Energy saving in tooling machines: a new unified approach to reduce energy consumption

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ABSTRACT

Tooling machines are included in some EU directives, which set specific targets for the reduction of energy consumption in the near future. This paper aims to introduce a design approach that can be useful both for safety functional decomposition and for energy consumption evaluation of a generic tooling machines. This design approach tries to unify the existing divergent approach to energy efficient and safe tooling machines.
A very simple application, already installed in some lathe machines currently produced in the EU, will give us all the necessary data (activity time counter) to perform a quantitative assessment in term of unified energy-efficient and safe machines.
Moreover, the main results of an extensive survey made by a lathe manufacturer on real machines utilization and some measurement of wasted energy during standby mode of different machines will be presented. Those measurements show that it is not possible to define a proper LCA design method without considering that the wasted energy is a function of the size and type of processes and the specific operating conditions of the machine.
Measurements, performed during stand-by of lathes with regenerative drives, are presented at the end of the paper.

KEYWORDS

Tooling machine design, energy saving, machine safety, LCA design

INTRODUCTION

In recent years the European Community has enacted a series of directives and regulations trying to limit the waste of electricity both within domestic and industrial environments. Directive 2005/32/EC [1] deals with the definition of eco-design requirements of products. This Directive titled Energy Using Products (EuP), was enacted in August 2007 and covers many product categories. Moreover, the Directive 2012/27/EU on energy saving in a wide range of products lays down the guidelines for specific targets aimed at the reduction of consumption and improved environmental characteristics of products from now to 2020 [2]. This last Directive was enacted on December 4th, 2012, and the first quantitative goals to be obtained for energy consumption reduction were set to be obtained in 2014.

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Some machine specific standards for the eco-friendly and energy-efficient design of tooling machines will be developed. Many energy-related products are mostly designed and produced by small and medium size enterprises (SMEs). However SMEs often lack resources for the assessment of the technological and commercial potential of their products and have had, so far, a scarce attention to the energy consumption of their machines [3].
The efficient use of energy from the standardization point of view has been addressed more than twenty years ago [4]. The problem of designing and constructing energy efficient machines has so far been mainly addressed at a regulatory level, by a Life Cycle Assessment approach (LCA) in ISO 14040 [5] and ISO/TR 14062 [6].

Current regulatory works

Because of the new EU directives, first mandatory measures by EC are expected at the end of this year [7] and some different approaches to improve tooling machine efficiency are still under evaluation. In addition, two different studies were sponsored by the European Commission, such as the one whose final report was issued by the Fraunhofer Institute in August 2012 [8].
CECIMO (the European Association of the Machine Tool Industries) promoted first a SRI (Self-Regulatory Initiative) and is trying to finalise a SRM (Self-Regulatory Measures) with the aim to:

1. provide data, definitions and the state of the art on machine tools energy efficiency;
2. promote a “checklist" for the optimal design of efficient machine tools. The machine builders, on the basis of a voluntary agreement with the SRM, will design new machines with this checklist assuring more efficient machines.

Information on CECIMO studies and proposals can be found in [9-11]. The main limitation of the CECIMO voluntary approach is that if at least 80% of the machine builders will not follows the SRMs, the overall effect on the market will be little more than negligible.
Also the International Standardization Organization is focusing on efficiency of tooling machines trying to assess: definitions, design approach and technical rules for evaluation of machine tools energy efficiency.
This standardization work is carried out by Technical Committee ISO/TC 39/SC10 and in particular the WG 12 of the SC is now developing the standards, such as ISO 14955-1 and ISO 14955-2 [12, 13]. Those standards will provide the principles and framework for the design of energy efficient machine tools. Other sections such as the 3-4-5 and over, still in a very rough Initial stage, will state the rules for specific categories of machines. As an example part 5 will define the rules for woodworking machines.
Such standards did not exist before and an early understanding of its impact is very important for engineers and researchers. Therefore, the energy efficiency of machine tools, which has been considered less important than energy saving in process industry, will soon become a major issue in manufacturing industry.
In this paper, we will refer to these upcoming standards generally by using the acronym ISO/DIS. Considering the already mentioned Directives and the new ISO/DIS, it is therefore necessary to develop a new design approach for energy efficient machine tools that can be effectively used by SMEs producing machine tools.
In public and private research facilities many of the efforts made over the years were focused on optimization and reduction of machine energy waste in the machining stage, without considering or underestimating the energy saving policies during the standby mode. The new standards will include every operation mode of the machine, including stand-by, and will represent a revolution on the way energy consumption is considered in the manufacturing. Even though the energy consumption in stand-by mode may seem negligible in comparison with energy consumption during cutting and moving, new machine safety standards have

introduced and are introducing more and more systems which require energy even when the machine is in idle state. This has increased the energy consumption significantly and this must be addressed carefully when the new ISO/DIS standard will be enforced.

The literature about energy saving in machine tools has always been scarce and the focus of the majority of energy saving papers in the scientific literature was about process integration and the reduction of heating. Very few studies have focused on energy saving in machine tools considering the overall machining cycles.

There are many different approaches to estimate energy consumption of industries and especially of machine tools for different materials, machining configuration and tools which can be found in published literature [14,15]. As meaningful examples, G. Campatelli et al. [16], showed an optimization through response surface methods, Jihong Yan and Lin Li [17] addressed multi objective optimization.

Some researchers have focused on finding analytical models based on kinematic and dynamic behaviour of the machine during the cutting phase, in order to relate the machining parameters to energy consumption [18]. The reduction of energy consumption through the optimization of the cutting conditions, spindle acceleration control and synchronization of the movements, is treated by Mori et al. [19]. A tool-oriented approach, comprising a logical and mathematical model, has been proposed by Balogun and Mativenga [20].

A more general view, taking into account the machine as a complex system, can be found in Dietmair and Verl [21], Kalpakjian and Schmid [22] and Avram and Xirouchakis [23]. A consumption estimation based approach is presented by Li and Kara [24], where a used phase focused approach can be found.

In particular, the last paper also takes into account the energy required by auxiliaries in a turning process, this article proposes a method to predict the total consumption under various cutting conditions.

Direct estimation of electrical consumption can be found, for example, in Gutowsky et al. [25] and an automatic technique of energy consumption monitoring is presented by Dornfeld [26]. In this last article and in Hu et al. [27], the authors also focused on the problem of monitoring energy consumptions during the various operations carried out by a tooling machine. The monitoring conditions are more considered in recent articles as in [28, 29].

All those works have given the tooling machine manufacturing industry the possibility of achieving remarkable goals of energy efficiency during the machining stage. But it is necessary to state that, also in very recent work, energy consumption during the machine standby mode has been totally underestimated or entirely ignored again as in Albertelli et al. [30].

In the last five years, more work based on energy saving methodology in manufacturing can be found and some new process-based approaches can be found, as in Borgia et al. [31] and Newman et al. [32].

Duflou et al. [33] try to take into account the entire life cycle of the machine tool: from design to dismantling, including the machining phase, as well as considering interaction with the environment where it is installed.

It can be stated that in the tooling machines designed in the last three years, the requirements for energy efficient and safe tooling machines were connected due to a totally new state of the art of newly introduced standards.

To reach a conformity to the new safety worldwide standard, for example for a proper Performance Level assessment [34-35], many new energy consuming devices and redundant systems have been provided. The requirement of reduction of energy consumption is often antithetical to safety requirements: for example, the designer needs a full time-redundant control of main axis movement/stop condition even when the machine is not in machining state (stand-by).

Moreover, many safety controls are often designed and integrated at the drive component level so these components cannot be switched off even if absolute rotational/translational encoders are used in the machine.
On the contrary there are still only a few studies on energy consumption when the tooling machine is on in a stop condition but fully operative (called sometime operational standby or ready to operation). From a safety point of view we can refer to category 2 safe stop with monitoring of IEC 60204-1:2009 [36]. Moreover, all the measurements made on machine on the market earlier than 2010 do not consider all the new safety devices and redundant systems because only a few of them had been installed on tooling machines.
The problem of power consumption of a machine, tool taking into account the standby mode is addressed by, Wang et al. [37], Yoon et al. [38]. Quite old data of energy distribution of the various components can be found in Kordonowy, [39] and in Dahmus and Gutowski, [40].
A short but very interesting work is the one by Li, W. and al, [41], solely focused on fixed energy consumption of six different machine tools.
A rough idea of the wasted energy due to the operative standby of a tooling machine with respect to overall energy use can be obtained, as an example, using a commercial tool implemented online by DMG/Moiri Seiki manufacturer [42].
Taking as an example their machining centres like CTX beta 800, one can observe that machine standstill energy utilization without any energy controller is 6.300 kWh, the energy required for machining is 10.800 kWh (less than double). In the same online tool it also possible to notice the considerable energy consumption difference (ratio 1.63) for the same machine under operational standby, safety category 2 safe stop of IEC 60204-1:2006 or category 0 safety standby (all the drives are off, called simply standby on [43]).
Moreover, any algorithm/methodology based only on economic or wasted energy optimization of a given cycle will not be useful in reality for safety reasons (e.g. unconditional switch of a device off after some time). Therefore, new methodologies have to be developed and this paper aims at suggesting some new directions.
In our opinion a new design approach for environmental evaluation of a machine should be based on the following requirements:
R_1: It shall be in full compliance with the principles of the new directives and forthcoming standards,
R_2: It shall be fully implementable in the typical design process of a tooling machine in order to take into account simultaneously the other applicable standards (for example safety requirements).
If these two requirement are missing, we will have very intelligent theoretical methodology which can be partially (or not at all) usable in environmental optimization of industrial products. As it is discussed in this paper, the possibility of unifying the vision of energy savings with that relating to the safety standards must be evaluated (*Unified Design Approach*).
Also the definition of life cycle and system boundaries of the machine must be considered in an unified way to fulfil R_1. This aspect will be covered in the next paragraphs.
As an example of the methodology the whole range of products by an EU Numerical Control (NC) lathe machine builder will be analysed in this paper. Those machines, at the current state, have all the new standard safety devices installed but no energy savings approach or measuring devices on them. A wide report of utilization data of different NC lathe machines of the builder, based on currently customer installed tooling machines, will be also presented in the paper. In the final section of the paper some energy consumption measurements for lathes with new regenerative drives will be shown.

ENVIRONMENTAL EVALUATION OF A TOOLING MACHINE THROUGH FUNCTIONAL DECOMPOSITION

The design approach of ISO/DIS for the energy impact description of a general tooling machine is used as guideline for the new design approach (see R_1). Some concepts or definitions of "safe design" of machines must be added [34], if the R_2 requirement has to be achieved.
The ISO/DIS approach tries to generalise the energy consumption evaluation through a functional based decomposition, the main phases of them will be described through the diagram presented on the left side of figure 1 for a clearer and shorter exposure.
During the next paragraph, starting from design methodology proposed in the ISO/DIS all the key steps of the unified proposed approach will be analysed and the difference with the ISO/DIS standardized will be shown.

Definitions and machine life cycle

Some of the fundamental definitions of the upcoming ISO/DIS are wholly included on the already existing definitions on the already mentioned safety standards as ISO 12100: the concept of a safe and efficient design seems to be achievable.
The ISO/DIS standard environmental evaluation starts from a fundamental hypothesis: the main environmental impact during the whole life cycle of a machine tool is during the use phase (in the article, we will refer to this very strong hypothesis as **HYP_1**).
Paragraph 4 of the ISO [6] states that, for a complete LCA approach, all the different stages of the product life-cycle should be investigated. However, for a typical usage profile of a tooling machine, the largest contribution to environmental impact is during the use stage, as described in the examples described in [6].
If a theoretical comparison between the two standards is done, the *life cycle* ISO/DIS definition fully encloses in the safety standard ISO 12100. The relevant factors for the two design aspects could be analysed with the wider definition of the ISO/DIS. The life cycle definition for the ISO/DIS can be found on point 3.5, and it comprises the following steps: raw material acquisition, production, distribution, use, disposal.
Moreover if the machine “intended use” definition of ISO 12100 standard is utilized, some very meaningful information also for the environmental evaluation of a machine also can be found. For example, if the “safe” definition of reasonably foreseeable misuse is considered as in paragraph 5.5 of [7], useful knowledge can also be found for a possible foreseeable energy misuse due to deficient design implementation. For example the inability, in some types of machines, of electrically sectioning auxiliaries, independently by NC, does not allow the implementation of some effective strategies to reduce consumption of the machine in standby mode. Again the unified requirements for safety and efficiency, according to the writers, can only be treated from the early stages of design.
The basic ISO/DIS assumption for machine utilization is: eight hours a day, 5 days a week, which is the most usual for machines utilized in industrial production.
Then, the system boundaries for environmental evaluation are specified in the ISO/DIS as shown in figure 3 of part 1 of the standard.
The system boundaries for safety evaluation standards is wider than the environmental one because many more different aspects should be taken into account, such as necessary timed input new tools, new lubricant, chips removal,… Those maintenance operations are very difficult to be included in “standardized cycles”, as it is requested in part 2 of the ISO/DIS (the so called shift regimes). From a unified design approach, the wider system should be evaluated and the environmental evaluation of this wider system has to be done both to estimate possible relevant energy consumption and safety related hazards.

Without entering into details, only using this wider safety system boundary, the designers can take into full consideration all the environmental aspects of utilization phase. This will show not only the energy consumption aspect but also environmental problems, i.e. problems due to wasted materials and safety of operators during working hours.
The ISO/DIS approach tries to generalise the energy consumption evaluation through some main steps shown in the diagram presented in figure 1 left for a clearer and shorter exposure.

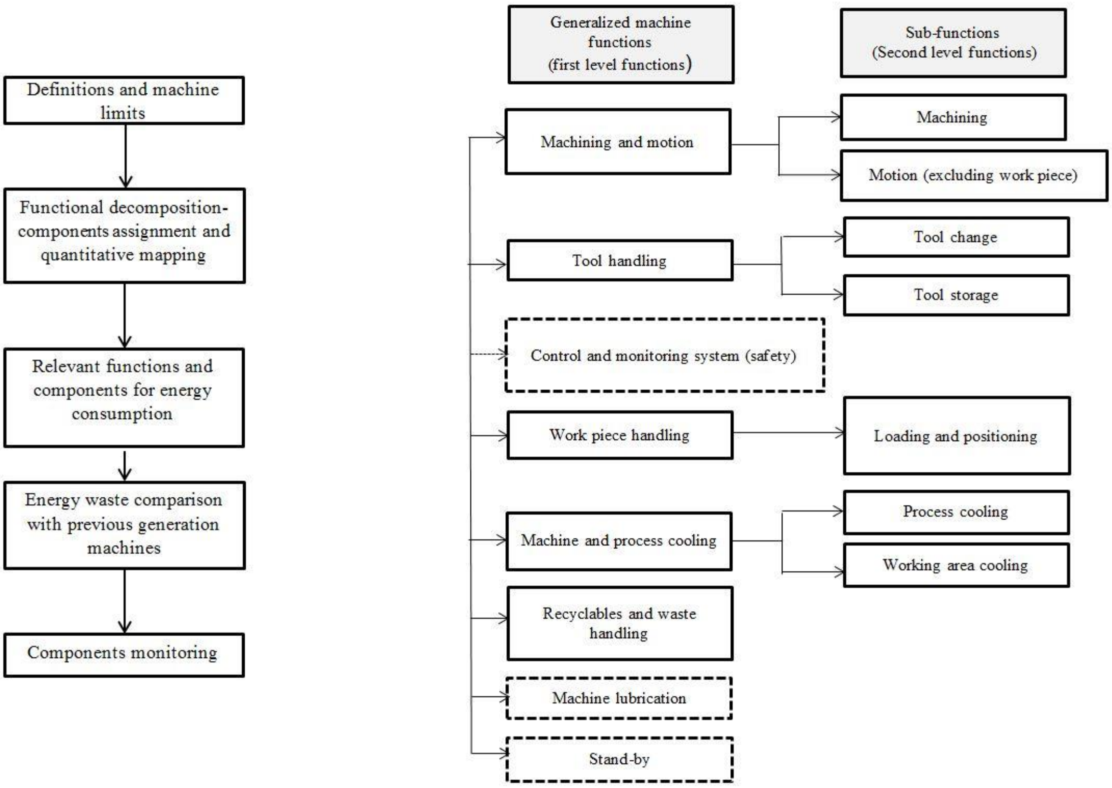

Figure 1. left - main steps of the approach used in this paper, right - first and second level functions defined for the Unified Design Approach

In the latest revision of the ISO/DIS draft, some new definition have been introduced:
- **modes of operation**: manual, automatic, …, making a direct link with the so called Safety Modes of Operation (SOM) already existing safety standards (type C standards).
- **operating states**: off, standby, warming, ready for operation, machining, these states are usually the ones imposed through machine NC. Energy consumption over the time of operating states is quite simple to measure and usually it is also possible to evaluate the device state (On, Off) of the various components during the operational states (see next paragraph and [13]).

During the next paragraph, starting from design methodology proposed in the ISO/DIS the key steps of the unified proposed approach will be analysed and the difference with the ISO/DIS will be shown starting from step2 in the next paragraph.

Functional decomposition, components assignment and quantitative mapping

The second step for environmental evaluation optimization for the ISO/DIS is to identify the machine tool functions (see definition 3.12 of ISO/DIS), which are useful in recognizing the machine components relevant for energy consumption.
The so called **first level functions** can then be decomposed into **second level functions** and, if wanted, additional ones. For the first level (generalized) functions, the standard identifies

six main functions: *machining* (including machining process, motion and control), *process conditioning and cooling, work piece handling, tool handling or die change, recyclables and waste handling, machine cooling/heating*. See Fig. 1 on the right, continuous line box. On applying the design approach to the production of an EU lathe machines builder, some changes are required be done in order to identify a hierarchy of functions aimed to accomplishing the R_2 of paragraph 2.

In regards to the first level functions of ISO/DIS, three generalized first level functions have been added by the authors. The first one relates to the **control, monitoring and safety system** divided from the general machining function of ISO/DIS. This function is becoming increasingly central in the design phase of any tooling machine in recent years. In particular, the safety components of any machine perform autonomous functions that should not depend on operating states given by NC. Those automatic or time stepped controls can be different from the NC ones in order to meet the requirements of reliability within the control systems related to safety, see ISO 13849-1[44]. In authors' opinion, it is better to underline this disconnection at a functional level. Also deeper new studies and measurements on energy consumption for these safety first level functions are required.

The second added function, **machine lubrication and other auxiliary services**, has been created to highlight some consumption often considered negligible from the viewpoint of the manufacturing process. Design of a tooling machine usually tries to centralize some services (e.g. for lubricating pumps of various guides and motion axes), this sometimes leads to antithetical energy saving strategies that must be carefully evaluated beforehand. This is the case of large size machines, consisting of multiple process units working simultaneously (e.g. multi-spindle machine) where the installation of an inverter technology for lubrication function is not often, still used nowadays. To be honest, when the inverter technology of lubrication component will be widely used a first level function it is not desirable at all.

Particular consideration should be given to what is usually called operating state: **stand-by**. The unified approach to the environmental and safety evaluation of this operational state it is crucial.

According to the authors, the possible inclusion in the first level functions of a standby mode should be evaluated, for the following reasons:

1. from the unified design approach perspective, at present, there are different NC/safety logics of so-called safety STOP. For example the standby with operational units on is also a safe-STOP of Cat. 2 with monitoring, a standby with drives off can be seen as the result of a safety STOP of cat. 0, referring again to IEC 60204-1. Many different safety functions are enabled/disabled with different safety logic during the machine utilization. Moreover, usually a given standby operating state must be assured. This state cannot be chosen, for example, through an energy saver automatic NC.
2. If the standby is defined as a first level function, the importance of the standby in terms of relevant energy waste will be more evident to the designer and the different standby states can be divided, if required, into second level functions. The energy waste due to all the un operational states (no machining) is often a very relevant part of new tooling machine as already exemplified in the introduction.

From the point of view of the machine safety, many of the monitoring components must remain switched on during standby (while some auxiliary components are off). In these conditions a precise measurement of energy wasting is not still available for the next generation of machines.

Finally, in our opinion, including the standby in the machining first level functions is crucial both for safety conformity and for energy waste reduction. If only a second level function has to be created for standby there is no clear distinction in overall energy evaluation between machining and un-operative states.

The second level functions (sometimes called sub-functions) must be established taking into account the relevant functions for the machine under observation: i.e. the second level functions definition greatly depends on the type of machine. According to the authors, second level functions are to be implemented in order to facilitate the subsequent identification of energy consuming components, in order to facilitate the designer in assigning components to various functions, as an example see [33].

Table 1. Ut_{su} for a small series production lathe machine

First level functions (FLF)	*Second level functions (SLF)*	*ut_{su} (ratio)*	*Hours per year (1870 total)*
Machining and motion (MM)	Machining Motion (excl. work piece)	0.50 0.20	935 374
Tool handling (TH)	Tool change Tool storage	0.01 0.01	18.7 18.7
Control and monitoring (safety)		1.0	1870
Work piece handling (WH)	Loading and positioning	0.05	93.5
Mach. and process cooling(MC)	Process cooling Working area cooling	0.41 1.0	766.7 1870
Recyclab. and waste handl. (R)	---	0.51	953.7
Machine lubrication (LUB)	---	0.50	935

Table 2. ut_{su} for a mass production lathe machine

First level functions (FLF)	***Second level functions (SLF)***	***ut_{su} (ratio)***	***Hours per year (1870 total)***
Machining and motion (MM)	Machining Motion (excl. work piece)	0.70 0.10	1309 187
Tool handling (TH)	Tool change Tool storage	0.01 0.01	18.7 18.7
Control and monitoring (safety)		1.0	1870
Work piece handling (WH)	Loading and positioning	0.03	56.1
Mach. and process cooling(MC)	Process cooling Working area cooling	0.41 1.0	766.7 1870
Recyclab. and waste handl. (R)		0.71	1327.7
Machine lubrication (LUB)		0.70	1309

Those assignments are multiple: a single component is often used in more than one function. By way of example in Tables 1, 2 and 3 the average utilization rates of second level functions (ut_{su}) for different lathes are shown. This ratios are estimated from data provided by a design department of a lathe machine manufacturer with thousands of machine already installed worldwide. The calculation of the average utilization ratios (ut_{su}) reported in Tables 1, 2 and 3 was done using the following formula:

$$ut_{su} = h_{y\_sub} \, / \, h_{y\_ON} \qquad (1)$$

where:

h_{y_sub} are the hours per year in a sub function;
h_{y_ON} are the hours per year of electrical circuit ON in all the sub-functions.

The real hours of utilization for the machining and motion second level functions of real machines will be presented in Table 5 of the paper using the data collected by the authors during a campaign of surveys on machines installed by customers. In these tables the second level subdivision of the control and monitoring function was not considered because there were no sufficient historical data for an estimate (no safety device installed). So these safety systems have always been considered switched-on (utilization ratio 1). To facilitate discovery of errors, utilization have been reported in ratios (from 0 to 1), and then in hours. For tables 1 to 3, 1870 hours/year of switching on electrical panel have been considered (170 hours/month for 11 months per year on average, not the same as the ISO/DIS).

Table 3. ut_{su} for a heavy pieces production lathe machine

First level functions (FLF)	***Second level functions (SLF)***	***ut_{su} (ratio)***	***Hours per year (1870 total)***
Machining and motion (MM)	Machining	0.80	1496
	Motion (excl. work piece)	0.10	187
Tool handling (TH)	Tool change	0.01	18.7
	Tool storage	0.01	18.7
Control and monitoring (C&S)		1.0	1870
Work piece handling (WH)	Loading and positioning	0.1	187
Mach. and process cooling(MC)	Process cooling	0.41	766.7
	Working area cooling	1.0	1870
Recyclab. and waste handl. (R)		0.81	1514.7
Machine lubrication (LUB)		0.80	1496

In particular in Table 1 the sub-functions ratios for a NC lathe machine used for a small series production are shown. In Table 2 the same subdivisions for a mass series production lathe are shown and in Table 3, the data for heavy pieces production (large machines with work piece up to 15000 kg). As we can see from the previous tables, the utilization ratios can be very different for different types of production, moreover, some of the functions can be simultaneous. An additional function to components quantitative mapping (*map_co*) has to be done to assure to recover energy consumption. This assignation is very hard to be done, additionally it is very difficult to be assured of quantitative trustable data using only the proposed ISO/DIS methodology which is, in our opinion, is oversimplified.
Without entering in full details in Table 4, a realistic components - functions quantitative mapping ratios (map_{co}) of some of the main components of the lathe of Table 3 are shown. The definition map_{co} is equivalent to the one in (1) used for utilization factors of second level functions.
These data are based on scheduled time tests of the same lathe builder. At the actual state of the tooling machines it is not possible to retrieve that information from the NC, even if it is responsible for the time switching of the components. This lack of knowledge is the state of the art it is one of the main limitations to a proper energy consumption decomposition.
It is also necessary to define a working coefficient ($coef_{ut}$) for some component for every given function in order to find the real switched-on hours of some components without affecting the simple data control of table 4 (this coefficient is missing in ISO/DIS).

In fact, there are some special cases:

1. different components can perform the same primary or secondary function (such as power-driven tool and standard passive tool for piece machining),
2. components working intermittently (for example some lubrication pumps operate 10 seconds every 7 minutes while the lubrication first level function is always active in the machine).

The dashed rectangle in Table 4 represents the special cases for this tooling machine.
Since the sum of ratios of utilization is 1.0, referring to the first example, $coef_{ut}$ will be 0.70 for machining with standard tool, and 0.30 for power-driven tool. If this $coef_{ut}$ is not used it could be possible that the resulting component mapping table is very difficult to check.
For the second example the pump is used for lubrication slides but it is switched on only 10 seconds every 7 minutes. In this particular case, the value $coef_{ut}$ to insert in the ratio of utilization table is 0.024 in order to take into account the intermittent operation of the pump controlled by NC.
At the end the hours of operation per year of the various components are:

$$util\,comp_{hours/year} = \sum_{i}^{subfunctions} h_{y\_ON} \times ut_{su} \times map_{co} \times coef_{ut} \qquad (2)$$

where:

$util\,comp_{hours/years}$ are the global annual power on hours of a single component
h_{y_ON} already defined in equation (1);
ut_{su} are the ratio of use of single sub function (Tables 1, 2 and 3);
map_{co} are the ratio of components mapping of Table 4;
$coef_{ut}$ are any other ratio of utilization necessary at component/second level functions.
It is simple to calculate the *electricity consumed (*e.g. Wh) for each component by multiplying (2) with $cons\_comp_{hour}$ that is an average consumption, in terms of power, such as W) estimated for the individual component for an hour of use.
Component consumptions for a single sub function will be measured with methodologies as in [13] using different *shift regimes*. From all the tables and examples given before, it is now clear that a “good” definition of some shift regimes will be the “central task” to be done for environmental evaluation of machines (upcoming part 3-4-5-…)..
According to the authors, not considering separately the standby as a first level function, causes optimization methodologies where the energy consumed during the standby of today machines [44] could be “concealed” or underweighted into standardized shift regimes. As final result the designer will fail on identification of both safety hazard and energy waste of un-operational states.
The validation of tables 1, 2 and 3 for lathe machines, is performed through a wide survey of already installed NC lathe machines in different SMEs. To have coherent long term data, the authors collected the data mainly from two “hour counters” in already installed lathe machines:
Counter 1- mechanical: installed on the main electrical unit of all machines; it is possible to check how long the main electric circuit is switched on from the machine installation in the customer facility. This number of hours can be used to check the 1870 hour/year hypothesis and for a better evaluation of h_{y_on} in equation (1).
Counter 2 - digital: installed on the NC for maintenance, it is possible to measurement and save the hours of main spindle rotation, which is assumed as a acceptable measure of real machining time and work piece handling for lathes.
Using these data is possible to define an overall machining ratio of a machine.

Table 4. Abstract of components functional mapping in ratio, heavy pieces production lathe.

First LF	***MM***		***TH***		***C&S***	***WH***	***LUB.***
Second LF	**Machining**	**Motion**	**Tool change**	**Tool storage**	**-----**	**Loading and position.**	**---**
Components							
Z axis motor	0.99	0.01					
Spindle motor	0.98	0.01				0.01	
X axis motor	0.99	0.01					
Drives	0.98	0.01				0.01	
Indexing turret		0.05	0.95				
Turret		0.05	0.95				
Tool storage		0.05		0.95			
Powered tools	0.97	0.01	0.01	0.01			
Hydraulic spindle						1.00	
NC unit (PLC)					1.00		
Encoders					1.00		
Hand wheels	0.05	0.80	0.05			0.1	
Head oil pump							1.00
Lubrication pump							1.00
Hydraulic sys.		0.1				0.90	
Powered rest		0.1				0.90	

This ratio is also effected by machine setting times, usually negligible:

$$over\_uti_{life} = h_{spi\_rot} / h_{es\_ON} \quad (3)$$

where:
h_{spi_rot} are the hours of spindle rotation from counter 2;
h_{es_ON} are the hours of electrical switch ON from counter 1.

The previous hypothesis of 1870 hours/year of electrical panel switch on is valid (with an approximation of max 10%) except for Type III, on the fifth row of the Table 5, where a better 2805 hours/year value has to be used.

Table 5. Working hours, survey 2012, lathe manufacturer.

Lathe model max. chuck diameter (mm) × bed length (mm)	*Spindle power (kW)*	*Year of built*	*Years consid.*	*Spindle running (h)*	*over_uti$_{life}$ eq. (3)*	*Customer*	*Type of prod.*
Type I 260×2000	12.5	1997	14.0	6631	0.25	N1	small series
Type I 350×3000	12.5	1999	12.0	10745	0.48	N2	small series
Type II 350×2000	18	1998	13.0	8548	0.35	N3	small series
Type II 350×2000	18	2005	6.5	8913	0.73	N4	mass prod.
	18	NC subst. in 2009	3.0	3772	0.67	N4	mass prod.
Type III 650×4000	39	2007	5.0	8843	0.63 (2805 h/year)	N5	heavy piece
Type II 300×2000	18	2002	10.0	4628	0.25	N5	small series

The over_uti$_{life}$ data shows a very clear dependence on:

EV_1. *type of machine* even if the same type of production is used. Probably because of bigger machines are more utilized for longer cycle times (i.e. bigger pieces to be produced),

EV_2. *type of production* even if the same size of machine is used, probably because mass production machines need shorter setup times,

EV_3. *customer, year, facility location, etc.* customers N3 and N5 has two very similar machine and equal type of production but the utilization is different.

It is important to consider that the survey was conducted by a SME lathe manufacturer in the market since sixty years. The results are valid for a considerable part of machine tools builders if the evidences of the COD *2013/0232* are accepted [3].

Taking into account all the three evidences (EV_x) it is possible to conclude that an effective identification of energy consuming components and energy waste in the design phase in the manufacturer facility is difficult to achieve. The identification of real energy savings must be calibrated to the specific customer needs, to the real machine use and to field measurements.

Relevant facts for components energy consumption in real machines

From surveys, like those in Table 5, it is possible to assert that the typical machine utilization scenarios, based on typical operating states and/or machine activities, differ significantly from a customer to another. So is very difficult to define and use properly a default shift regime for a generic NC machine, as specified on [12,13]. The authors identified a possible way to base a unified methodology for unified safety design and an screening of hypothetical energy consumption during design stages.
By looking at definitions within type C safety standards, for example: the lathe safety standard [3] is possible to consider size, operating states and SOM in a coherent methodology.

Table 6. Lathes harmonized standards subdivision in groups and sizes, from ISO 23125

Group subdivision	*Group name*	*Size subdivision*
Group 1	Manually controlled turning machine without numerical control	Small or large
Group 2	Manually controlled turning machines with limited numerically controlled capability	Small or large
Group 3	Numerically controlled turning machines and turning centres	Small or large
Group 4	Single or multi-spindle automatic turning machines	No size subdivisions

This latter standard contains tables defining lathes groups with two different sizes each as shown in Tables 6.
Every different lathe group has:

- different operating states permitted or not allowed depending from the group,
- different machining capabilities (different and more complex machines from group 1 to 4).

For a complete table of the possible operational SOM related to lathe groups see [35].

According to evidence EV_1, we have possible "measures" to define a size based classification of energy consumptions as clearly emerges from surveys of table 5. Size is technically defined on lathe safety standard through a maximum diameter of the clamping device and maximum distance between tip and tailstock. This reasoning can be extended to any type of tooling machine, considering the proper type C safety standard.
The required ISO/DIS identification of energy consumptions through components must take into account the fact that the complexity of a given machine and its possible operating modes are already regulated in a type C harmonized safety standard. Many of energy related requirements are in safety standards: some theoretical studies based on efficiency at very high travel velocity of axes cannot be applied because unsafe condition will be reached.

The design of efficient and safe machines problem become a single optimization constraint challenge for the single client oriented lathe machine..

MONITORING: STAND-BY ELECTRICAL MEASUREMENTS

Energy consumptions detection during standby, especially for new machines on the market, is required to validate some of the major hypothesis of the article, the energy wasted during the non-operative phases can be very high. As an example some measurements performed on new lathe machines are presented.
A portable analyser, HT PQA824 [46], has been utilized by the authors to expose electrical quantities of lathes during some standby operational modes. The instrumentation was connected, using a typical three phases connection system, as shown on figure 2 together with so the full electro-mechanic representation of spindle axis of a lathe.
The analyser is able to perform and record many different electrical measurements up to 10 milliseconds resolution, the meaningful ones will be presented in the following figures and tables.

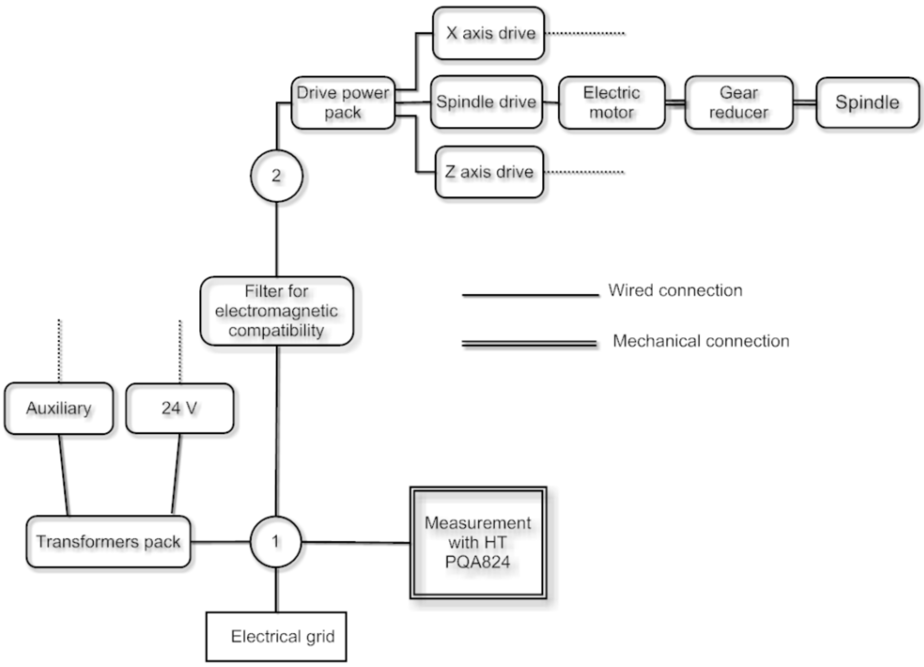

Figure 2. Portable analyser connection to the electric system of the machine

The measurements made on a high energy consuming lathe model is presented on Table 7 as an example. The measurements are related to heavy duty, group 3 large size with 57 kW spindle motor power and regenerative drives of new generation. This machine is able to carry a work piece up to a mass of 15000 kg. The spindle motor has been maintained steadily during all the measurements.
The first column of Table 7 contains active components during measurements. Moreover some specific components measurements are presented in the table. It is clear that for these specific measurements the analyser is connected to other points of the electric system of the machine: e.g. during the regenerative measurements the analyser is connected at point 2 on figure 2. Machine power consumption after switching the emergency button, is shown in the last row. In the latter situation only the auxiliaries were active and measurement of this system changed from three-phase 380 V to single phase 220 V without neutral conductor.

Additionally one can note also that the spindle fan has considerable waste of energy: the power factor (0.58) of this commercial fan is very low.
From these results it appears:

EV_1. Stand-by energy consumption are not negligible at all for an energy evaluation of the current tooling machines, especially those machines with a low utilization rate (see again Table 5).

EV_2. The so called *Auxiliary Services* of current machines are also critical for energy waste (see hydraulics, fans,…), also the power factor of those components is often critical (see energy waste of the hydraulic power system on the table).

Table 7. Stand-by energy measurements for a large size lathe, heavy pieces production, with regenerative drives.

Components Energy supply state	Operat. State	Data: Phase 1 (A)	Phase 2 (A)	Phase 3 (A)	Phase-phase Voltage (V)	Active Power (kW)	Reactive Power (kvar)	Apparent Power (kVA)	Power factor cos(φ)
Axis Torque ON, hydraulic system ON, 24V auxiliary power supply ON, powered turret drive ON, regenerative drives ON, spindle fan ON	Operat. stand-by	8.6	8	9.7	225	5.32	2.78	6	0.89
Spindle fan	Operat. stand-by	3	3.2	3	224.1	1	1.9	2.1	0.58
Hydraulic power system	Operat. stand-by	7.8	7.7	7.8	224.5	4	3.3	5.2	0.8
Only regenerative drives	Operat. stand-by	3.3	3.8	3.4		0.267	1.23	1.3	0.21
			Mono phase (A)						
Only auxiliaries 220V ON	emergency STOP		1.9		111	0.17	0.127	0.22	0.8

ENERGY WASTE COMPARISON WITH PREVIOUS GENERATION MACHINES: MEASUREMENTS OF REGENERATIVE DRIVES

The draft ISO/DIS allows comparison between machines of different generations through:

- Comparison of states of the art (e.g. qualitative/quantitative comparison based on Annex A and B tables).
- Comparison with previous generation of machine tool of similar functionality (performance, productivity, accuracy).
- Monitoring of results, including parameters covering higher productivity, higher accuracy, higher functionality of new generation machine tools.

In particular, according to the authors, the comparison with annex A and B tables of the standard is debatable. Using those annexes, a designer could have an idea of the energy savings with the introduction of alternative technologies versus the ones currently used. According to the authors, this approach is too coarse. It could lead to inaccurate assessments or even to misleading results especially for complex machine with multiple modes of operations.
To prove this possible lack of consistency on the proposed approach of ISO/DIS standards, some measurement of real regenerative capabilities of tooling machines are presented as an example. The introduction of this type of drivers in new machine is strongly supported in the annexes of the ISO/DIS.
According to the authors, at least three main factors have to be take into account for a correct evaluation, if a truly LCA approach has to be used :

1. quantity of energy recovery from last generation regenerative drives for a single brake.
2. energy consumption of a regenerative axis drive over time is compared to an old drive made mainly by passive components.
3. higher cost of a regenerative drive in compared with the old one.

Measurements on regenerative drives of the lathe on table 7 are presented. The latter was subjected to a series of test consisting of an acceleration ramp, followed by a deceleration one, interspersed with few seconds at constant spindle rotation speed, equal to 500 rpm. Various data are extracted from axis drive, with 2 and 4 milliseconds sampling times. These data are motor rotation speed, active power supplied from drive and torque from electric motor.
Motor and spindle axis moments of inertia, expressed in kgm^2, are calculated to derive a share of actually regenerated energy during engine braking, through the formula:

$$I_{tot} = T_{mot}/\dot{\omega} \quad (4)$$

where:
T_{mot}, in Nm, is the motor torque net of losses which are estimated with additional operating tests without piece;
$\dot{\omega}$ is the engine acceleration, in rad/s^2.

The I_{tot} value is verified by the sum of moments of inertia of lathe main spindle transmission components, taking into account the gear reducer reduction ratio $\tau = 4.13$ (see again figure 2).
Power measured during the test is shown in Fig. 3, abscissa shows the time in seconds, ordinate the power, expressed in W. Dotted line indicates the zero power level, it takes negative value below this line, this means energy is provided to the network (power regeneration during brakes). This phase is highlighted by the ellipse in the same Fig. 3.
By integrating the power with respect to time yields the energy E_{power_reg}:

$$E_{power\_reg} = \int_{t1}^{t2} Power\ dt \quad (5)$$

Energy theoretically available for regeneration is obtained by knowing the inertia and piece initial rotational speed:

$$E_{theo\_reg} = \frac{1}{2} \times I_p \times \omega_{max}^2 \quad (6)$$

where:
I_p is the moment of inertia calculated as the sum of I_{tot} and work piece inertia;

ω_{max} is the spindle maximum rotation speed, in rad/s,
E_{theo_reg} is the energy of the system before the braking,
E_{power_reg}, provides the real measured regenerated energy.
From all our measurements the E_{power_reg} is around a maximum of 30% of the total energy available. The measurements are made using data available from the digital oscilloscope currently installed into the drives without introducing any other analyser or device.
Moreover, the quality of regenerated energy is also important, measurements of reactive power and current/voltage harmonic distortion can be are made, using the same portable analyser connected on point 2 on figure 2.
As a measure of the quality of regenerated energy, the Total Harmonic Distortion (THD%) up to the order 40 of current and voltage is calculated from measurements. THD% is an index used to detect the presence of harmonics, the voltage measure (THDV%) is defined in the standard EN 50160 [47].

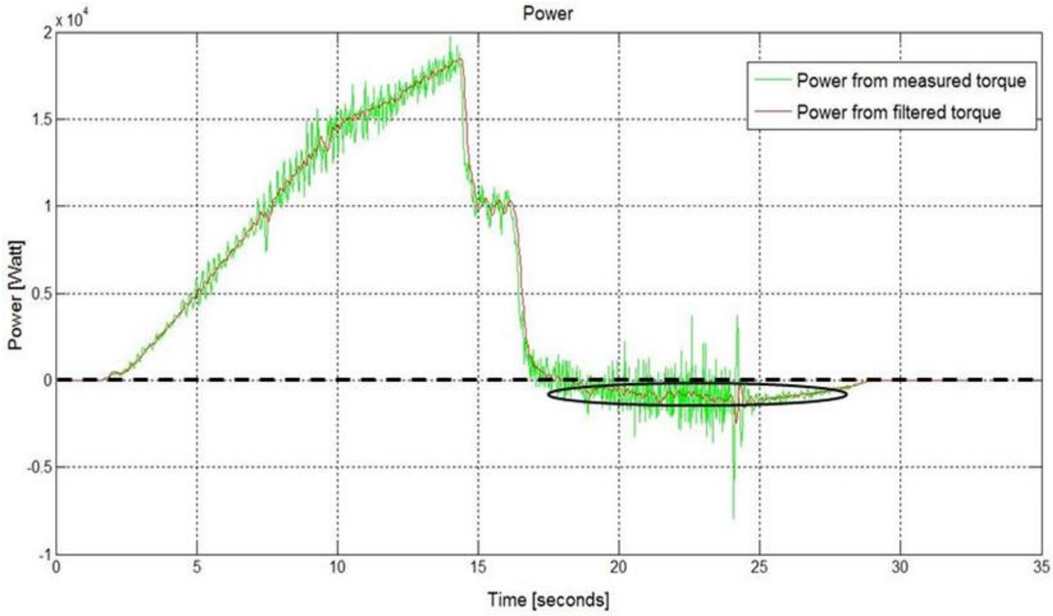

Figure 3. Measured power during tests, regenerated power into the ellipse.

The usually acceptable limit of 8% is often exceeded during the test . In particular, THDV% reaches its maximum value of to 58%, at the beginning of regenerative brake.
So, also due to this high harmonic distortion, a low pass filter must be added in the electrical circuit to prevent the emission from the machine of high distorted regenerated energy. The final maximum regenerated energy at point 1 of the electric circuit in figure 2 will be in the order of 20% of the total energy available because of this filter (measurements are omitted for brevity).
According to these exposed measurements, regenerative drive can lead to real energy savings only for a high ratio of utilization machines with frequent acceleration/deceleration ramps. It must be remembered that regenerative drives have active components and so they waste energy even when they are in any standby mode. Non-regenerative drives instead, are consistently and essentially of passive components. In addition, they have higher cost of purchase when compared to equivalent older ones. So they do not waste energy during the standby.
At the end, according to authors measurements, the quantitative validity of simple approaches as the one of annexes A and B cannot be assumed as a general result.

CONCLUSIONS

In the near future, tooling machines will have their own environmental LCA labelling, based on new directives and related standards under development. The energy optimization of a tooling machine, referring to the ISO/DIS standards, should be reported in terms of a qualified environmental claim: evaluation measurements shall be implemented to achieve reliable and reproducible results.
Through the article it has been shown that the hypothesis of environmental savings by using a typical functional decomposition of the machine only during the design stage can lead to theoretical, but not measurable, energy savings.
In the last five years, many new safety devices and safety operational requirements were implemented into the NC machines, and more design changes are expected for minimum performance level assessment of safety functions. The resulting new “safe tooling machines” have redundant systems and devices. From the “safety view” these cannot be switched off even in the stand-by modes.
The relevance of those “not operative” states on energy consumption are especially investigated in the article through measurement of last generation lathes of a manufacturer.
Moreover, considering the full intended use of a tooling machine and if only a functional or device based optimization approach is used, undesired results can be caused. As an example an optimized energy consumption based on timed removal of energy to drives may cause a non-conformity of the machine to safety standards.
The following point out some of the emerging evidence from surveys, measurements and some already implemented long term time counters on tooling machines:

- some of the so called “operating standby” and safety modes of new machines are very relevant from an energy consumption point of view. Conforming the ready to operate, emergency stop and un-operative standby into standardized working cycles and functions can cause relevant confusion/errors relevant to energy consumption estimates. Considering safety, standby and, ever, lubrication as energy first level functions will cause a direct and visible measure of energy saving during the design of next generation tooling machines,
- utilization ratios and types of production are relevant for energy consumption and time varying ratios are shown through the survey summarized on table 5. Rapidly and fully reconfigurable energy saving paradigms are welcome. These new energy saver applications must be carried on the machine NC and also all the safe constraints of the machine could be assured from different safety PLC. Moreover trying to divide dividing functional machining operation into several second level functional SOMs (e.g. automatic, manual, setup, maintenance) will cause a unifying approach. Finally, safety constraints (for example safety limited speed of axes for a given SOM) and energy savings optimization should be considered at the same design stage. Measurements for safety and environmental evaluation can be also unified on a single application using mainly devices that are already present on tooling machines. Currently those possibilities are underutilized and other expensive devices are often installed to provide if not equal, similar capabilities.
- the environmental claim using tables of predictable energy savings is also debatable. As an example, the energy saving measurements of a regenerative drive for a heavy duty lathe is presented in the paper. As a result of the measurements, the energy saving due to regenerative drive is demonstrable only for machines with high utilization ratios with many acceleration/deceleration ramps.

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