumed that each station consumes the same amount of energy in average; however, there is variation in energy consumption of booths and ovens. Capacity of each resource is one; in essence, just one car body can be painted during the operations. We have used from one create module which produces car body entities.

To simulate the transportation system of automotive paint shop, we have used from Leave and Enter modules with 10 minutes handling time between the stations, and 10 minutes set up time for each station. We have assumed that 10 car bodies can use simultaneously from energy in each section. Plots are used to show the current utilization of gas and electricity. Animation has been designed based on the current automotive paint shop layout. Figures below show the block diagram which has been built by arena model with details.

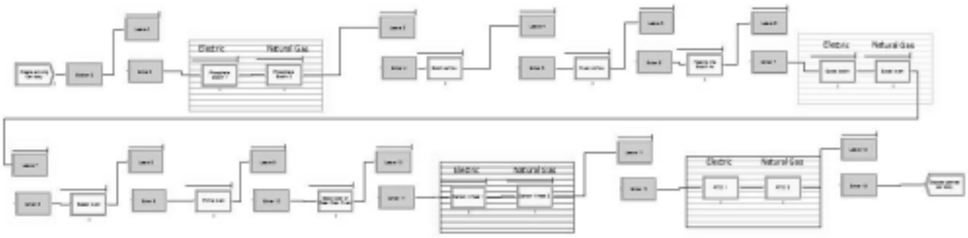

Figure 1. Block diagram created by Arena software

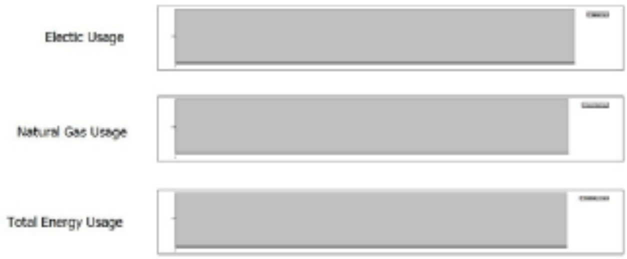

Figure 2. Plots used for showing energy flactuations

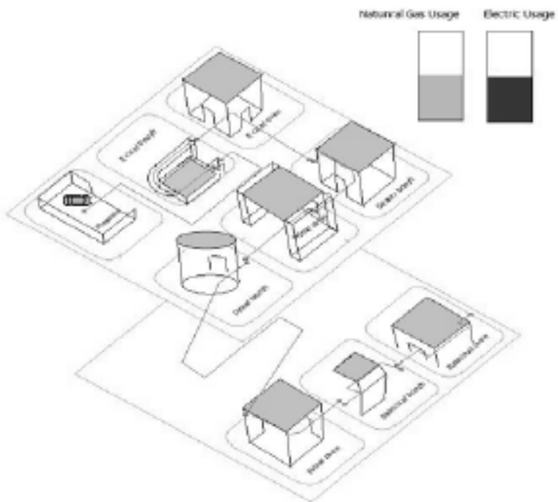

Figure 3. Animation used for better visualization

The results for the simulation above are as follows:

- Electricity usage = 0.1002
- Natural gas usage= 0.1006

As we can see in the result we have too much energy consumption in this sector. In next chapter we will see how to reduce energy consumption with the resolving optimization problems.

4. Optimization

To optimize the automotive paint shop energy model we investigated the results for optimum facility layout, automation and equipment refurbishment.

4.1. Facility Layout planning and simulation

There are several mathematical methods for optimizing the layout, but mathematical methods are time consuming and rarely present the appropriate results. According to Wang et al (2008) integration of visual functions with simulation techniques can be reliable for facility layout planning. After a comparison between heuristic search methods by Lacksonen (2001), Genetic Algorithm performs better than others in terms of finding optimum solution. The primary problem of other methods is the Proliferation of the results. Thus, we have used from GA to find an optimum facility layout for our case.

Genetic algorithms successfully applied in facility layout problems (Tate and Smith, 1995, Cheng and Gen, 1996, Meller and Gau, 1996, Tam, 1992). However, most of them address the material handling costs, rather than performance indices. By integrating GA with simulation study we can cope with the previous issue. (Azadivar and Wang, 2000)
There are several assumptions for resolving facility layout problem with GA:

- The plant floor should be rectangular and the direction of each station should be known.
- Only one car body at a time can be in the process.
- The transporters handle only one car body.
- The sequences of tasks are the same for car bodies.

In order to use from Genetic algorithm in facility layout problem, we have to understand the below points: (Chan and Tansari, 1994)

- String representation
- Fitness function
- Population size and number of generations
- Genetic operators

(1) String representation

We can present our model by changing the layout structure to coding language. For example, the series of 3-2-5-1-9-8-6-4-7 in our case which includes 9 locations.

(2) Fitness function

Fitness function is our objective function for layout problem. To assess the fitness function, we use from fitness value, and a good string can be ranked by the fitness value. The objective function for placing n machines to n locations can be formulated by the below expression:

$$\text{Min} \sum_{i}^{n} \sum_{j}^{n} f_{ij} d_{p(i)p(j)} C_{ij} \quad (i > j)$$

Where

f_{ij} = rate of material flow between i and j.
d_{ij} = rectangular distance between i and j.
C_{ij}= cost of material handling

(3) Population size

Genetic algorithm searches for the optimum result in several generations. The number of strings in each generation is assigned as population size.

(4) Genetic operators

Genetic algorithm consists of three operators which are reproduction, crossover and mutation. Reproduction operator generates new strings randomly. Crossover operator Combines the parent strings and makes a new offspring. Mutation operator reverses the structure of strings.

4.2. Equipment refurbishment

Equipments are important to have a good quality in automotive paint shop. With the new equipments in painting sector we can reduce the costs, use from the space efficiently, reduce the energy consumption, reduce the process time, and reduce the wastes and VOCs.

We have investigated Paint booth in automotive paint shop which has the most utilization in the operations, and it releases high volume of emissions to the environment.

Painting section of automotive industry can be improved significantly by the refurbishment of the paint booth equipments.

(1) Paint booths

Generally, Paint booth is the integration of painting equipments and color system In order to apply the coat to the car body. We can reduce the energy usage and VOC emissions in automotive paint shop by improving the paint booth system. According to Darvin et al (1998), it is not economically preferable to control the emissions which release by the paint booth. However, we can improve our equipments to reduce the amount of emissions. Thus, we have investigated the types of spray guns in this chapter.

(2) Spray Guns

Normally, spray painting in automotive paint shop has to be done manually. The efficiency of spray painting is evaluated by transfer efficiency. Transfer efficiency is the amount of paints which have applied to the layer of car bodies by the spray gun. Basically, Spray guns work based on the atomization which separates liquid by air pressure. We have categorized the spray guns as below:

Conventional spray guns: There are two types of conventional spray guns which are siphon feed and gravity feed. Gravity feed spray guns use less energy since they operate at low pressure. The advantageous of conventional spray guns is good rate of atomization, but they release mist and fog which causes low quality painting.
Transfer efficiency in conventional spray guns is between 20%-40%.

HVLP (High volume low pressure spray guns): This kind of spray guns operates in high volume of paints and low pressure which makes the spray gun moves in more controllable pattern than the conventional spray guns. Therefore, the transfer efficiency of HVLP spray guns is at least 65% (Heitbrink et al, 1996). Many companies use from HVLP spray guns in order to reduce paint consumption, increase the quality. It has also some disadvantageous like high initial cost and poor atomization system.

LVLP (Low volume low pressure) spray guns: These kinds of spray guns are quite similar to the HVLP spray guns. They difference is on atomization system which works with the lower pressure. HVLP spray guns consume lower energy rather than LVLP spray guns.

Powder coating spray guns: We can achieve even to more uniform surface by the power coating spray guns. These kinds of spray guns have more transfer efficiency than others (e.g. up to 98%). Lots of companies prefer to use from power coating spray guns since there is no need for reworking actions. Powder coating spray guns also release the least VOCs in comparison with the other spray guns.

4.3. Automation

Two chief causes can be given for developing automation in the automobile industry. Today car factories are mainly focused on the software development and lean manufacturing. Automation can be widely used in automotive paint operations since it reduces the material consumption, process time and the number of machines. It can also reduce the energy usage and increase the finish quality of the products. We can get advantage from automation in many sections of automotive paint shop in order to increase the safety of the production line. For instance, sanding area is one of the unsatisfactory areas for human working. There are also several other hazards which should be considered such as noxious fumes in the air, risk of flush fires, and noise from the spray gun nozzle. Production line becomes smoother with robots in comparison with conventional paint shop. There are also some other advantages in automating the process such as reduction in booth size, less wastes, fast installation, easy maintenance.
Above all, we should consider that achieving the appropriate rate for automation is important since high rate of automation increases the initial cost.
In this chapter we will mention some technological improvements in automating the process of car painting.

Spray coating: According to Groover (2001), Robots are applied in automotive paint shop to automate the spray coating system. There are several specifications for those robots:

- Capable of moving smoothly to paint the car body uniformly.
- Joint arm robots for better movement.
- Design for the least manual work.
- Compatible with all paint materials, including solvent paints, water-borne paints and powder paints.

Conveyers: Robots are applied in transporting the car bodies. Robots can make it easier to tracking and controlling the car bodies while they are conveyed into the paint booth. Direction of movement can be also adjusted by the multi traveling axes. Conveyer robots should have the following specifications:

- Integrated operating axis.
- Maintain sufficient tension on the cables.

Opening, Holding and Closing: In order to automate the opening, holding and closing doors and hoods, robots are used. So, we can get better performance in painting the internal side of car bodies. In this situation the atomizer change with the gripper tools needed for opening, holding and closing operations. These robots should have the following specifications:

- Design for easy maintenance.
- Easy for cleaning.
- Different arm lengths to be flexible.
- The controllers and drivers should be same for both painting robots and door robots.

5. Case studies

Case 1

Company X has a car assembly plant located in US. It produces more than 1000 cars per year. Plant has 9 locations with 3 rows and 3 columns. We have shown the “from-to” and “handling costs” charts for automotive paint shop plant in the tables below:

Table 3. From to chart (per month)

	1	2	3	4	5	6	7	8	9
1		100	3	0	6	35	190	14	12
2			6	8	109	78	1	1	104
3				0	0	17	100	1	31
4					100	1	247	178	1
5						1	10	1	79
6							0	1	0
7								0	0
8									12
9									

Table 4. Handling cost chart ($ per trip)

	1	2	3	4	5	6	7	8	9
1		1	2	3	3	4	2	6	7
2			12	4	7	5	8	6	5
3				5	9	1	1	1	1
4					1	1	1	4	6
5						1	1	1	1
6							1	4	6
7								7	1
8									1
9									

The company manager decides to improve the efficiency of production line by reducing the energy which uses during the production. The study focuses on the simulation and modeling study of energy consumption and finds a best layout location for the automotive paint shop. Genetic algorithm has been applied to the layout optimization.

We have extracted the best layout answers in terms of the lowest travelling cost (e.g. 4154.4 $):

- 6-1-7-2-5-4-9-3-8
- 7-1-6-4-5-2-8-3-9
- 7-4-8-1-5-3-6-2-9
- 8-4-7-3-5-1-9-2-6
- 9-2-6-3-5-1-8-4-7
- 6-2-9-1-5-3-7-4-8
- 8-3-9-4-5-2-7-1-6
- 9-3-8-2-5-4-6-1-7

In order to check the performance of the above answers, we have used from the model which simulated by Arena. We are interested in finding the best layout plan which reduces the energy consumption during the painting process.

After trying all possible conditions which has produced by genetic algorithm, the outputs can be seen in the table below:

Table 5. Result of energy utilization from simulation

Layout plan	Sequence of stations	Electricity usage	Natural gas usage
A	1-2-3-4-5-6-7-8-9	0.1002	0.1006
B	6-1-7-2-5-4-9-3-8	0.1010	0.0998
C	7-1-6-4-5-2-8-3-9	0.1020	0.1004
D	7-4-8-1-5-3-6-2-9	0.1005	0.1011
E	8-4-7-3-5-1-9-2-6	0.0917	0.0928
F	9-2-6-3-5-1-8-4-7	0.1013	0.1009
G	6-2-9-1-5-3-7-4-8	0.1005	0.1003
H	8-3-9-4-5-2-7-1-6	0.0917	0.0934
I	9-3-8-2-5-4-6-1-7	0.1001	0.1018

As it has shown in the table, we will have the lowest electricity consumption from the "I" layout plan, and we will have the lowest gas utilization from "B" layout plan.

Case 2

Company Y assembly plant is a major car assembly plant in the UK. The company owners have big problem in spending too much money on electricity and gas bills. They tried to find the optimum solution by studying the painting process. They have decided to renew the mission statement of the organization in order to improve the efficiency of the paint shop by refurbishing the equipments and using robots in some of the human work stations. Before applying those changes, they will assess the possible results with the simulation study.
Several solutions have been presented in brainstorming sessions by managers and engineers that we can see at below:

Paint booths improvement: In order to reduce the energy usage and VOC emissions, one manager has proposed to refurbish the paint booth equipments by upgrading old machines to new ones. The process time will be effected, and we can have a higher throughput rate in our assembly line. There are also some other factors which attract the managers to do refurbishment, such as safety issues, quality improvement, customer satisfaction.
After investigating the financial aspect of the proposal, they come up with changing the spray guns. The company used from the conventional spray guns which use too much energy and material. HLVP and powder spray guns are selected to operate instead of the previous spray guns.

Automation: There is overall agreement in automating the paint process since they haven't changed the company procedures from the starting point of corporation. Robots have been used in some situations instead of human workers. Robots use more energy than the labors; however, they will reduce the process time of operations. Robots have better performance in terms of uniformity and quality of the finished layer. In order to reduce the process time, robots are used in spray coating, conveying, opening and closing.

Simulation methods are used to find the best solution for optimizing the energy consumption. Table 6 shows the process times of each section before and after applying the changes.

Table 6. Automotive process times for the new changes (days time unit)

Station	Time required	New process times
Phosphate booth	TRIA(0.1,0.3,0.5)	TRIA(0.1,0.15,0.25)
Booth airflow	TRIA(0.1,0.2,0.3)	EXPO(0.1)
Oven airflow	TRIA(0.1,0.15,0.2)	EXPO(0.1)
Heating the booth air	TRIA(0.1,0.2,0.3)	TRIA(0.1,0.15,0.2)
E-coat booth	TRIA(0.1,0.3,0.5)	TRIA(0.1,0.15,0.25)
Sealer oven	TRIA(0.1,0.2,0.3)	EXPO(0.1)
Prime oven	TRIA(0.1,0.15,0.2)	TRIA(0.1,0.15,0.2)
Base coat	TRIA(0.1,0.2,0.3)	TRIA(0.1,0.2,0.3)
Carbon wheel	TRIA(0.1,0.3,0.5)	TRIA(0.1,0.15,0.25)
RTO	TRIA(0.1,0.3,0.5)	TRIA(0.1,0.15,0.25)

Electricity usage= 0.08928236
Natural Gas usage= 0.08969416

The results show that refurbishing equipments and automating the processes decrease the energy consumed by painting process.
Normally, the simulation study helps the manager of company Y to make the decision easier, and investigate all the possibilities for the special purpose.

6. Conclusion

Energy calculations play important role in Automotive painting since there is significant energy consumption in this sector. By estimating the amount of energy we have used in automotive paint shop, we can make some improvements in this sector. We have used from modeling and simulation to estimate the amount of energy which uses during the painting operations. IDEF diagrams can model the painting system in several sectors for better understanding from the process. As we do the next levels of IDEF diagrams, we can simplify even further for simulation purposes. Arena software has been applied to simulate the energy flow of automotive paint shop. For more visualization, we have animated the process of automotive painting. Usually, optimization takes place after the outputs have been analyzed. We have optimized the painting facility layout using genetic algorithm by reproducing some genes as local optimum answers. Then, we have evaluated the answers by the simulation program in terms of the energy used to choose the best answer as the global optimum. By the integration of modern technology and the painting process we can even save more energy in the operations. Equipment refurbishment has been also examined in providing optimum energy utilization during the painting process. We have looked at the paint booths which consume high amount of energy. Painting system can be improved significantly by automating the tasks. Robots perform the painting job with the greater accuracy than humans and they can maintain a good level of energy during the painting operations. Finally, we have presented two scenarios to explore the application of the mentioned ideas. The objective of both case studies is to minimize the energy consumption of the paint shop. The energy which used during the automotive paint shop has been calculated in both cases. Results from case studies insist on the fact that simulation and modeling can integrate with the painting process to optimize the energy utilization.

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