GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

19.5 A theoretical energy consumption prediction model for prismatic parts using STEP AP224 features

R. Sercan Altıntaş [1], M. Ural Uluer [2], H. Özgür Ünver [1], S. Engin Kılıç [2]

[1] Department of Mechanical Engineering, TOBB University of Economics and Technology, Turkey

[2] Department of Mechanical Engineering, Middle East Technical University, Turkey

Abstract

The rate of global warming increases sharply, thus energy and resource efficiency in manufacturing gain vital importance. In order to increase energy and resource efficiency, first consumed energy amount must be quantified accurately for each manufacturing process. Furthermore, CO_2 is one of the top green house gases that contributes to global warming and its emission can be derived from the quantified energy consumption data. In this study, a prediction model for determining theoretical energy consumption during the manufacturing processes of prismatic parts is presented. The prediction model relies on the STEP Application Protocol 224 features for volumetric information and material properties of prismatic parts.

Keywords:

Process Energy Prediction; Energy Efficient Manufacturing; Carbon Footprint

1 INTRODUCTION

The rise of human population and industrialization have pioneered the rise of energy consumption so that the world's energy demand is expected to be 47% higher in 2035 than current levels [1]. With increasing demand of energy, the concern about energy availability and its environmental impacts are growing. Despite expected increase in the use of renewable sources for electricity generation, most of our electricity is likely to be generated from carbon based energy sources such as coal, natural gas and petroleum over the next years [1]. The U.S., one of the leading countries in energy consumption, gathers 83% of energy from carbon emitted sources and this ratio is expected to be 78% in 2035. Figure 1 illustrates U.S.'s primary energy sources in energy production [2]. Carbon based energy sources accounts more than half of the world's greenhouse gas emissions [3].

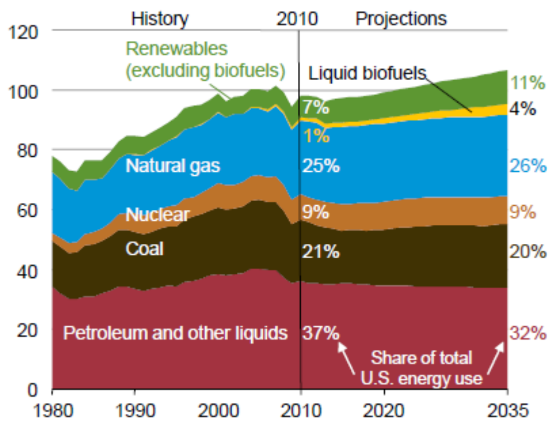

Figure 1: Primary energy sources in the U.S. [2].

In U.S., the most energy consumed end-use sector is industrial sector with 31% of total consumption [4]. Figure 2 depicts the share of industrial sector among the other end use sectors. Moreover, industrial energy consumption is expected to show the second largest increase in total primary energy use by the end of 2035 [4]. Manufacturing activities are also held on 19% of the world's greenhouse gas emissions [5].

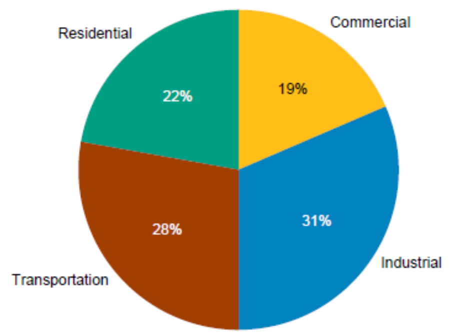

Figure 2: End use sector shares of total energy consumption in U.S. [4].

With the expectation of rise in industrial energy consumption and electiricity costs, energy efficiency gains vital importance. Most of the G-20 countries attempt to build energy efficiency policies such as energy certification schemes, regulatory building codes, tax reductions etc. [6]. In order to use energy more efficiently and reduce carbon emissions, first the energy used for each manufacturing process should be monitored. Then reduction strategies can be developed and energy efficient work shops can be created.

Machining is one of the manufacturing operations that is widely used at industrial sector to produce finished goods. Machining is a material removal process which aims to generate the shape of the workpiece from raw material or to improve the surface quality of the previously formed workpiece by removing redundant material in the form of chips [7]. A machining operation can be a cutting process such as turning, milling, drilling etc. or an abrasive process

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

such as grinding, honing, lapping etc. [8]. Milling is one of the most versatile cutting processes, and it is inevitable for the manufacturing of prismatic parts.

In this study, a theoretical energy consumption prediction model for prismatic parts utilizing STEP AP224 features is proposed. Theoretical energy consumption calculation is based on the tool tip energy consumed to remove the predefined STEP AP224 features. The ultimate aim of this study is to develop a software that predicts theoretical energy consumption and calculates carbon emissions of each STEP feature which is designed and machined afterwards. This information can provide engineers the knowledge of the environmental impacts of the part at design stage. Software developing phase is still an ongoing process and a model for determining auxiliary energy consumption is planned as a future work.

2 FEATURE BASED DESIGN AND STEP

CAD Systems provide engineers a platform to design part models with geometrical and topological data. This low level representation of data is inadequate to denote the part model in downstream applications such as CAM and CNC activities. In order to represent the part model data with a high level of information feature modeling was introduced. Features provide not only geometrical and topological data but they also provide tolerances, material specification and surface finish data. The creation of features are separeted into two categories: Feature Based Design (FBD) and design with feature recognition. FBD is based on creating a part from predefined features stored in a feature library. On the other hand, in design with feature recognition, features are obtained by geometrical data created by CAD software [9,10].

FBD, which is planned to use in this study, keeps the dimension data as variables and defines the geometry of the features in order to instantiate the feature during modelling phase. FBD helps better understanding of the design intent and also makes explicit product data available in a neutral format which can be used directly with downstream applications.

2.1 Basics of STEP

To meet the natural requirements of feature technology, a few attempts were made by national organizations. IGES, VDFAS, SET data formats are among those attempts. They all represent the geometric aspect of the design well. However, they did not succeed in supplying high level of information between CAD and CAM systems. ISO 10303, formally known as STEP(Standard for the Exchange of the Product Model Data), is an international standard that aims to provide a natural mechanism capable of representing product model data throughout the life cycle of a product [11]. STEP, having a mechanism that is capable of describing a product independent from any other system, is a basis for implementing and sharing product databases and archiving [12,13].

STEP is organized as a series of parts, each published individually. These parts fall into one of the following series: application protocols (APs), description methods, integrated resources, application interpreted constructs, abstract test suites, implementation methods and conformance testing. STEP uses a formal specification language, EXPRESS, to define product data for both integrated resources and application protocols. The use of formal language enables accuracy and agreement of representation and aid development of implementations [11].

2.2 Feature Based Design with STEP AP 224

An application protocol (AP) includes the definitions of scope, context, and information requirements of an application. In this study, AP 224 (Mechanical Product Definition for Process Planning Using Machining Features) and its feature library are used. This application protocol specifies an application protocol for the representation of information needed to produce a mechanical part definition for process planning of a single piece or an assembly product for machining operations, and define the integrated resources necessary to meet these requirements [12]. A manufacturing feature defined as a shape that represents volumes to be removed by machining to obtain the final part geometry from the initial stock. Manufacturing features break down into three categories in STEP AP224: transition features, machining features and replicate features. Figure 3 illustrates the manufacturing features by their categories [9].

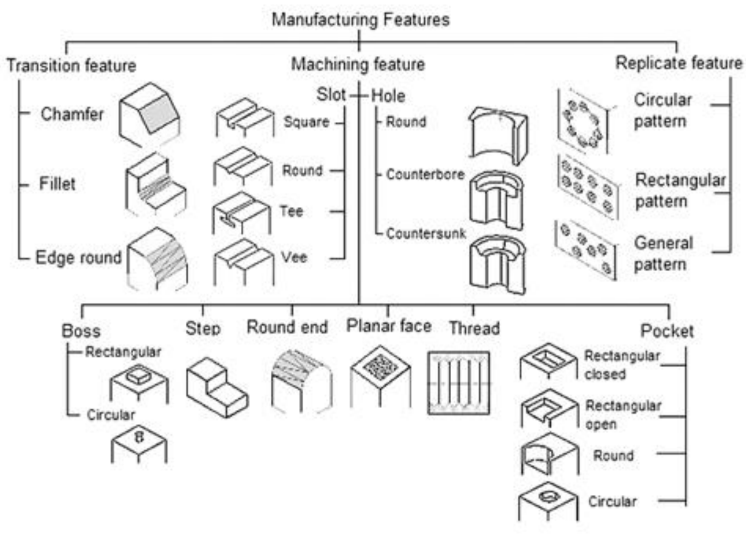

Figure 3: STEP AP 224 Manufacturing Features List [9].

Amaitik and Kılıç [9], represents STEP-FM (STEP-based Feature Modeller) in order to develop FBD system for designing prismatic parts using predefined STEP features. Modelling process in STEP FM starts with the selection of stock shape, then goes on with feature selection and feature parameters' definition. Feature parameters for hole features are listed in Table 1. The process continues with placement and orientation of the created feature. Feature modelling process ends with STEP data generation phase. Exported as STEP-XML data file format, the designed part can be used directly in donwstream applications since it contains high-level part data.

Table 1: Feature parameters of Hole feature.

HOLE	
Feature	**Parameters**
Round Hole	D, L, Bottom Condition
Tapered Round Hole	D, DF, L, Bottom Condition
Countersunk Hole	1st Hole, 2nd Hole
Counterbore Hole	1st Tapered Hole, 2nd Hole

3 THEORETICAL ENERGY ESTIMATION METHODOLOGY

Rahimifard et al. [14] divide energy consumption of manufacturing operations into two groups which are direct energy and indirect energy. Direct energy is defined as the energy of the required processes such as milling, turning, painting, etc. Indirect energy, on the other hand, is the consumed energy by the services to maintain required conditions for the work place such as lighting, heating, etc. Direct energy can be broken down into two sub-categories:

$$E_{direct} = \sum E_{process} + \sum E_{handling} \quad (1)$$

where $E_{process}$ is the energy consumed by manufacturing process and $E_{handling}$ is the energy consumed by the automated handling materials like robots and conveyors. Uluer et al. [10] defined the energy consumption while manufacturing a part by the following equation:

$$E_{part} = \sum E_{process} + \sum E_{handling} + \sum E_{indirect} \quad (2)$$

During a manufacturing process, like milling a manufacturing feature to a prismatic stock, there are two types of energy consumption [14].

$$E_{process} = E_{th} + E_{aux} \quad (3)$$

E_{th} is the theoretical energy which is required to carry out the actual metal removal processes. E_{aux} is the auxiliary energy which is consumed either by supplementary activities or by auxiliary equipments such as cooling pumps, tool changers, chip handling equipments. According to Dahmus and Gutowski [15] auxiliary energy consumption covers 30-50 % of the total energy consumption in automated milling machines. Auxiliary energy can be divided into two subgroups: constant auxiliary energy ($E_{aux\text{-}const}$) and variable auxiliary energy ($E_{aux\text{-}var}$) [10].

$$E_{aux} = E_{aux\text{-}const} + E_{aux\text{-}var} \quad (4)$$

Constant auxiliary energy is the energy consumed by supplemental components or services, even when the machine is on standby mode. Operations such as lighting and components like embedded computer for the CNC machine tools are both examples for constant auxiliary energy. Variable auxiliary energy is time dependent and may change during machining operation. Energy consumption of servo motors, spindle motors and automatic tool changers are examples of variable auxiliary consumption. Li et al. [16] identified and classified auxiliary energy components:

$$E_{aux\text{-}const} = E_{computer} + E_{light} + E_{fan} + E_{misc} \quad (5)$$

$$E_{aux\text{-}var} = E_{servo} + E_{spindle} + E_{ATC} + E_{cool} + E_{chiller} \quad (6)$$

3.1 Theoretical Energy Estimation Model

Theoretical energy consumption while milling a manufacturing feature can be determined by multiplying V_{rem} (mm^3), which is the removed material volume, with k_c (J/ mm^3), which is the specific cutting energy.

$$E_{th} = k_c \cdot V_{rem} \quad (7)$$

Since the milling operation is investigated in this study, the removed volume for each feature must be calculated autonomously. Also rough cutting volumes and finish cutting volumes for each feature must be calculated seperately. Specific cutting energy is defined as the energy required to remove a unit volume of material. For milling operations, k_c is calculated by the following equation [17]:

$$k_c = \frac{(1 - 0{,}01 \cdot \gamma_0) \cdot k_{c^{1,1}}}{h_m^{m_c}} \quad (8)$$

where γ_0 (°) is the effective rake angle; $k_c^{1,1}$ (J/mm^3) is the specific cutting energy for 1 mm chip thickness and m_c is an exponent which varies with the material of the workpiece. h_m is the avarage chip thickness and calculated by the following equation [17]:

$$h_m = \frac{360 \cdot f_z \cdot a_e}{\Pi \cdot D_c \cdot \omega_e} \cdot \sin\kappa \quad (9)$$

where f_z is the feed per tooth(mm/tooth), a_e (mm) is the width of cut, D_c (mm) is the cutter diameter, ω_e (°) is the engagement angle and is K the cutting edge angle.

3.2 Carbon Footprint Estimation Model

Jeswiet and Kara [18] have offered a model that calculates the carbon emissions of a manufacturing process directly from the consumed energy data. This method offers a Carbon Emission Signature (CES^{TM}) that has a unit of kg CO_2/GJ. CES^{TM} relies on the primary energy sources of an electric power grid. In order to estimate the emitted carbon amount for a manufacturing process, the following equation can be used:

$$CE_{process} = E_{process} \cdot CES \quad (10)$$

In the scope of this study, the theoretical energy consumption prediction model is presented. The amount of carbon emitted by the theoretical energy consumption(CE_{th}) can be found by the following equation [18]:

$$CE_{th} = E_{th} \cdot CES \quad (11)$$

CES can be calculated by the following equation [18]:

$$CES = \eta \cdot (112 \cdot \%C + 49 \cdot \%NG + 66 \cdot \%P) \quad (12)$$

where C, NG and P represent the fractions of coal, natural gas and petroleum, respectively. The coefficients, 112, 49 and 66 represent the amount of carbon emitted per gigajoule of heat released in each case in kilograms and η is the conversion efficiency. The fractions for C, NG and P are 28.9%, 45.4% and 0.2% respectively and they are based on

Turkey's electricity generation by primary resources data presented by Turkish Electricity Transmission Company [19]. With using a common conversion efficiency of 0.34, CES for Turkey can be calculated as 160.85 kg CO_2/GJ.

4 CASE STUDY

A part with three STEP AP224 manufacturing features is designed to demonstrate the developed model. Technical drawing of the case study part is depicted in Figure 4. The stock's size is 200 mm x 250 mm x 40 mm. There are three features to be removed on the stock which are rectangular open pocket, round hole and open slot. The removal process starts with a side milling operation. Then, rough and finish cutting operations for the rectangular open pocket feature are followed, respectively. Same operations for the rectangular open pocket feature are repeated for round hole feature. Ultimately, rough and finish cutting operations for open slot feature take place.

Three different raw materials are used in this study in order to present three design alternatives: Structural Steel (AISI1050), Tool Steel (AISI O2) and Aluminum (6013). Cutters and inserts for milling operations are selected from SECO Tool Catalogues to acquire accurate pragmatic calculations [17]. Nano Turbo R217.69-1010.0-06-2AN cutter and Nano Turbo R217.69-2020.0-06-4AN cutter are chosen as cutters. They have 10 mm and 20 mm cutter diameters, respectively. Inserts are chosen as recommended to be compatible with the cutter and also be applicable with the stock material. For structural steel and tool steel stocks, XOMX060204R-M05F40M inserts and for the aluminum stock XOEX060204R-E03F40M inserts are chosen.

Cutting edge angle (K) is specified by the cutter type. Feed per tooth (f_z) values depend on the chosen cutter, engagement angle (ω_e) and stock material. Width of cut (a_e) and engagement angle (ω_e) values depend on the pathway which the NC-code programmer creates for the operation. Effective rake angle (γ_0) value is the sum of cutter's rake angle and insert's rake angle. Specific cutting energy ($k_c^{1,1}$) and the coefficient m_c rely on the material properties of the stock.

Average chip thickness values are calculated for each manufacturing feature using Equation 9 and theoretical energy consumptions are calculated for each manufacturing feature using Equation 8, as well. Then, theoretical energy consumption amounts are calculated by using Equation 7. Also, the carbon emission amounts computed by using Equation 11. The total theoretical energy amounts consumed for manufacturing the case study part depending on the material of work piece are shown in Table 2. The expanded case study results for each feature and operation are presented in Table 3.

According to the case study results, part which is milled out of an AISI O2 stock consumes highest amount of theoretical energy, AISI 1040 comes next and Aluminum 6013 stock consumes lowest. The carbon emission amount ranking changes correspondingly. Since cutting conditions are assumed as identical for all materials, this theoretical energy consumption prediction results seem to be logical. However, this study does not take account of auxiliary energy consumptions and in order to make more efficient predictions auxiliary energy consumption model is planned as a future work.

Table 2: Case study results.

Material	Eth(kJ)	CEth(g)
AISI 1040	942,97	151,676
AISI O2	1414,26	227,483
Aluminum 6013	419,79	67,523

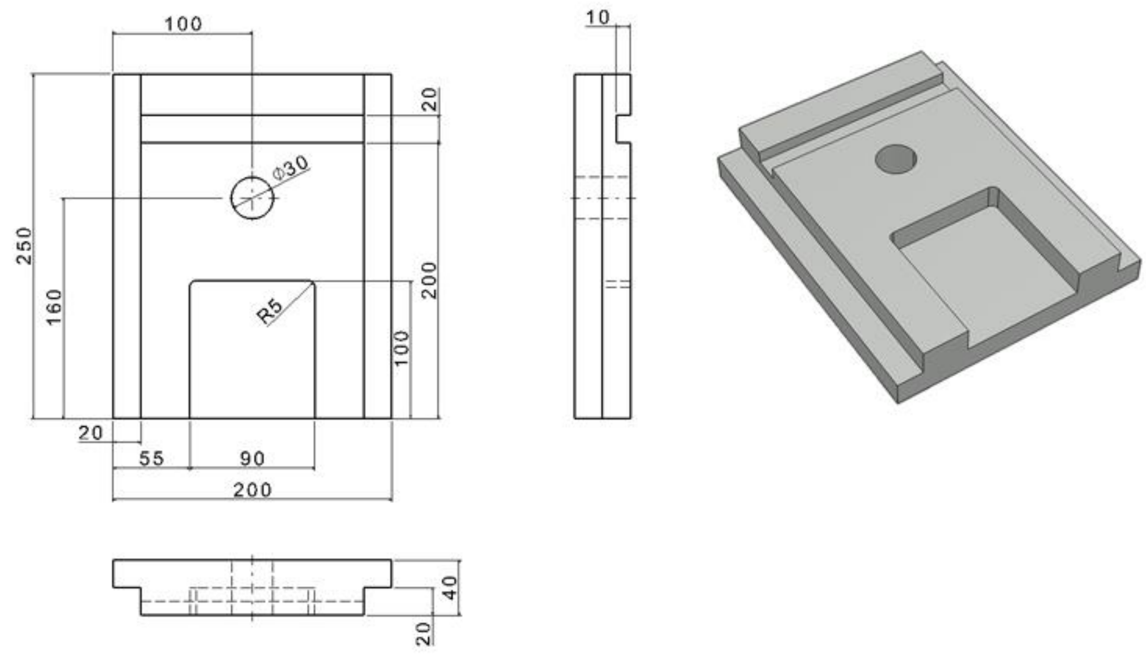

Figure 4: Technical drawing of the case study part.

Table 3: Expanded case study results.

Feature/Op.	Op. Type	Material	hm(mm)	kc(J/mm3)	Vrem(mm3)	Eth(kJ)	CEth(g)
POCKET (Rectangular Open Pocket)	Rough	AISI 1040	0,045	2,775	152000	421,80	67,847
		AISI O2	0,038	4,163	152000	632,74	101,777
		Aluminum 6013	0,051	1,236	152000	187,80	30,207
	Finish	AISI 1040	0,050	2,694	28000	75,45	12,135
		AISI O2	0,043	4,023	28000	112,64	18,119
		Aluminum 6013	0,057	1,197	28000	33,51	5,390
SLOT (Open Slot)	Rough	AISI 1040	0,045	2,775	24000	66,60	10,713
		AISI O2	0,038	4,163	24000	99,91	16,070
		Aluminum 6013	0,051	1,236	24000	29,65	4,770
	Finish	AISI 1040	0,033	2,982	8000	23,86	3,837
		AISI O2	0,029	4,525	8000	36,20	5,823
		Aluminum 6013	0,038	1,335	8000	10,68	1,718
HOLE (Round Hole)	Rough	AISI 1040	0,045	2,775	19634	54,48	8,764
		AISI O2	0,038	4,163	19634	81,73	13,147
		Aluminum 6013	0,051	1,236	19634	24,26	3,902
	Finish	AISI 1040	0,050	2,694	8639	23,28	3,744
		AISI O2	0,043	4,023	8639	34,75	5,590
		Aluminum 6013	0,057	1,197	8639	10,34	1,663
SIDE MILLING	Rough	AISI 1040	0,045	2,775	75000	208,13	33,477
		AISI O2	0,038	4,163	75000	312,21	50,219
		Aluminum 6013	0,051	1,236	75000	92,66	14,905
	Finish	AISI 1040	0,045	2,775	25000	69,38	11,159
		AISI O2	0,038	4,163	25000	104,07	16,740
		Aluminum 6013	0,051	1,236	25000	30,89	4,968

5 CONCLUSION AND FUTURE WORKS

This work aims to develop a methodology which aids engineers to predict energy consumptions and carbon emissions of machining processes at the part design and process planning stage of manufacturing. Utilizing this tool, design engineers can change the cutting conditions and decide between the design alternatives with energy consumption data. By this way, they can not only create more environment-friendly process plans but also decrease environmental impact during manufacturing.

The implementation of the proposed model to CATIA v6 is an ongoing process. Verification of the proposed model by taking measurements from CNC Milling Machine at the Technology Center of TOBB University of Economics and Technology is planned as a future work. Development of a model for predicting auxiliary energy consumption for prismatic parts is also a future work, as well.

6 REFERENCES

[1] International Energy Agency, 2012, World Energy Outlook. Available at : http://www.worldenergyoutlook.org/publications/weo-2012 [Accessed 18 April 2013].

[2] U.S. Energy Information Administration, 2012, Annual Energy Outlook 2012. Available at: http://www.eia.gov/forecasts/aeo/pdf/0383(2012).pdf [Accessed 18 April 2013].

[3] World Resources Institute, 2005, World Greenhouse Gas Emissions. Available at: http://www.wri.org/chart/world-greenhouse-gas-emissions-2005 [Accessed 18 April 2013].

[4] [4] U.S. Energy Information Administration, 2011, Annual Energy Review 2011. Available at: http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf [Accessed 18 April 2013].

[5] The Intergovernmental Panel on Climate Change, 2007, Climate Change 2007 Mitigation of Climate Change. Available at: http://www.ipcc.ch/pdf/assessment-

report/ar4/wg3/ar4_wg3_full_report.pdf [Accessed 18 April 2013].

[6] International Energy Agency, 2011, G-20 Clean Energy, And Energy Efficiency Deployment and Policy Progress. Available at: http://www.iea.org/publications/freepublications/publication/G20_paper.pdf [Accessed 18 April 2013].

[7] Schey, J.A., 2000, Introduction to Manufacturing Processes, 3rd ed. : McGraw Hill, ch. 16, pp 617-725.

[8] Kalpakjian, S., Schmid, S. R., 2003, Manufacturing Processes for Engineering Materials, 4th ed. Upper Saddle River, NJ: Prentice Hall, ch. 8, pp. 404-504.

[9] Amaitik, S.M., Kılıç, S.E., 2005, STEP-based Feature Modeler for Computer-aided Process Planning, in: International Journal of Production Research, Vol. 43, No. 15, pp. 3087-3101.

[10] Uluer, M. U., Ünver, H. Ö., Akkuş, K., Kılıç. S.E., 2013, A Model for Predicting Theoretical Process Energy Consumption of Rotational Parts using STEP AP224 Features, 20th CIRP International Conference on Life Cycle Engineering, Singapore.

[11] International Standards Organization, 1994, ISO 10303-1 Industrial automation systems and integration - Product data representation and exchange - Part 1: Overview and fundamental principles, Geneva, Switzerland.

[12] International Standards Organization, 2006, ISO 10303-224 Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 224: Application Protocol: Mechanical Product Definition for Process Planning Using Machining Feature, Geneva, Switzerland.

[13] Zhao, Y.F. , Habeeb, S., Xu, X., 2008, Research Into Integrated Design and Manufacturing Based on STEP, International Journal of Advanced Manufacturing Technology, Vol. 44, pp. 606-624.

[14] Rahimifard, S., Seow, Y., Childs, T. , 2010, Minimising Embodied Product Energy to Support Energy Efficient Manufacturing, in: CIRP Annals – Manufacturing Technology, Vol. 59, pp. 25-28.

[15] Dahmus, J.B., Gutowski, T.G., 2004, An Environmental Analysis of Machining, Proceedings of the 2004 ASME International Mechanical Engineering Congress and RD&D Exposition, Anaheim, California, USA.

[16] Li, W., Zein, A., Kara, S., Herrmann, C., 2011 An Investigation into Fixed Energy Consumption of Machine Tools, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering (LCE2011), pp. 268-273, Braunschweig, Germany.

[17] SECO Tools, 2012, MN2012 - Milling in: Machining Navigator Catalogue.

[18] Jeswiet, J., Kara, S., 2008, Carbon Emissions and CES™ in Manufacturing, in CIRP Annals – Manufacturing Technology, Vol. 57, pp. 17-20.

[19] Turkish Electricity Transmission Company (TEİAŞ). Available at: http://www.teias.gov.tr/ [Accessed 17 March 2013].