

Energy-efficiency based classification of the manufacturing workstation

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Abstract. EU Directive 92/75/EC established for the first time an energy consumption labelling scheme, further implemented by several other directives. As consequence, nowadays many products (e.g. home appliances, tyres, light bulbs, houses) have an EU Energy Label when offered for sale or rent. Several energy consumption models of manufacturing equipments have been also developed. This paper proposes an energy efficiency – based classification of the manufacturing workstation, aiming to characterize its energetic behaviour. The concept of energy efficiency of the manufacturing workstation is defined. On this base, a classification methodology has been developed. It refers to specific criteria and their evaluation modalities, together to the definition & delimitation of energy efficiency classes. The energy class position is defined after the amount of energy needed by the workstation in the middle point of its operating domain, while its extension is determined by the value of the first coefficient from the Taylor series that approximates the dependence between the energy consume and the chosen parameter of the working regime. The main domain of interest for this classification looks to be the optimization of the manufacturing activities planning and programming. A case-study regarding an actual lathe classification from energy efficiency point of view, based on two different approaches (analytical and numerical) is also included.

1. Introduction

EU Directive 92/75/EC established for the first time an energy consumption labelling scheme, further implemented by several other directives. As consequence, nowadays many products (e.g. home appliances, tyres, light bulbs, houses) have an EU Energy Label when offered for sale or rent. Their energy efficiency is rated in terms of a set of energy efficiency classes. The labels also give other useful information to the customer as they choose between various models. The algorithms for evaluating the energy efficiency are specific for each type of product. In the context of continuously extending the application of sustainable development concept, the environmental impact of the manufacturing activities is increasingly taken into account. In connection to this, many researches have been already dedicated to define the energy efficiency of manufacturing equipments and to assess their energy efficiency [1-3]. Several energy consumption models of manufacturing equipments have been also developed [4].

The energy needed to perform an industrial process has two main components: the energy for actually running the process, consumed inside the process, and the energy required for underlying the



process, consumed by the workstation. The researches approaching the energy efficiency of the manufacturing equipment presented in the dedicated literature [5-8] address to both above-mentioned components, put together. In [9], the energy classification of the industrial processes has been already addressed, by defining energy classes and by developing an algorithm for energy labelling.

This paper proposes an energy efficiency – based classification of the manufacturing workstation, aiming to characterize its energetic behaviour. Hereby, the concept of energy efficiency in the case of the manufacturing workstation is defined firstly, in holistic manner (considering both consumed and embodied energy). On this base, a classification methodology with multiple targets, covering aspects related to needed guidance in the acquisition stage but also to the design of the exploitation regime is has been developed. It refers to specific criteria and their evaluation modalities, together to the definition & delimitation of energy efficiency classes. The methodology lies on approaching the energy class as the simplest energetic model of the workstation. More precise, the energy class position is defined after the amount of energy needed by the workstation in the middle point of its operating domain, while its extension is determined by the value of the first coefficient from the Taylor series that approximates the dependence between the energy consume and the chosen parameter of the working regime. The domain of interest for this classification looks to be the optimization of the manufacturing activities planning and scheduling.

In what concerns paper structure, the next section deals with energy classification of industrial products. The third section proposes a methodology for workstation energy classification. The fourth section presents a case study, namely the energy labelling of an actual lathe. The final section is dedicated to conclusion.

2. Energy classification of industrial products

2.1. Rational behind classification

Classification is a general process related to categorization, the process in which ideas and objects are recognized, differentiated, and understood [10]. As result of classification, one may assign labels to resulted categories, in this case the label meaning a description applied from the outside [10]. By starting from these definitions, let us consider for the instance that classification refers in general to items (objects, processes, procedures etc.).

The *item* has, in general, several *features* (e.g. the features of an object might be considered the shape, the magnitude, the colour etc.). Each feature can be characterized by one or more physical issues called *attributes* (e.g. the magnitude is characterized, in an orthogonal reference system by length, width and height). Every single item is individualised by the particular values of these attributes giving the *attributes vector*.

Items assessment may be realized by distinction or by similitude between them, after choosing one ore more assessment criteria. To make *distinction*, the evaluation of features through measuring their attributes is followed by putting in evidence the differences between them, while for *classification* the items are grouped in classes defined after common values of attributes.

2.2. Industrial products classification

Here by *industrial product* we mean any product resulted after an industrial manufacturing process (e.g. steel bar, bread, car, plastic bag, machine tool are all industrial products). If intending to classify the industrial products belonging to a given category, then the first action to be performed is to identify all products *existing at classification moment*. After this, the product feature corresponding to *classification criterion* need to be evaluated by measuring its attributes in each case. On this base, an indicator I reflecting the product position on the scale of classification criterion follows to be calculated. Afterwards the *classification domain* results between the limit values of the indicator, I_{min} and I_{max} , corresponding to the worst and to the best product, respectively. The *product classes* issue by dividing the classification domain in subdomains, corresponding to subintervals of $[I_{min}, I_{max}]$, figure 1. The number of classes depends on the extension of classification domain and on how coarse the

product assessment is intended to be. Classes may be labelled by letters (e.g. from A, the best, to D, the worse) or by numbers.

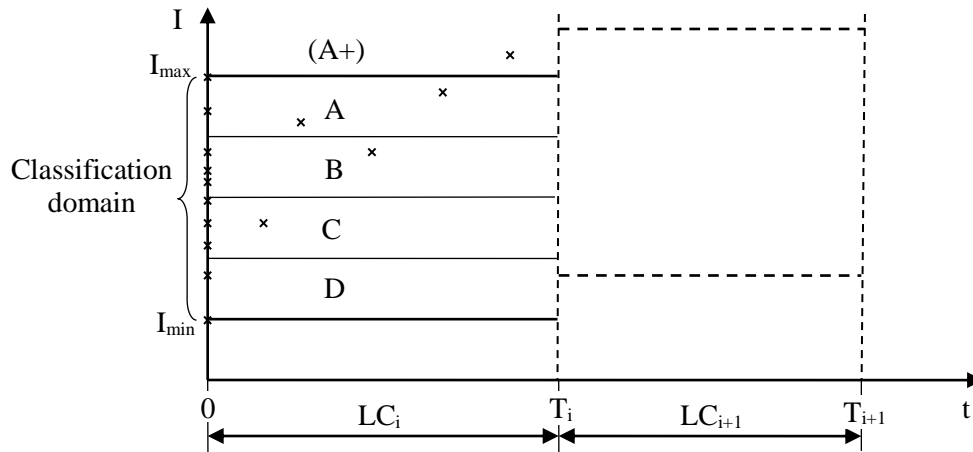


Figure 1. Industrial products classification.

In the picture from above, each point marked by an “x” means a product, its coordinates (t, I) representing the moment when the product was launched on market (obviously, some of them coexisting at the classification moment $t = 0$) and the value of product feature indicator, respectively. The classification operates for a time interval T_i equal to a conventional life cycle LC_i adopted with respect to the life cycles of the products existing at the initial moment. Thereafter, the classification needs to be reconsidered and updated, for the time interval $[T_i, T_{i+1}]$ and so on. New products may appear during the classification validity. If some of the newly developed products overpass the level of class A, then new classes $(A+, A++ \text{ etc.})$ are defined until the time of introducing a new classification (at T_i moment) has come.

2.3. Energy classes

The implementation of sustainable development concepts in all human activity domains has determined EU authorities to take a wide range of measures aiming to reduce the global energy consumption. As consequence, an important feature of industrial products that consume energy for achieving their functions has become the *energy efficiency*. In order to promote the manufacturing, selling and using of products with high energetic performance, the assignment of energy labels to diverse categories of products, according to their energy class, is becoming more and more popular. Energy labels are currently applied to cars, buildings, tyres, electric lamps, home appliances etc.

The energy label gives also, besides information about energy efficiency (which is the most important issue), other information utile to the consumer of the considered product. For example, in tyres case, the energy label refers to energy efficiency, to adherence on wet surfaces, on snow and to functional noise.

In what concerns the energy efficiency, there is not available a unitary, standard procedure for calculating and expressing it for all product types. For example, at washing machines the label refers to the amount of energy required for an annually number of washing cycles, at cars to the emission of CO_2 released in atmosphere when running 100 km, for electric lamps to the ratio between flux of light and absorbed power etc.

Present paper addresses the assessment of workstation energy efficiency, which is also an industrial product. Here by *workstation* we mean the manufacturing equipment required for achieving a task issued from a job afferent to a given manufacturing order. The energy efficiency of generic workstation w can be calculated as ratio between *Result* and *Effort* (figure 2).

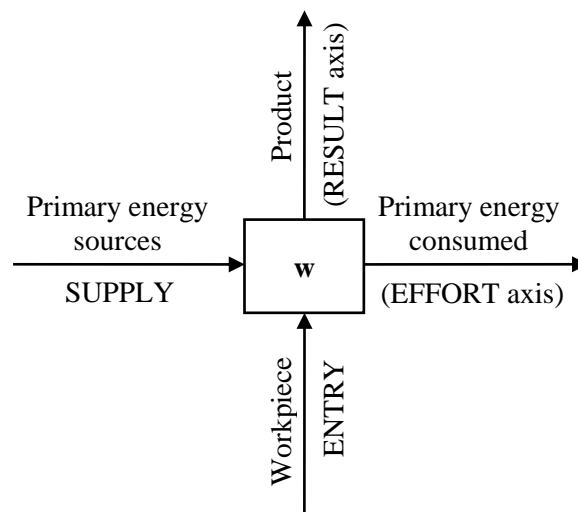


Figure 2. Workstation flows.

Workstation duty is to support the deployment of a manufacturing process that transforms the workpiece in manufactured part (product). In the present paper context, *Effort* means the primary energy consumed by workstation, while as *Result* one may choose one of the attributes characterizing workpiece transformation in product (e.g. the area of the manufactured surface or the volume of detached material, in the case of machining process).

3. Method for workstation energy classification

3.1. Utility area definition

There is a wide range of manufacturing tasks to be achieved in practice. For example, if only referring to machining, task might mean machining a plane exterior surface, a conical external surface, an interior or exterior thread, a cylindrical gear teeth etc. For achieving a given task, several procedures are available in general, e.g. a cylindrical hole can be machined by drilling, boring, turning, grinding etc. Each of the mentioned procedures can be realized on a multitude of workstations. As consequence, a rational energy classification of the manufacturing workstation can be developed only after limiting the classification target group. In this purpose, the *utility area* notion will be defined in relation to the addressed subject.

Let us consider three generic tasks (t_1 , t_2 and t_3), each of them possible to be achieved by one or more of the procedures $p_1 \dots p_4$, which may take place each on one or more of the available workstations $w_1 \dots w_5$. The graph illustrating all possible connections between the mentioned tasks, procedures and workstations is presented in figure 3.

After analyzing the graph, three possibilities to define the utility area can be revealed:

- *Task – Workstation* utility area, obtained by associating to task the workstations able to achieve it (from the example presented in figure 3, three such utility areas result, as shown in figure 4-a)
- *Procedure – Workstation* utility area, obtained by assigning to procedure the workstations which can achieved it (the four utility area issuing from sampled graph are depicted in figure 4-b)
- *Task – Procedure – Workstation* utility area, with tree-type structure, which connect the task with its afferent procedures and workstations (one of the three possible such utility areas is highlighted in figure 3 with thicker arrows & contours and bold characters and includes the task t_1 , the procedures p_1, p_2, p_3 and the workstations $w_1 \dots w_4$)

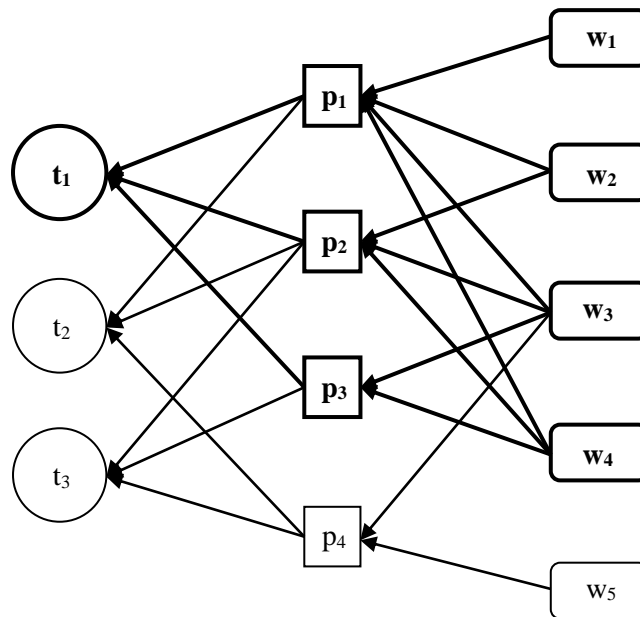


Figure 3. Task – procedure – workstation graph.

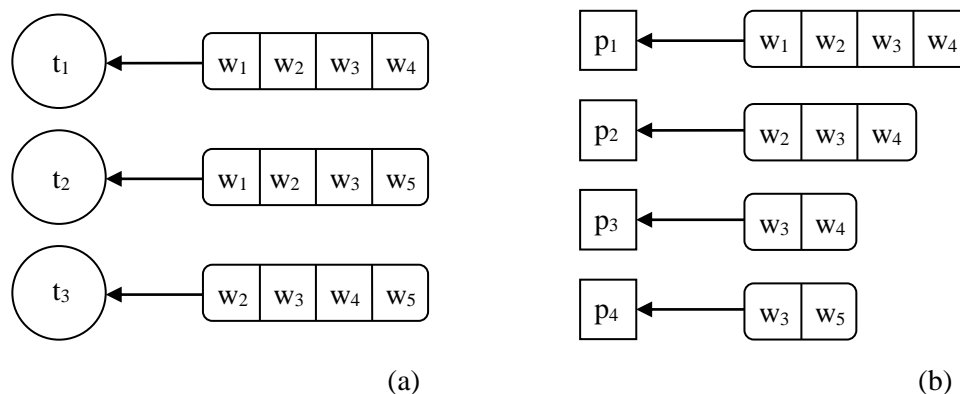


Figure 4. Utility areas: (a) Task – Workstation type; (b) Procedure – Workstation type.

Because the first type of utility area definition may include redundancies, while the third type may lead to a classification too complicated and difficult to manipulate, the *Procedure – Workstation* definition of utility area seems to be the most suitable and will be adopted for applying the workstation energy classification.

3.2. Energy classes delimitation

A new methodology for *manufacturing processes* energy classification has been already developed and presented in [8]. It is applied on utility areas resulted by associating to each manufacturing task the procedures available for its achievement and is based on defining energy classes for the manufacturing procedures. By keeping the same approach when looking to *manufacturing workstation* energy classification, applied on utility areas defined as specified in previous section, the energy classes' delimitation is presented in generic manner in figure 5. The case of the utility area formed by procedure p_1 and workstations $w_1 \dots w_4$ has been addressed there.

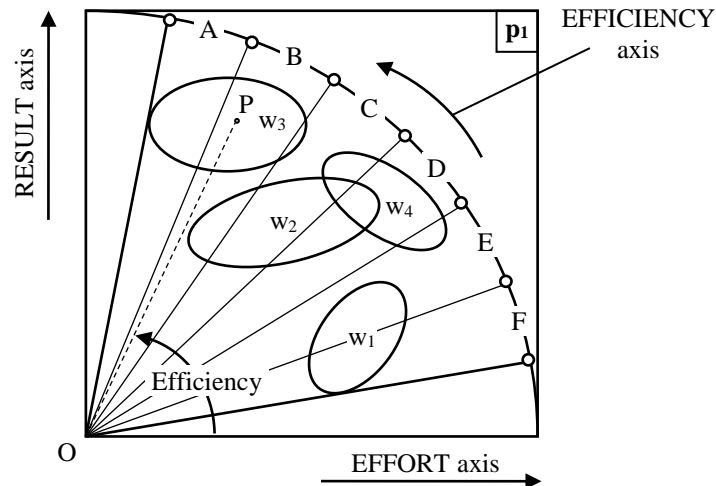


Figure 5. Effort – Result – Efficiency (ERE) diagram for p_1 procedure.

According to the definition of workstation energy efficiency presented in section 2.3 and illustrated in figure 2, the *Effort* means the primary energy consumed by workstation, while the *Result* consist in an attribute characterizing workpiece transformation in product. The locus of points whose coordinates correspond to all operating points of a given workstation, resulted by applying different manufacturing regimes when performing the same procedure, defines a close domain assigned to it in the graphic representation from figure 5 and will be referred from now on as *workstation efficiency domain*. The classification domain is comprised between the lines passing by origin and by the points afferent to the worse and the best energy efficiency, after searching inside the efficiency domains of all considered workstations. The angular sector of each generic efficiency class results by dividing the classification domain in several (in figure 5 - six) subdomains. By similitude with already existing energy-labeling of other industrial products, according to current EU directive [11], the efficiency classes for manufacturing workstations will be labeled by letters from A (the most efficient) to F (the least efficient, if considering six classes).

The energy label of an actual workstation issues from the energy class where its middle operating point belongs. The *middle operating point* position corresponds to the situation when the workstation is operated with mean values of the manufacturing regime parameters (e.g. the point P for workstation w_3 , see figure 5).

Note 1: The workstation efficiency domain may overlies on more than one efficiency class. Hereby, the energy class of workstation w_2 (according to figure 5) is stated as $C_{-0.55}^{+0.70}$, corresponding to the relative extension of partially covered domains from B and D classes (70% respective 55%).

Note 2: The same workstation may have different energy labels if classified for different utility areas.

4. Case study

The classification of a lathe from energy efficiency point of view is further presented as case study. The utility area inside which the classification is realised refers to the workstations achieving the procedure of machining cylindrical exterior surface on parts made from steel with mild mechanical properties. The volume of detached material has been chosen as *Result* indicator. It is possible to apply two different approaches, namely analytical and numerical, depending on the type of model used for characterizing the lathe energetic behaviour.

4.1. Analytical approach

In this case, the analytical model giving the lathe energy specific consumption is supposed to be known. According to [6], the shape of such a model is:

$$SCE_d = C_0 \cdot v^{e_1} \cdot f^{e_2} \cdot a^{e_3} \cdot D^{e_4} + \frac{C_1}{v \cdot f \cdot a}. \quad (1)$$

In relation from above, SCE_d means the specific consumption of direct energy (measured, for example, in J/mm³), v , f and a – the cutting regime parameters (speed, feed and cutting depth, respectively), D – the mean diameter of turning, while C_0 , C_1 , e_1 , e_2 , e_3 , e_4 are constant parameters, specific to considered lathe. Because the lathe embodies a significant amount of energy consumed for its manufacturing, the specific consumption of embodied energy SCE_e should also be considered:

$$SCE_e = E_e \cdot \frac{t_w}{LC} \cdot \frac{1}{V} = \frac{K}{v \cdot f \cdot a}. \quad (2)$$

Here E_e means the amount of energy embodied in lathe, LC – the lathe life cycle, t_w – the actual working time, V – the removed material volume, and K – a constant resulted after development calculus. Due to similitude of SCE_e final expression with the second term from (1), the total specific consumption of energy can be calculated as:

$$SCE = SCE_d + SCE_e = C_0 \cdot v^{e_1} \cdot f^{e_2} \cdot a^{e_3} \cdot D^{e_4} + \frac{C_1'}{v \cdot f \cdot a} \text{ with } C_1' = C_1 + K. \quad (3)$$

The lathe energy efficiency EE is, in fact, the inverse of SCE . After calculus, its expression is:

$$EE = \frac{v \cdot f \cdot a}{C_0 \cdot v^{e_1+1} \cdot f^{e_2+1} \cdot a^{e_3+1} \cdot D^{e_4} + C_1'} = EE(v, f, a, D). \quad (4)$$

A middle operating point P can be assigned to each workstation by analyzing its manufacturing capacity relative to a given utility area. In current case study, P is defined by values of the five variable parameters: v_0 , f_0 and a_0 (related to turning regime) respective D_0 and l_0 (related to machined surface's dimensions, diameter and length). The position of P_0 inside the workstation efficiency domain (see 3.2. and figure 5), which determines the basic energy label of the lathe, results by calculating its coordinates (V_0 , E_0), meaning the volume of detached material,

$$V_0 = \pi \cdot D_0 \cdot l_0 \cdot a_0, \quad (5)$$

and the amount of energy consumed in this purpose,

$$E_0 = EE(v_0, f_0, a_0, D_0) \cdot V_0. \quad (6)$$

The energy efficiency domain is comprised between the points corresponding to the extreme values of EE , namely EE_{min} and EE_{max} . A simplified yet effective procedure to be followed in order to find these limits is to choose firstly the most influent of the four variable parameters from (4) (e.g. f) and to develop then EE in Taylor series, after freezing the other parameters at values corresponding to middle operating point. By neglecting the terms of degrees higher than one, we have:

$$EE(f) \cong EE(v_0, f_0, a_0, D_0) + (f - f_0) \frac{\partial EE}{\partial f}(v_0, f_0, a_0, D_0). \quad (7)$$

The values EE_{min} and EE_{max} can be now determined by replacing in (8) f with f_{min} and f_{max} (it should be noticed that the correspondence between the extreme values of EE and f might be direct or inverse, depending on the sign of the second term from right member). The extreme values of energy consumption, E_{min} and E_{max} finally result, if multiplying EE_{min} and EE_{max} by V_0 .

According to [6], in the case of a Mori Seiki NL2000Y/500 lathe, the values of the parameters of model (1) are: $C_0 = 1.92$, $C_1 = 85.4442$, $e_1 = 0.4481$, $e_2 = -0.6851$, $e_3 = -0.8214$, $e_4 = -0.804$. The estimated amount of lathe embodied energy leads to $K = 10$. The considered coordinates of the middle operating point are $D_0 = 65$ mm, $v_0 = 100$ m/min, $f_0 = 0.2$ mm/rev and $a_0 = 2$ mm. By replacing the numerical values from above in formula (4), (5) and (6), we obtained $EE_0 = 0.304$ cm³/KJ, $V_0 = 20.42$ cm³ and $E_0 = 67.1$ KJ. After analytically calculating the derivative of EE function relative to f , its value in the middle operating point results as 1.1. If $f_{min} = 0.1$ mm/rev and $f_{max} = 0.3$ mm/rev, then the estimated values of EE_{min} and EE_{max} , according to (7), are 0.184 and 0.414 cm³/KJ respectively.

4.2. Numerical approach

If the analytical model giving the lathe energy specific consumption is not available, the lathe energy efficiency and its energy label can be numerically determined. In this purpose, a dataset including information about machined parts dimensions, corresponding cutting regime parameters and measured energy consumption need to be created. An excerpt from such dataset, artificially generated in the case of the same lathe from above, is presented in Table 1.

Table 1. Dataset excerpt.

| Crt. no. | D [mm] | l [mm] | v [m/min] | f [mm/rev] | a [mm] | V [cm ³] | E [KJ] |
|----------|--------|--------|-----------|------------|--------|----------------------|----------|
| 1 | 65 | 50 | 100 | 0.2 | 2 | 20.4204 | 67.0728 |
| 2 | 70 | 45 | 95 | 0.12 | 3 | 29.6881 | 107.8321 |
| 3 | 85 | 120 | 100 | 0.25 | 2 | 64.0885 | 162.1696 |
| 4 | 80 | 65 | 120 | 0.18 | 1.2 | 19.6035 | 98.6341 |
| 5 | 150 | 100 | 110 | 0.1 | 1.3 | 61.2611 | 287.2152 |
| 6 | 120 | 150 | 115 | 0.3 | 1.5 | 84.8230 | 203.9901 |
| 7 | 100 | 200 | 125 | 0.2 | 2.2 | 138.2301 | 329.6467 |
| 8 | 180 | 70 | 100 | 0.24 | 1.7 | 67.2929 | 184.3075 |
| 9 | 165 | 80 | 95 | 0.22 | 1 | 41.4690 | 217.8800 |
| 10 | 90 | 180 | 130 | 0.16 | 2.7 | 137.4133 | 330.8792 |

The energy efficiency, EE , of each monitored process results by dividing the calculated volume of removed material V to measured energy consumption E . The mean of EE values in all recorded cases can be assimilated to EE_0 , the energy efficiency of the middle operating point. From the dataset of addressed case study, we found $EE_0 = 0.315$ cm³/KJ.

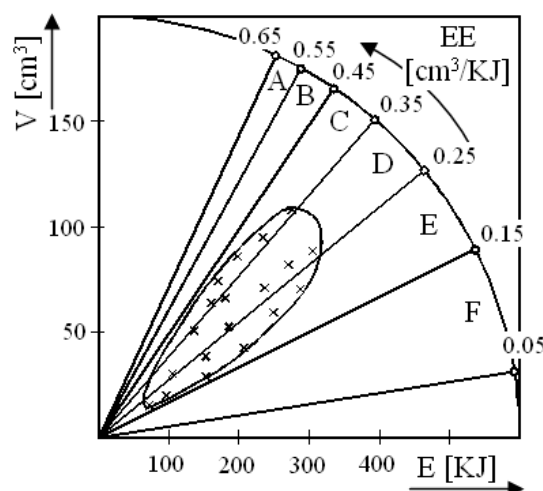


Figure 6. Lathe efficiency domain.

By graphical representing the points corresponding to each manufacturing process in (V, E) coordinates and by delimiting through a close curve the domain occupied by these points, the lathe efficiency domain position in the Effort – Result – Efficiency diagram results as depicted in figure 6. The domain calculated limits are $EE_{min} = 0.190 \text{ cm}^3/\text{KJ}$ and $EE_{max} = 0.419 \text{ cm}^3/\text{KJ}$. If the efficiency classes limits are the ones presented in diagram, then the efficiency class of assessed lathe is $D_{-0.8}^{+0.7}$.

5. Conclusion

This paper proposes the efficiency – based classification of the manufacturing workstations, aiming to characterize their energetic behaviour. The energy efficiency of the manufacturing workstation is defined in holistic manner (considering both consumed and embodied energy). A classification methodology has been developed, with application on Procedure – Workstation utility areas. The energy classes have been defined with the help of Effort – Result – Efficiency diagram. The energy classification of an actual lathe has been addressed as case study, by two different approaches – analytical and numerical. The case study results show that:

- The classification method is consistent, feasible and effective.
- The two approaches in implementing the classification method lead to similar results.
- The energy classification problem has relevance, as an important variation of specific energy consumption can be noticed when performing the same procedure on same workstation with different manufacturing regimes.
- The classification method is helpful in: *i*) process planning, for choosing the workstation to perform a given procedure, *ii*) process programming, for finding the suitable cutting regime, and *iii*) workstation acquisition, for selecting between the offers existing in market.

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7. References

- [1] Ma J, Ge X, Chang S I, and Lei S 2014 Assessment of cutting energy consumption and energy efficiency in machining of 4140 steel *Int J Adv Manuf Technol* **74** 1701–1708
- [2] Park H-S, Nguyen T-T and Kim J-C 2016 An Energy Efficient Turning Process for Hardened Material with Multi-Criteria Optimization *Transactions of FAMENA* **XL-1** 1-14
- [3] Salonitis K, and Ball P 2013 Energy efficient manufacturing from machine tools to manufacturing systems *Procedia CIRP – Manuf. Systems* **7** 634-639
- [4] Zhou L, Li J, Li F, Meng Q, Li J and Xu X 2016 Energy consumption model and energy efficiency of machine tools: a comprehensive literature review, *Journal of Cleaner Production* **112** 3721-3734
- [5] Yoon H-S, Lee J-Y, Kim M-S and Ahn S-H 2014 Empirical power-consumption model for material removal in three-axis milling *Journal of Cleaner Production* **78** 54-62
- [6] Guo Y, Duflou J R and Lauwers B 2014 Energy-based optimization of the material stock allowance for turning-grinding process sequence *Int J Adv Manuf Technol* **75** 503–513
- [7] Priarone P C 2016 Quality-conscious optimization of energy consumption in a grinding process applying sustainability indicators *Int J Adv Manuf Technol* **86** 2107–2117
- [8] Radovanovic M and Madic M 2010 Methodology of neural network based modeling of machining processes *International Journal of Modern Manufacturing Technologies* **2** 77-82
- [9] Frumușanu G, Badea N, Afteni C and Epureanu A 2017 Method for energy-efficient planning of the industrial processes, submitted to *Innovative Manufacturing Engineering & Energy Conference (Iași, Romania)*, in review
- [10] <https://en.wikipedia.org/wiki/Classification>, <https://en.wikipedia.org/wiki/Labelling>
- [11] Directive 2010/30/EU on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products