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Development and Application of an Eco-design Tool for Machine Tools

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Abstract

Improving the energy efficiency of machine tools is one of the challenges regarding the European energy saving goals. This work presents a new tool, enabling an effective quantification of a machine tool's (MT) energy consumption during all life phases. Scope of the presented tool is the fast and efficient estimation of a MT's cumulated energy demand and the systematic derivation of improvement measures regarding ecological performance. This work will present a framework, as well as the required calculations for this task. Using model and rule-based procedures, only a minimal set of input parameters is required to identify the hot-spots regarding energy consumption and improvement potential. Applications of this tool as well as a systematic approach to derive measures to increase the energy efficiency based on the output of the tool are presented on practice-oriented examples from industry.

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Keywords: machine tools; life-cycle assessment; energy efficiency

1. Introduction

Modern machine tools (MTs) are complex mechatronic systems with high demands on productivity and quality. The substantial number of MTs produced in Europe is reflected by the annual turnover of 22.5 billion € in 2012 generated by the MT industry [1]. These MTs reach from single machines to series products and show heterogeneity in implementation as well as in operation. During their operation MTs generally require substantially more energy and resources then during their construction. Hence, MTs are active products [2, 3] and have to follow the eco-design measures by the directive 2009/125/EC [4]. MT manufacturers are now challenged to establish a continuous energy and resource efficiency improvement in their product developments, as encouraged by the branch organization CECIMO for the purpose of self-regulation [5].

During the development of a new product, the degree of influence on the final product is reduced in each new development stage, while the information available about the final product is increased. The continuous improvement process of a MT is challenged by this opposed developments of information and degree of influence on the final product, as well as by customer-specific engineering. Customer specific engineering increases the diversity and thus limits the applicability of rule-based improvements procedures. Since the time effort for custom specific engineering is limited by cost factors, the question is how to identify and address the relevant ecological improvement potentials in a time efficient way. This work presents a new approach to evaluate the ecological performance of MTs in the design phase, in order to address the issue outlined above. The scope is thereby the required framework layout, implementation and application of the resulting eco-design tool for MTs.

2. State of the Art

Eco-design describes the consideration of the ecological performance during the product development [6], whereas the ecological performance refers to the interference of the products with the environment [7]. To quantify the ecological performance of a MT, two methodologies are required: Firstly, a methodology to acquire the relevant mass and energy flows, and secondly a methodology to aggregate the

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collected data and quantify the ecological performance. Metrological approaches to quantify mass and energy flows on MT are presented by Gontarz et.al. in [8] and Verl et.al. in [9]. ISO 14955 [10] generalizes this procedure into a measurement methodology. ISO 14955 further establishes the system boundary required for energetic MT evaluations as shown in figure 1.

To aggregate the collected data, carrying out a life cycle assessment (LCA) is a well-established method. The general procedure is given by the ISO standard 14040 [11]. The realization of a MT LCA is shown by Narita et.al. in [12]. In general such a LCA provides a detailed insight into the ecological performance of a product at the expense of a significant time-demand required for measurements and other data extraction. Another approach to quantify the product specific ecological performance is given by the cumulative energy demand (CED) as described in the VDI standard 4600 [13]. The CED is the sum of all energy and resource consumptions mapped to the required primary energy demand. The VDI standard 4600 [13], as well as other sources – e.g. Bey [14] – provide the required specific energy equivalents for this procedure. The CED can be calculated for each product life phase separately, leading to the life phase specific primary energy demand (LPED). In [3], the CED is used to quantify the ecological improvement potential of the MT industry.

Data acquisition for mass and energy flows on MTs is state of the art. Regarding the aggregation of this data, LCA and CED, are both established approaches, but a general procedure to apply LCA or CED on a MT in the development phase is lacking – especially in industry. However, the capabilities of a CED regarding the identification and estimation of ecological improvement potential of MT are proven. It is further assumed, that the CED specific effort complies better with the time available during the MT development, than the one of a LCA. This work therefore focuses on a generalized CED procedure for MTs embedded in a framework to support the development of ecological MTs.

3. Empirical basis

This work bases on mass and energy flow measurements on 35 different MTs performed by inspire AG and the institute of machine tools and manufacturing (IWF) within multiple industry projects. Among others, these measurements have contributed to the eco-design potential analysis by the Swiss association of mechanical and electrical engineering industries (Swissmem) [3], the ISO standard 14955-1 [10] and the training program of the Swiss federation [15]. In line with the work of other researchers [16-19] – the measurements have identified the following improvement potentials classification regarding the energy and resource efficiency of a MT:

- Functional fit: For an optimal efficiency, MT components have to be selected with respect to the intended use. I.e. speed control of a pump instead of a valve is required to satisfy a variable demand with optimal efficiency.
- Dimensioning: The efficiency of machine components generally depends on the operational point. Over-dimensioning is thus a common problem in the energy efficient design of MTs.
- Factory integration: MTs tools are substantial heat sources, while showing a significant sensitivity to thermal effects (elongation of structural parts). This implies energy intensive conditioning of the shop floor by the technical building services (TBS) and/or thermal compensation of the positioning errors.
- Operation without use (OWU): MTs have a substantial base load in electric power consumption. Hence non-productive times can have a crucial impact on the total energy demand.

To establish a generalized CED methodology for MT, the data acquisition steps and calculation procedures have to be designed in a generic way, while assisting the user in the typical challenges of a MT CED calculation. Previous applications have identified the following omnipresent challenges:

1. Problem decomposition: A MT is a complex assembly of components. Hence the problem has to be separated into several smaller but easier to examine sub-problems.
2. Heat loss and treatment: MTs produce a substantial amount of heat loss to be treated by the TBS. The information to quantify the TBS efforts is often lacking on the side of the MT manufacturer.
3. Schedule characterization: The MT operational schedule has to be characterized in a way suitable for a CED. In reality, the schedule characterizations are manufacturer specific or even non-existent.
4. Evaluation and presentation of results: Results of the CED must be evaluated and presented, such that improvement measures can be derived systematically. Otherwise expert knowledge is required.

Based on the existing empirical basis and experience, an efficient eco-design tool must be capable to identify improvement potentials according to the four presented classes, while assisting the user during the four challenges discussed above.

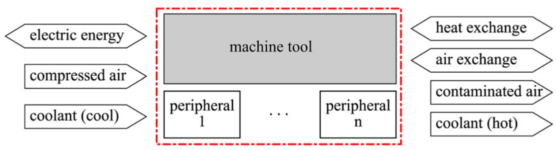

Figure 1: System boundary (red) of a MT according to ISO 14955-1 [10].

4. Approach

This work implements a three step procedure for MT CED calculation: First the machine is decomposed into its components, whereas a CED calculation is performed for each of these components in the second step. The third step includes the presentation and evaluation of the obtained and aggregated results.

4.1. Decomposition into machine components

MTs are assemblies of various components, for which data sheets are generally available. By performing the analysis on the level of components, the already available data sheets can be exploited in order to accelerate the parameterization. This step is also in line with ISO 14955-1 [10], recommending a data acquisition on component level. Examples for components are spindles, axis drives, pumps, coolers and control devices. The total number and types of components depends on the type of machine under investigation.

4.2. Quantification of primary energy content

Using the standard CED procedure adapted for MTs, the total primary energy demand is obtained. In order to include the relevant contributions to the primary energy demand, the MT life-cycle model presented in figure 2 is used.

For the calculation and analysis, the primary energy demand E_{MT} of a MT is divided into the part E_{use} accounting during the operational phase of the MT (see figure 2) and the energy incorporated within the machine tool due to its production phase E_{grey}:

$$E_{MT} = E_{grey} + E_{use} \tag{1}$$

Quantifying the grey energy content of the machine requires an estimation of the LPED during the procurement of raw materials (*raw*), production (*pr*), packaging (*pa*) and transportation (*tr*) of the machine. Furthermore, the benefits of material recycling (*rec*) have to be analysed for each of the N_c components:

$$E_{grey} = \sum_{i=0}^{N_c} \left(E_{raw,i} + E_{pr,i} + E_{pa,i} + E_{tr,i} - E_{rec,i} \right) \tag{2}$$

Where $E_{x,i}$ is the grey energy demand of the *i*-th component in

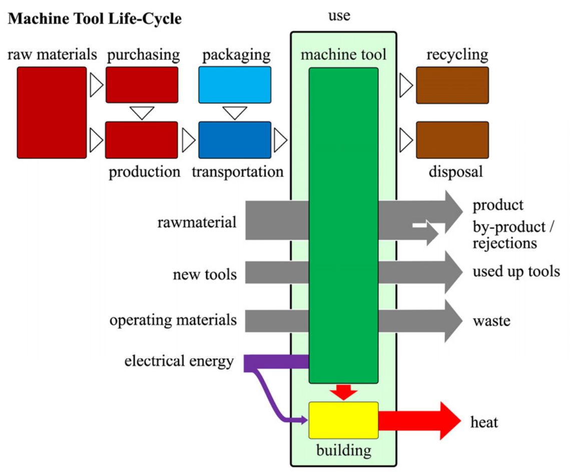

Figure 2: Generic machine tool life-cycle used for the CED including the driving material and energy flows. The contributions of the use phase are indicated by the light green zone.

a certain life-stage *x*. The quantification of the right hand terms in (2) follows the standardized procedure of a CED calculation as presented in [13].

During the use phase, electric power consumptions (*el*), resources flows (*res*), scrap material (*scrp*), tool usage (*tool*) and TBS load (*tbs*) account for the LPED:

$$E_{use} = \sum_{i=1}^{N_c} E_{el,i} + E_{res} + E_{scrp} + E_{tool} + E_{tbs} \tag{3}$$

The evaluation of (3) is based on the concept of machine states as recommended by ISO 14955-1 [10]. Each element in the set of machine states $\mathcal{S}$ – namely off, standby, ready and processing – leads to a characteristic machine behaviour. Given the relative time shares of each machine state $S \in \mathcal{S}$ as $r_{lt,S}$ and the state specific power consumption of the i-th component in the particular state as $P_{i,S}$, the primary energy equivalent of the components electric energy consumption is

$$E_{el,i} = \left(\sum_{S \in \mathcal{S}} P_{i,S} \, r_{lt,S} \right) t_{lt} \, e_{el} \, . \tag{4}$$

t_{tl} is the total machine life time and e_{el} the specific primary energy equivalent for electric energy. This energy equivalent depends on the country where the MT is finally used [14].

The primary energy demand due to consumed resources – such as compressed air or lubricants – is estimated based on an average consumption per time $\dot{m}_{res,r,s}$ of the resource type *r* during a specific set of states $\mathcal{S}_{res,r} \subseteq \mathcal{S}$. Given the set of consumed resources as $\mathcal{R}$ and their specific primary energy demand as $e_{res,r}$, the cumulated energy demand of all resources can be calculated:

$$E_{res} = \sum_{r \in \mathcal{R}} \sum_{S \in \mathcal{S}_{res,r}} r_{lt,S} \; t_{lt} \; \dot{m}_{res,r,S} \; e_{res,r} \tag{5}$$

During processing scrap material – such as chips or pinch-offs – will account. M_p describes the set of processed material, where each material $M \in \mathcal{M}_p$ is machined with a throughput of $\dot{m}_M$ and a utilization level of $r_{use,M}$ (ratio between weights of machined part and semi-finished raw material). This results into the following primary energy demand for scrap material:

$$E_{scrp} = r_{lt,prc} \; t_{lt} \sum_{M \in \mathcal{M}_p} \dot{m}_M \left(1 - r_{use,M}\right) \; e_{scrp,M} \tag{6}$$

The specific primary energy demand $e_{scrp,M}$ varies depending on the post treatment applied. The scrap material is assumed either to be recycled, burned while reusing its specific heating value $H_{i,M}$ at efficiency η_b, or disposed by land filling:

$$e_{scrp,M} = \begin{cases} e_{raw,M} - e_{rec,M} & \text{for recycling} \\ e_{raw,M} - \eta_b \, H_{i,M} & \text{for burning} \\ e_{raw,M} & \text{landfill} \end{cases} \tag{7}$$

During the MT operation, grey energy containing tools will be required. Characterizing each of the N_{tools} used by their tool life time t_{tl} and the usage relative to the total processing time r_{tool}, the primary energy demand due to tool use can be calculated as following:

$$E_{tool} = \sum_{j=1}^{N_{tools}} \frac{t_{lt}}{t_{tl,j}} r_{lt,prc}\, r_{tool,j}\, E_{tool,j} \tag{8}$$

The grey energy $E_{tool,j}$ of the tools can be estimated according to (2).

To apply the concept of machine states to the CED, the relative time shares $r_{lt,S} \forall S \in \mathcal{S}$ have to be known. The rule based approach presented in figure 3 can be used to quantify these shares. Aim of this approach is to identify all non-productive machine times and assign them with a machine state on the example of a representative observation time interval and a representative batch. This is achieved by estimating the set-up times, cycle times, tool change times and idle times, as well as the batch size. Additionally the number of working weeks per year, working days per week and shifts per day has to be provided.

For a TBS, a MT is a load: Due to the thermal losses generated by the machine, cooling is required. To estimate this cooling effort, following three assumptions are made:

1. All (electrical) power consumed by the MT is transferred into thermal losses
2. Heat not extracted by active water cooling (WC) of the MT is transferred to the ambient air and has to be removed by the air conditioning (AC)
3. The TBS subsystems WC and AC are powered by electrical energy

Based on these assumptions, the primary energy required by the TBS is calculated by

$$E_{tbs} = \left(\frac{Q_{WC}}{\varepsilon_{WC}} + \frac{\left(\sum_{S \in \mathcal{S}} P_s\, r_{lt,S}\right) t_{lt} - Q_{WC}}{\varepsilon_{AC}} \right) e_{el}. \tag{9}$$

The energy efficiency ratios ε_{WC} and ε_{AC} of the WC and the AC respectively depend on the energy efficiency class of the installed TBS system as stated in table 1. Q_{WC}, the amount of heat extracted by WC, can be estimated using the inlet and outlet temperatures $\vartheta_{WC,in}$ and $\vartheta_{WC,out}$, as well as the mass flow rate $\dot{m}_{WC}$ and specific heat capacity c_{WC} of the WC fluid. These parameters are generally known by the manufacturer auf the MT. Given $\mathcal{S}_{WC} \subseteq \mathcal{S}$ as the set of machine states where the WC is active, the extracted heat energy by WC is:

$$Q_{WC} = \left(\vartheta_{WC,out} - \vartheta_{WC,in}\right) \dot{m}_{WC}\, c_{WC} \sum_{S \in \mathcal{S}_{WC}} t_{lt}\, r_{lt,S} \tag{10}$$

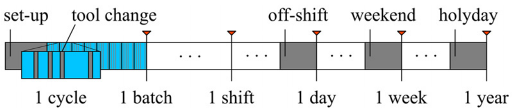

Figure 3: MT application model to determine the relative time shares of the machine states. Except during the indicated interrupts (grey), the machine is assumed to be processing (blue).

Table 1: Energy efficiency ratio (ε) for water cooling (*WC*) and air conditioning (*AC*) in different building classes (adapted from [20])

Efficiency Class	ε_{WC} [–]	ε_{AC} [–]
A	5.05	2.6
B	4.85	2.5
C	4.45	2.3
D	4.05	2.1
E	3.65	1.9
F	3.25	1.7
-	3.05	1.6

4.3. Anaylsis and evaluation of the resulting CED

In order to analyze the estimated CED results, the framework offers different analyses: Life phase specific primary energy demand (LPED), component and machine state specific electric energy demand (EED) and state specific primary energy demand (SPED). The LPED as displayed in figure 4, presents an overview and helps identifying the significant contributions to the total energy demand. It further visualizes the contributions to the MT CED due to factory integration (TBS). EED point of view (figure 5) assists in evaluations of the functional fit and dimensioning. EED, as well as SPED (figure 6) indicate losses due to OWU. In combination, the three presented analyses are capable of identifying improvement potentials according to the classification in section 3.

4.4. Implementation

The presented calculation approach for the CED of a MT is implemented in Microsoft Excel (ME), which fits both, simplicity in use and dissemination in the industry. Four subsequent steps make up the implementation: First the user is guided through the decomposition of the MT into components. Second, the data for the component based CED calculation is obtained. In the third step, the time shares of the machine states as well as the configuration of the TBS are defined, using separate calculation sheets. The fourth and last step includes the presentation of the CED data and performed analysis. Wherever possible, the presented energy equivalents by VDI 4600 [13] are used. Additional energy equivalents are obtained from literature [8, 14, 21]. The finalized tool, including additional illustrations, can be obtained online at tools.zuestengineering.ch.

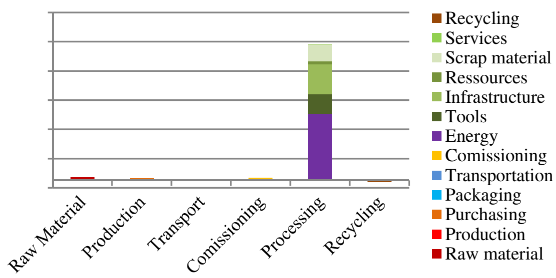

Figure 4: Exemplary life phase specific primary energy demand display of the resource flows presented in figure 2 implemented in the framework

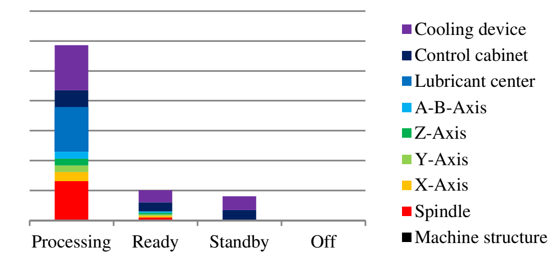

Figure 5: Exemplary display of the state and component specific electric energy demand provided by the framework

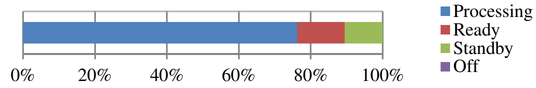

Figure 6: Exemplary display of the state specific energy demand provided by the framework

5. Application

Table 2 shows a compilation of selected examples. All three MTs implement different processes and use-cases. The presented framework enabled to estimate the current CED, identify potential measures and quantify their expected improvements regarding primary energy demand. Common (e.g. electric energy demand) as well as uncommon (e.g. scrap material) energetic cost factors can successfully be identified and assigned according to the classification in section 3. Combining the achieved reductions in primary energy demand on the machine and the TBS, significant reductions are possible (see row *achieved benefit* in table 2).

6. Discussion and Outlook

This work provides the framework layout and theory for a fast and generic estimation of the MT CED in the design phase. It presents the required methodology to address the common challenges in MT CED: Problem decomposition, heat loss and treatment, operational schedule characterization, as well as evaluation and presentation of results. The implementation is realized in ME and the tool is available online. Three examples from industry demonstrate the usability of the selected approach, especially regarding the identification and classification of improvement potential. This is achieved by two features of the tool: First, the tool assists during the improvement potential classification. Seconds, the tool enables a fast quantification of improvement measures regarding the primary energy consumption. Following, together with the mentioned online resource, this work provides a usefull tool for industry to estimate the CED of a MT in development. Furthermore, the tool enables the systematic identification of improvement potential regarding the four main challenges: Functional fit, dimensioning, factory integration and operation without use.

MTs are complex mechatronic system consisting of multiple interacting components. They further show the characteristics of an active product: A dominating LPED of the use phase. The presented tool is especially designed to deal with this kind of system regarding the estimation of the CED. Hence, the presented tool can be applied to machines of other technologies, sharing the properties of MTs presented above.

The selected temporal resolution of machine states simplifies the configuration, but limits the informative value regarding thermal dynamics. Estimated energy flows are averaged for each machine state. Information about peak load – i.e. cooling demand during energy intensive but short process intervals – is limited in significance. Hence, the rule-

Table 2: Exemplary applications of the presented eco-design tool in MT industry.

	Case 1	Case 2	Case 3
Tool user and case description	Manufacturer of MTs for sheet metal cutting.	Manufacturer of high precision grinding machines operated at two shifts	Milling machine manufacturer for process durations in the order of days and three shift applications.
Results of the Analysis	95% of primary energy is consumed during the use phase. The energy due to sheet metal waste is in the same magnitude as the electric energy demand. A significant amount of the electric energy is consumed by the cooler during non- productive time phases.	The use phase counts for >95% of the primary energy demand. The fixed speed cooling lubricant pump stands out with a total contribution of 33% to the electric energy demand: Operating under various loads while being dimensioned for the most demanding operational point, the overall efficiency is decreased.	Nearly all primary energy (98%) is consumed during machine use, mainly for electric energy (50%), infrastructure use (17%) and scrap material (26%).
Classification	**Functional fit and OWU**	**Functional fit and dimensioning**	**Factory integration and OWU**
Measures taken	Implementation of new cooling concept with standby mode and an improvement of the supplied nesting algorithm	Re-think of the present cooling lubricant pump and integration of a speed control of the pump instead of a valve.	Development impulse for a software based standby and shut-down, as well as a central lubricant and coolant supply on factory level.
Achieved benefit	Total reduction of primary energy demand of 60%, whereas the reduction in electric power demand is about 70%.	Over all operational points, the speed control leads to a reduction in electric and TBS energy demand of 25%. This translates to a reduction in total primary energy demand of about 20%. Additional costs for this measure can be justified by the payback time of 4000 hours [22]	The combined measures are expected to reduce to total primary energy demand by 30%. This is also due to the higher efficiency enable by resource supply on factory level

based indicators used in the presented tool have to be double checked depending on the use case of the machine. Ecological improvements on the products manufactured on the MT enabled by improvements on the machine itself benefit from a scaling effect, since a single MT is generally producing multiple parts. An example for such a tertiary improvement is less friction due to a better surface quality. However, these effects are beyond the system boundary (see figure 2) of this approach and thus not considered within the presented framework. The presented CED framework for MT relies on a predefined part quality which must not be reduced by the tested energy efficiency measures.

At the current stage, the presented approach estimates the primary energy demand only. Since the estimation is done based on specific energy equivalents, other analyses can be enabled easily. Examples are a financial analysis based on specific cost, or an analysis of the ecological impact based on eco-indicators as presented in [23]. Future research must further include the rule based quantification of toxicity and legal compliance of resources used. At the current stage, the tool requires a manual handling of such questions. The presented approach could be further extended to support not only the evaluation of new concept, but also the quantification of improvements achieved, as for example required for [5].

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