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APPROACH FOR THE DEVELOPMENT OF ENERGY-EFFICIENT MACHINE TOOLS

The life cycle costs of machine tools are much higher determined by their energy costs than what is often roughly assessed. The growing demand for consumer goods and especially possibilities of individual mobility in major parts of the developing world – e. g. Asia – will lead to serious problems in meeting the demand for an abundant energy supply and will increase the cost for energy further in the near-term future. Harder efforts are necessary to “reach more with less” – using less energy than today to reach a defined goal in production. The paper deals with a methodology to design machine tools with a high “energy efficiency”. Based on the property-driven design methodology by Weber a systematic approach is shown to enhance the design of machine tools. Energy efficiency is a new additional and central property in the design process. To attain these given properties characterisations are determined by the engineer to fulfil these properties. On the developing-path the characterisations are defined in more detail step by step, and after each step it is assured if the accounted properties where met by the defined characteristics. The approach is to first analyse existing machine tools and therefore define prior energy consumers. The identified major consumers are afterwards systematically addressed to reduce their energy consumption. The result is an enhanced machine tool with state-of-the-art energy usage. This addresses the objectives of the EU and takes pressure of the energy supply by reducing the energy demand in production.

1. INTRODUCTION

1.1. OBJECTIVE TARGET AND MOTIVATION

With the background of an ever increasing worldwide primary energy consumption in the context of shrinking natural resources and the global climate change it is inevitable to reduce the energy usage in the developed countries sharply. The share of the producing

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industry on the primary energy consumption in Germany was around 40 % in 2005 [1]. Therefore a key goal for the next decades is the increase of the energy efficiency [2].

The energy efficiency is defined by the unspecific output (O) – for e. g. volume – divided by the energy usage (E). Compared to the electrical efficiency which defines the proportion of the usable energy with the input, it is not a dimensionless unit, and it can adopt different units (e.g. m³/kWh) [3]:

Energy efficiency
$$\varepsilon = \frac{Output}{Energy_{in}} = \frac{O}{E_{in}} \tag{1}$$

Along with the energy efficiency, the energy effectiveness is also a key aspect. It characterizes the meaningful use of the energy.

1.2. ASPECTS OF THE ENERGIE EFFICIENCY OF PRODUCTION SYSTEMS

Fig. 1 shows basic aspects of the energy efficiency of a production system (PS). The PS includes several machines and represents a process chain (PC) for the manufacturing of a work piece. A single machine tool and a whole PS have at first an energy-efficiency in operation (production). Second there exists the energy consumption for the manufacturing and removal (including recycling) of the machine or PS, which can be distributed over the lifespan output and affects the energy efficiency also. A PS is by this characterised through a complex interaction of the sub-systems (the single machines). The replacement of an output-limiting machine tool therefore can increase the energy efficiency (the production efficiency) of the PS, even if the new machine tool consumes more energy then the replaced one. The afterwards introduced methodology is based on a single machine and their sub systems. This methodology can be further used for a whole PS, the single machines in the PS are thus threaded like the sub-system of a single machine.

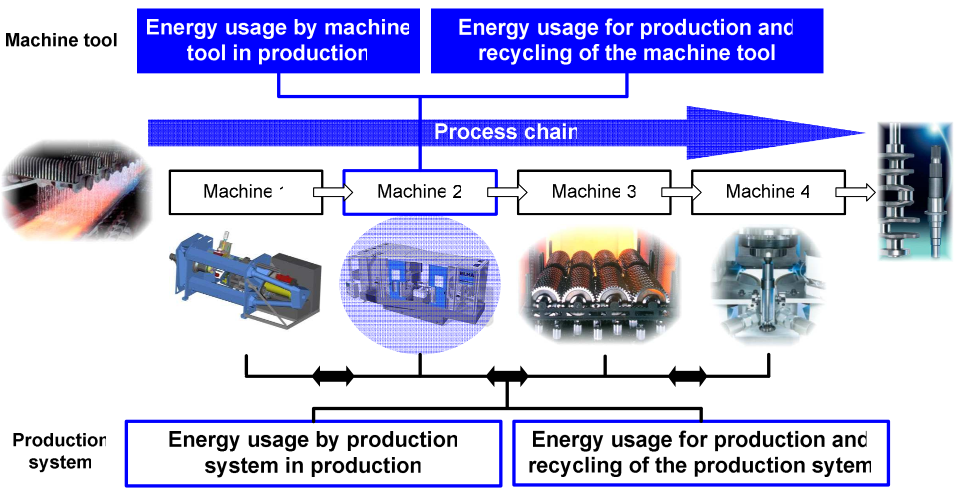

Fig. 1. Energy consumption aspects of machine tools and production systems

2. CRITICS OF ACTUAL APPROACHES OF DESIGN METHODOLOGIE

2.1. CRITIC OF ESTABLISHED METHODOLOGIES

Since the 1950's it was attempt to systematize the abstractive-intuitive design process with prescriptive (purporting) design methodologies in German-speaking countries. The main works are referable to Rodenacker [4], Pahl/Beitz [5] and Roth [6]. Later these influential concepts of Pahl/Beitz where continued by Feldhusen and Grote. These concepts lead to the VDI standard 2221 [7] and 2222. They represent a basic consensus of German design methodologies around 1990. The classic methodologies are confronted with growing critics, primarily because of their weak industrial application base [8]. The strict chronological succession of the phases and the accentuation of abstraction by functions and functional structures have not gained momentum in industrial applications [9]. There is a stringent methodology to go from requirements to solutions by means of abstractions of functions and their active principles, without enclosing of initial existing technological solutions and systems. This gives the advantage of generating new principal solutions, which can lead to new technological systems. Contrary in praxis existing solutions and technical systems are taken into account, even though new technical systems are designed and even more if an existing systems is over-worked. In particular when designing complex technical systems – for e.g. machine tools, vehicles or airplanes – a competitive design solution compulsory takes existing systems into account. Furthermore, the classical methodologies do not accommodate the growing importance of mechatronical systems and components. In fact the methodologies are adoptable to all domains, but their spreading outside classical mechanical design is weak. This fact was addressed by the introduction of the VDI 2206 [10], which abut more on system technology and attempt to build a bridge between several domains to give a general framework for mechatronical design. The VDI 2206 gives an effective concept for the project-oriented design of mechatronic systems. The critic of the VDI 2206 on the one hand is on the fact that the core of the design process – the concept determination – is not shown in detail. On the other hand the critic is given that not all systems can be modularised into domain-specific sub-systems and that successful mechatronic designs are characterised by a holistic system design.

Independently of the so-called European school, design methodologies and design theories where developed in Asia and North America, giving a wider approach to the design process, not focusing especially on concrete technological systems like machine tools. Well known are the General Design Theory (GDT) by Yoshikawa [11] and the Axiomatic Design by Suh [12]. The core of the Axiomatic Design deals with the connection between the requirements – and the thereof derived functional requirements (FR) – and the design parameters (DP). This connection can be mathematical described by an equation in form of a matrix. Furthermore Suh has formulated axioms, from which the first one is the most important. It suggests that each of the functional requirements should be fulfilled without affecting the other [13]. The international approaches are relatively abstract concepts of the design process, which is owed by the fact that these methodologies or theories are not exclusively for complex technical systems like machine tools. The core suggestion of the

Axiomatic Design – to establish a (single) mathematical equation in form of a matrix between functional requirements and design parameters – is theoretical desirable, but practically not realizable because of the number of variables which characterises a complex technical systems.

2.2. PROPERTY-DRIVEN DEVELOPEMENT BY WEBER

By introducing the property-driven development (PDD) – respectively the characteristics-properties modelling (CPM) – Weber attempt to unify the prescriptive approaches of the European school and the international approaches [14]. The principal concept is shown in Fig. 2. It defines the design process as a process which has to reach given properties (= requirements) by defining characteristics, to ensure these properties – e.g. geometrics or materials. The connections between the properties and the characteristics are the central element of the methodology. The characterisations are deeply interacted (connections in Fig. 2), which is the main difference to the Axiomatic Design.

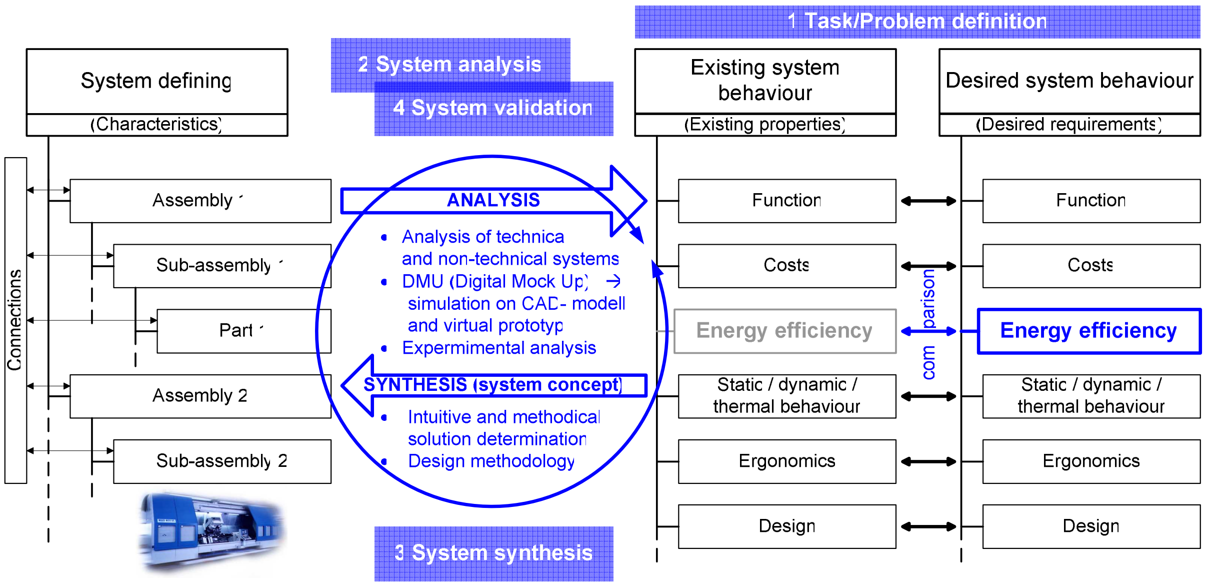

Fig. 2. Property-driven development by Weber

These connections can be described mathematically – like the connections between the FR's and the DP's of the Axiomatic Design – by a matrix-equation. Technical systems are characterised by an enormous number of parameters and a relative diffuse requirement space. A mathematical formulation of these connections is theoretical possible and desirable – equal to the Axiomatic Design – but it is practical not realistic for all parameters (which give the characteristics) of the system. However, for critical aspects this is possible, e.g. a FEM-simulation of the resonance frequencies of a system gives the connection of some characteristics (geometrics, stiffness and others) and the dynamical system behaviour (resonance frequencies and modal forms) of the system. The backward connection, to derivate characteristics of a technical system through the knowledge of the resonance frequencies and modal forms is much more difficult and shows clear the principal problems of the synthesis in the design process.

3. DESIGN TO EFFICIENCY

Based on established methodologies of product design, afterwards a holistic approach is introduced. The principal concept is centred on the improvement of existing machine tools and PS, based on established process chains. The identification of weak points of present system designs backed by the new criteria of energy efficiency is central to the methodology.

3.1. GENERAL METHODOLOGY

The given methodology is based on the property-driven development by Weber. Taking into account several cycles – from the first concept of the system design to the final detailed system design – a correlation to the classical concepts of the VDI 2221 can be drawn. With regard to the modularisation and the domain-specific design in the several cycles a correlation to the VDI 2206 is shown. The core design conflict between the fulfilling of the requirements and the defining of the characteristics is correlated to the core conflict between the FR's and the DP's in the Axiomatic Design. Fig. 3 shows the general methodology and the interconnections to the several established design methodologies.

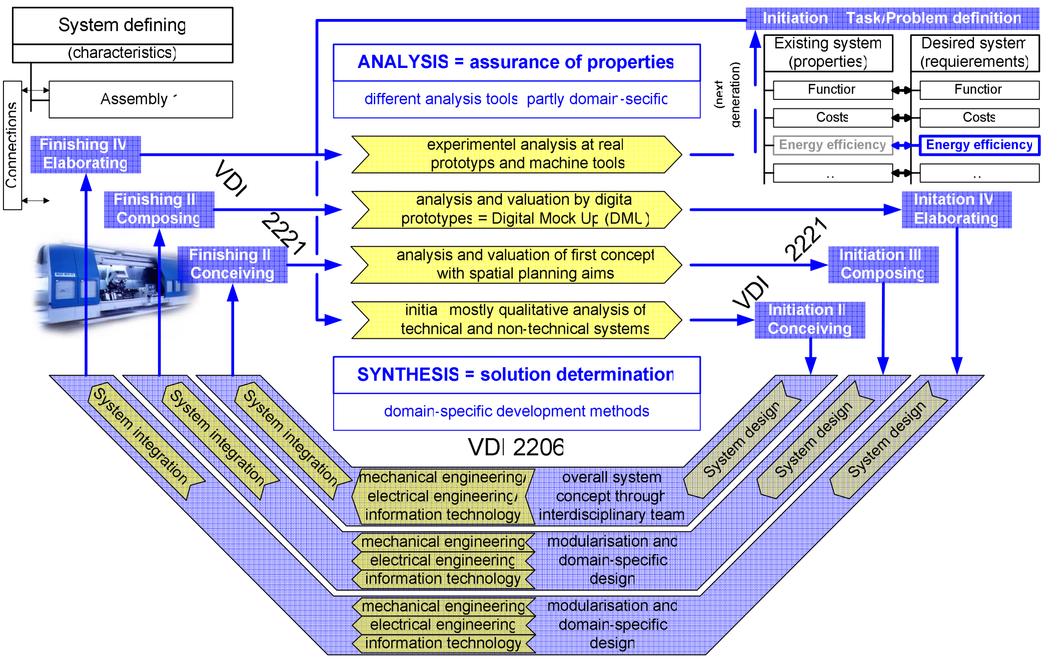

Fig. 3. General design methodology for energy-efficient systems

Established design methodologies have not yet considered energy efficiency as a central requirement of technical systems. As an inherent part of the methodology it is necessary to take energy efficiency as a central requirement into account, like the static, the dynamic or the thermal behaviour of a machine tool. In contradiction to established methodologies an initial analysis of existing technical systems is considered fundamental. Fig. 4 shows the general concept.

In a first step the task is analysed and detailed further. This contains the defining of requirements, including the new requirement of energy efficiency. Next the (existing) technical system – the machine tool – is structured by its relevant energy consumers. Afterwards it is determined which systems consume which amount of the overall energy usage. Therefore the definition of relevant machining processes is necessary. At the end of this phase the sub-systems are classified (e.g. through an ABC analysis) by its energy usage, the major energy consuming systems are addresses further subsequently. The following synthesis utilises a systematic approach to reduce the energy consumption of the systems. Several options are considered, starting with the complete elimination of the energy usage and ending with the option of energy recovering. Finally a new analysis step follows – the verification of the system design. The system behaviour is predicted by several tools – like a FEM-analysis – and evaluated in the context of existing systems or the initial design of the system. Through digital prototypes a valuation of the current design is possible.

Further – here not described – synthesis and analysis steps exist, which define the system in more detail step by step and therefore include an even more detailed digital model of the system as result. Return cycles are included, technical solutions can be abolished or reworked. The final system behaviour is analysed on the prototype or pilot machine, further advancing the digital prototype for future developments.

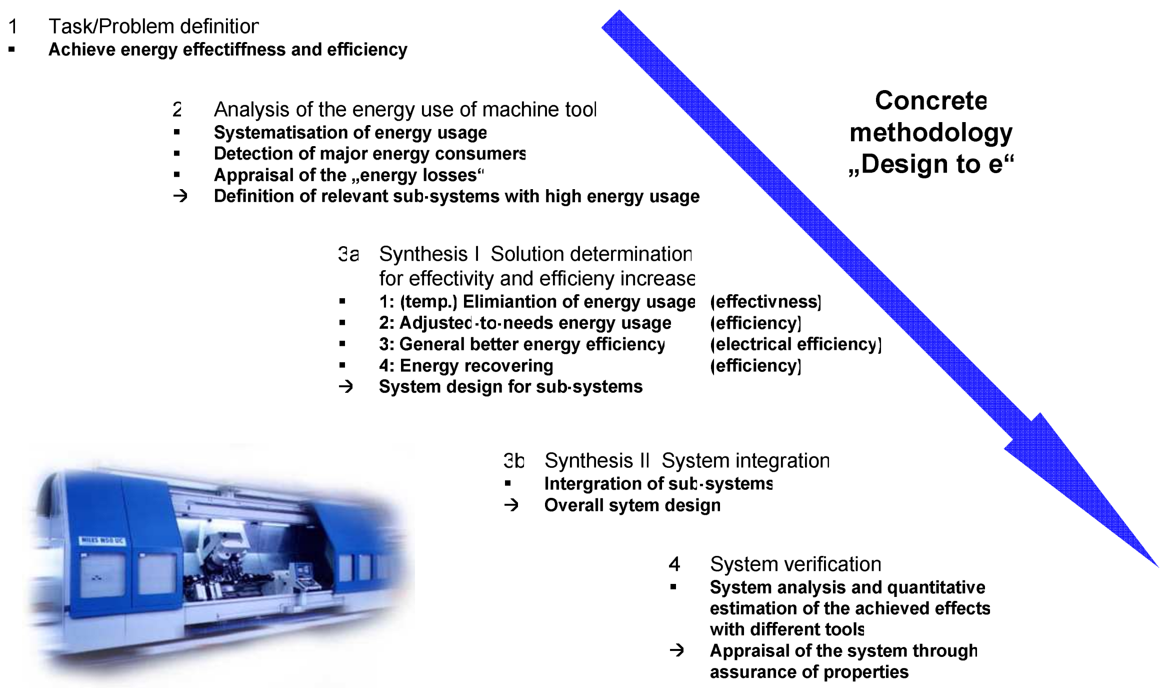

Fig. 4. Concrete methodology for energy efficiency: „Design to e“

3.2. ANALYSIS OF THE ENERGY FLOW

A detailed knowledge about the energy flows of the sub-systems is necessary for the design of energy-efficient machine tools. Fig. 5 shows the energy flow of a technical system in general. The system boundary can be a PS, a machine tool or a sub-system. The systematic analysis of energy flows should be realised in the given order. The energy infrastructure includes the transforming, allocation and storage of energy. The energy recirculation respectively the secondary energy usage is also a function of the energy infrastructure. Following the necessity these energy system can be further detailed in sub-systems.

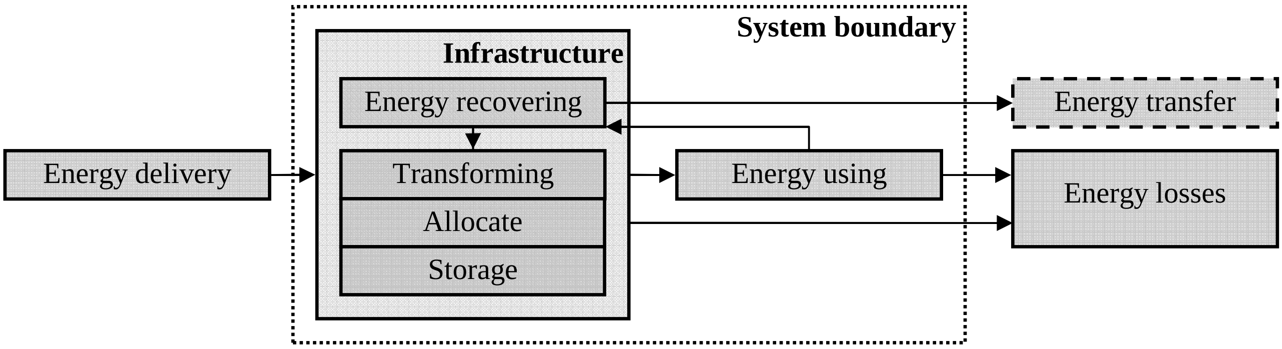

Fig. 5. Energy-flow model of a technical energy system

It is a non-trivial process to systematically define sub-system structures of an overall system for analysing the energy flows in such a system. The classification of a machine tool or a PS can be deducted according to constructional, functional (machining) or energetic aspects, linking the latter seams to be the most sufficient one.

The energy input of a machine tool consists mostly of electrical energy and potential energy in form of compressed air – which is by itself produced from electrical energy. During the machining process these electrical energy (with 100% exergy) is converted thru several transformations into thermal energy (nearly 100% anergy). Therefore the analysis of the electrical-energy flows is central to the methodology. In the first step all electrical and pneumatically energy consumers have to be defined and structured as per their installed nominal power. In the achievement of this step the energy infrastructure can be defined, which is a derivation of the installed nominal power. A feasible classification of the sub-systems of a machine tool after energetic and functional aspects shows table 1. According to this the main consumers of the analysed 3-axis-milling machine are the support drives (~ 50%) and the cooling-system (~ 12%). Only then the main-drive follows with roughly around 7%. After calculating the electrical energy usage for the pneumatic maintenance – given through a specific factor of the energy usage for the supply of a unit compressed air (kW/m^3h^{-1}) by the producer of the compressor – this consumption (around 2.5 kW) reaches nearly half of the electrical consumption of the main-drive (5 kW). Fig. 6 shows the qualitative energy flow of a support drive as an example. A detailed measurement of the relevant data promotes further information in the next step.

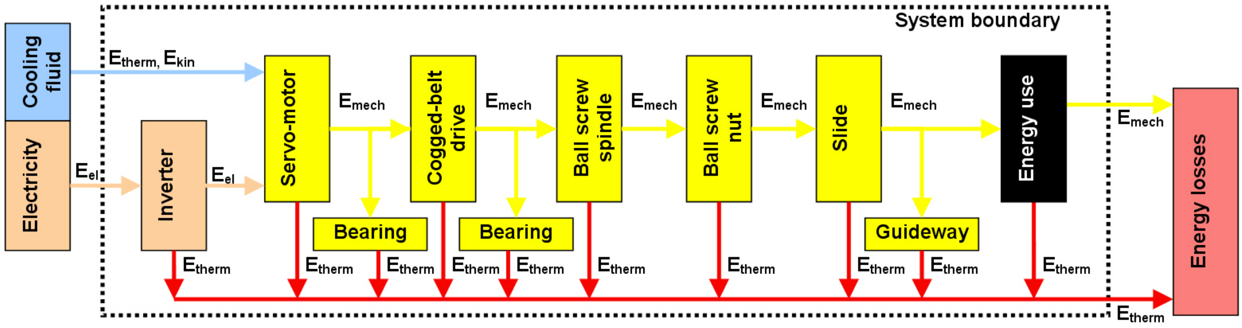

Fig. 6. Example for an energy flow in a machine tool support drive

Afterwards machining processes and cycles have to be declared, because the energy consumption of a machine tool is mainly dominated by the process which has to be put into effect. First conclusions can be drawn by analysing the power input during the machining process of each sub-system and by allocating the power input on the different operating statuses.

Table 1. Classification of sub-systems and operation modes

machine tool subsystems		P_{nom} [kW]	P_{nom} [%]	stand-by	ready for production	production		
						tool change	positioning	machining
servo drives	main drives	5,00	6,98		○	◑	◑	●
	support drives	51,50	71,93		○	●	◑	◑
auxiliary drives	coolant	11,99	16,75				●	●
	cooling	0,64	0,90	◑	●	●	◑	●
	hydraulics	0,96	1,35		●	●	●	●
	chip conveyor	0,25	0,35		◑	●	●	●
	air cleaner	0,53	0,74		◑	●	●	●
	tool changer	0,20	0,28			●		
controller	CNC	0,24	0,34	●	●	●	●	●
others		0,40	0,39	◑	◑	◑	◑	◑
installed nominal power		71,60	100,00					
compressed-air *	sealing air	2,43		●	●	●	●	●
	clamp-systems					●		

* medium compressed-air usage according to manufacturer, realised by state-of-the-art compressors 0,0868 $kW/(m^3h^{-1})$

The actual researches show the mismatches between the installed nominal powers of sub-systems, in which the servo drives dominate the electrical installed nominal input by around 75% and the energy consumption during the machining process in which the auxiliary systems are accountable for around 75% of the energy consumption.

Therefore the detailed investigation of the energy usage of sub-systems, in context of their operational statuses, is essential for the energy consumption analysis of machine tools in their life cycle. Suitable operating statuses are for example power off, stand-by, ready for production and production – production including tool change, positioning and machining. These have to be verified through measurements and be further detailed if necessary.

3.3. SYNTHESIS

After defining the key energy consumers, these consumers are systematically addressed. In principle a defined key energy-consumer or key energy-usage can be tackled in different ways:

- 1 (temporary) Elimination of energy usage → effectiveness
- 2 Adjusted-to-needs energy usage → efficiency
- 3 General better energy efficiency (electrical efficiency) → efficiency
- 4 Energy recovering → efficiency

With the elimination of the energy usage (1) it is attempt to eliminate the energy usage completely. An example for this approach is a cooling cycle which is not longer necessary, due to new thermal stable materials or an active compensation of thermal displacements.

The so-called adjusted-to-needs energy usage (2) holds the biggest potential in reducing the energy consumption of the auxiliary systems. For example the cooling-lubricant system or the workspace exhaustion could be operated in interconnection with the spatial volume.

General better energy efficiency (3) could be achieved by new active principles or higher energy efficiency of existing active principles without affecting the machining process. New bearing with less friction are an example for this approach.

The energy recovering (4) means the secondary usage of energy, which would otherwise be lost. The generator mode of electrical servo drives to refeed energy into the link is an example for this secondary energy use.

Tab.2 shows the implementation of the methodology for some sub-systems.

Table 2. Examples to achieve higher energy efficiency for the sub-systems of a machine tool

Reduction of energy consumption / Examples of energy consumers	1 Elimination of energy usage	1 Adjusted-to-the-needs energy usage	1 General better energy efficiency	1 Energy recovering
NC - Axis	▪ Clamp axis when not used	▪ Temporary connection of electrical windings or of additional servo drives	▪ Using efficient EFF1-motors ▪ Using bearings with less friction ▪ Reducing the mass of slides	▪ Feed electrical energy back to link/grid when breaking an axis by using a servo motor as generator
Cooling of a servo drive	▪ Temporary elimination of cooling cycle when servo motor doesen't reach a criticial temperature	▪ Adjusted cooling of motors by variegating the flow rate of cooling water	▪ Reduction of the resistance in the cooling system ▪ Cooling system with better efficiency e.g. stirling motor cooling	▪ Using the heated cooling water in an thermo-electrical generator to produce energy
Cooling lubricant usage	▪ Use dry processing when possible	▪ Adjusted usage of cooling lubricant defined by the chip volume	▪ Using CO_2 coolant instead of water chip cooling (for chip cooling)	

3.4. VERIFICATION

After the systematic identification of the sub-systems and the following design upgrading, it is necessary to judge the achieved effects. This appraisal is a new analysis step in the design process, for which different tools are available. In particular the property prediction by virtual prototypes – the so-called Digital Mock Up (DMU) – is centre to this step [15]. When the achieved effects can be judged – or even assessed –, a technical system or sub-system can be compared to the initial state. Therefore an energy-efficiency index (EEI) – also called energy-performance label – can be introduced, which compares the energy efficiency of the initial system with the energy efficiency of the upgraded design:

Energy efficiency index
$$EEI = \frac{\varepsilon_{set}}{\varepsilon_{current}} \tag{2}$$

To compare machines and PS the energy productivity offers a better approach, which is – compared to the energy efficiency (e. g. m³/kWh) – a production based indicator (e. g. work pieces/kWh or features/kWh) [16]:

Energy productivity
$$\varepsilon_P = \frac{Output_P}{Energy_{in}} = \frac{O_P}{E_{in}} \tag{3}$$

Energy-productivity index
$$EEI_P = \frac{\varepsilon_{P,set}}{\varepsilon_{P,current}} \tag{4}$$

Fore the appraisal of the lifespan energy consumption of a machine or PS and their sub-systems – in addition to the energy consumption of the system in production (E_P – includes machine maintenance and repair) –, it is necessary to take the energy consumption for the production (E_{tP}) and removal (E_R) of the system into the consideration and distribute it over the lifespan of the system (e.g. for machine tools between 20.000 h and 60.000 h):

Lifespan energy usage
$$E_{Sys\_i,ls} = E_{tP,Sys\_i} + E_{P,Sys\_i} + E_{R,Sys\_i} \tag{5}$$

When compared to the lifespan output of the system, the lifespan overall energy efficiency can be introduced:

Lifespan energy productivity
$$\varepsilon_{P,Sys,ls} = \frac{O_{P,sys,ls}}{E_{Sys,ls}} \tag{6}$$

To judge the achieved effects of the design upgrade for each sub-system, lifespan energy productivity can be calculated for each of the sub-systems. In principle the whole energy consumption of a machine tool has to be broken down to the sub systems of the machine tool and has to be distributed over the lifespan for each single sub-system:

$$\varepsilon_{P,Sys\_i,ls}{*} = \left[\frac{E_{tP,Sys\_i}}{O_{P,Sys,ls}} + \frac{E_{P,Sys\_i}}{O_{P,Sys,ls}} + \frac{E_{R,Sys\_i}}{O_{P,Sys,ls}} \right]^{-1} \quad (7)$$

If the energy consumption for the production of the machine tool and their sub-systems is unknown, the energy consumption of the sub-systems can be related to the price (C) of the sub-systems. Due the knowledge of the proportion of the energy costs ($C_{E,P}$) in production (actually around 5% [17]), and the assumption of a price for the electrical energy (C_E around 0,1 €/kWh), a correlation between the cost of the sub-systems (C_{Sys_i}) and the energy consumption for their production can be drawn (the factor z takes the energy consumption for the removal of the system into account and can vary – normally 1…1,5). This can only be an approximation of the reasonability of the design upgrades, but it can be used for a quantitative statement:

$$\varepsilon_{P,Sys\_i,ls} = \left[\left(\frac{\frac{1}{C_E} \cdot C_{E,P} \cdot \frac{C_{Sys\_i}}{\sum C_{Sys}}}{O_{P,Sys,ls}} \right) \cdot z + \frac{E_{P,Sys\_i}}{O_{P,Sys,ls}} \right]^{-1} \quad (8)$$

The energy productivity of the overall system – a serious connection of the sub-systems – can be deducted from the sub-system with the following equation:

$$\varepsilon_{P,Sys,ls} = \left[\sum_{i=1}^{n} \left[\varepsilon_{P,Sys\_i,ls} \right]^{-1} \right]^{-1} \quad (9)$$

The energy-productivity index for the overall system can be deducted by accumulating of the achieved effects of all sub-systems. The index must be reduced and can be used for judging the reasonability of the design upgrade:

$$EEI_{P,Sys\_actual,ls} = \cdot \frac{\left[\sum_{i=1}^{n} \left[\varepsilon_{P,Sys\_i\_set,ls} \right]^{-1} \right]^{-1}}{\left[\sum_{i=1}^{n} \left[\varepsilon_{P,Sys\_i\_current,ls} \right]^{-1} \right]^{-1}} = \frac{\sum_{i=1}^{n} \left[\varepsilon_{P,Sys\_i\_current,ls} \right]^{-1}}{\sum_{i=1}^{n} \left[\varepsilon_{P,Sys\_i\_set,ls} \right]^{-1}} \quad (10)$$

The index can be further classified in different energy classes (similar to white goods), but this is not a subject of this paper. The classification is influenced by a wide variety of external factors, e.g. the kind of machine tool or the kind of the production process.

* It is a theoretical indicator which gives the energy productivity if only the current considered system would be necessary to produce the work piece and only this sub-system would consume energy. The indicator could not be compared to the indicator for the overall system (e.g. machine tool), which has a serious connection for the energy productivity of all sub-systems. He is only valuable for the before/after comparison of sub-systems.

4. CONCLUSION

The methodology shown in this paper addresses the increase of energy efficiency of machine tools. It can be used further to increase the efficiency of production systems. In this case the single machine tools of the production systems are handled like the sub-systems of a machine tool. Its core methodology practicable best at increasing the energy efficiency of existing machine tools and production systems by systematically defining and addressing their weak systems in regard to the energy efficiency. Further research is necessary to address links in production systems and by finding design methodologies for absolute new production systems which realize new process chains.

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