Comparison of Machine Tools Regarding Energy – The Difficult Path to an Energy Label

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Abstract

Cutting machine tools are a central part in the production of technical goods. They cause a substantial amount of industry's energy consumption, and thus, will be focused by the Ecodesign of Energy-related Products (ErP) Directive 2009/125/EC. Analogical to consumer products, machine tools have to become verifiable more efficient. Therefore, suitable evaluation values are needed. These values were explained at some examples for existing approaches for energy labels in consuming and industrial products. The usability in production technique will be considered. The aim of this presentation is to investigate new approaches for finding characteristic values that are relevant for machine tools, location-independent and to gather with less data acquisition and measuring effort.

Keywords:

machine tools, energy efficiency, energy label

Introduction

The main article to this presentation was published in the proceedings of the International Chemnitz Manufacturing Colloquium ICMC 2012 and 2nd International Colloquium of the Cluster of Excellence eniPROD. Since this topic attracts wide interests and become relevant in many working fields of eniPROD, the presentation was revised and some slides were added. The references of the article were adapted and updated for this print.

R. Neugebauer, U. Götze, W.-G. Drossel (eds.), Energy-related and economic balancing and evaluation of technical systems – insights of the Cluster of Excellence eniPROD, Proceedings of the1st and 2nd workshop of the cross-sectional group 1 "Energy related technologic and economic evaluation" of the Cluster of Excellence eniPROD, Wissenschaftliche Scripten, Auerbach, 2013.
URN: http://nbn-resolving.de/urn:nbn:de:bsz:ch1-qucosa-105232

Energieeffiziente
Produkt- und Prozessinnovationen
in der Produktionstechnik

Comparison of Machine Tools Regarding Energy – the Difficult Path to an Energy Label

Werkzeugmaschinen energetisch vergleichen – Der schwierige Weg zum Energielabel

Dr. Volker Wittstock, Jörg Paetzold

1. Introduction
2. Existing approaches
3. Methodology for a workshop-orientated evaluation of energy efficiency
4. Measurements using a mobile systems
5. Conclusions

1. Introduction

EU-requirement: verifiable reduction of energy consumption

- **since 1998**
  ISO 14020 et seq. - (→ 14021, 14024, 14025)
  "Environmental labels and declarations" *[1]*
- **2005**
  EuP-directive 2005/32/EC (Energy-using Products)
- **2009**
  ErP-directive 2009/125/EG (Energy-related Products) *[2]*

Source: VDI-Nachrichten, 11/04/2008

2009 CECIMO Self-Regulatory Initiative (SRI) → WG in TC 39 (ISO 14955) *[3]*

2010 FhG-Institutes IZM + IPK → EC Product Group Study (ENTR Lot 5) *[4]*

inhomogeneous product group "machine tools" → **400** types/machine categories

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2. Existing approaches

Energy Indicators

Efficiency η *[5]*

- relation between effort and benefit
- $\eta = \frac{Input}{Output} = \frac{effort}{benefit}$
- dimensionless, (%)

Specific Energy Consumption E_{spec} *[5]*

- for a functional unit (FU)
- $E_{spec} = \frac{Energy}{FU}$
- kWh/workpiece, kWh/m², …

Energy Efficiency Index EEI

- comparative value normalized to a base value (benchmark)
- $EEI = \frac{E_{actual}}{E_{reference}}$
- dimensionless, (%)

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2. Existing approaches

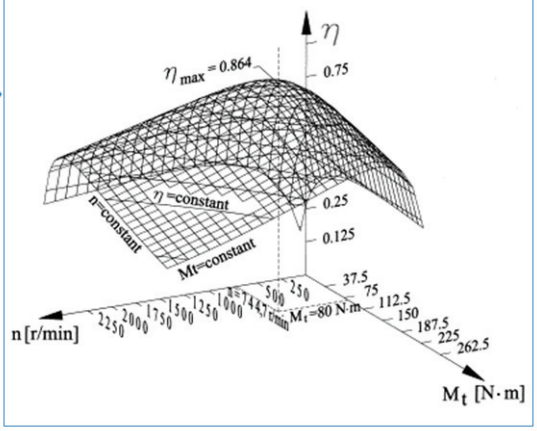
Example: Efficiency map for spindle and feed axis

- **efficiency calculation** for a system:

$$\eta = \prod_{i=1}^{n} \eta_{component\_i}$$

- different efficiency at different operation points (various spindle-speed, torque, feed-rate, …)
  ➔ "field of efficiencies"
- efficiency is **technology-dependent**
- **problems**
  - defining reference value
  - concerning non-productive components and times

Characteristic efficiency diagram for a machine tool (without auxiliary systems) *[6]*



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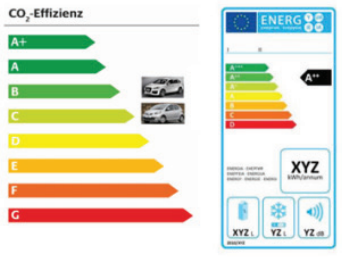
2. Existing approaches

ISO 14020 et seq. - Environmental labels and declarations

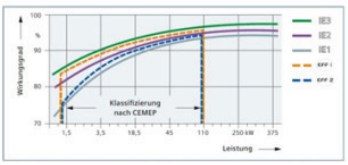
buildings *[7]*
- residential
- non-residential

consumer goods
- heating pumps*[8]*
- white goods *[9]*
- cars *[10]*

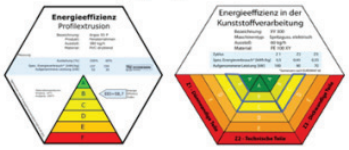


- …

industrial goods
- electro motors *[11]*



- Plastics Processing Machinery *[12]*



- …

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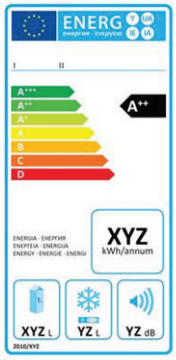
2. Existing approaches - **consumer goods**

ISO 14020 et seq. - examples

✓ ?

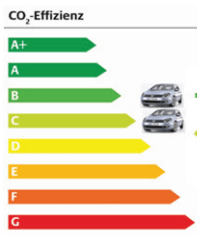
EU-label for refrigerators *[13]*

- corrected effective volume
- defined test parameter
- base value: calculated reference annual energy-consumption (average value of 1998)
- level A dived in sublevels A+ … A+++



German CO_2-label for cars *[10]*

- CO_2-emissions
- **passenger** car ? → **empty** vehicle weight



VW Golf 2,0 TDI
1351 kg
÷ 126 gCO_2/km
= 0,093 gCO_2/(kg*km)

VW Golf 1,2 TSI
1234 kg
÷ 121 gCO_2/km
= 0,098 gCO_2/(kg*km)

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2. Existing approaches - **industrial goods**

✓ Plastic Processing Machinery *[12]*

- application of DIN ISO 14021 *[1]*
  → Self-declared environmental claims (Type II environmental labeling)
- orientation on label for heating pumps
- manufacturing processes:
  - extrusion (1)
  - injection moulding (2)
- reference value:
  - theoretical required energy for material melting
    ➔ practically not reachable

(1)

(2)

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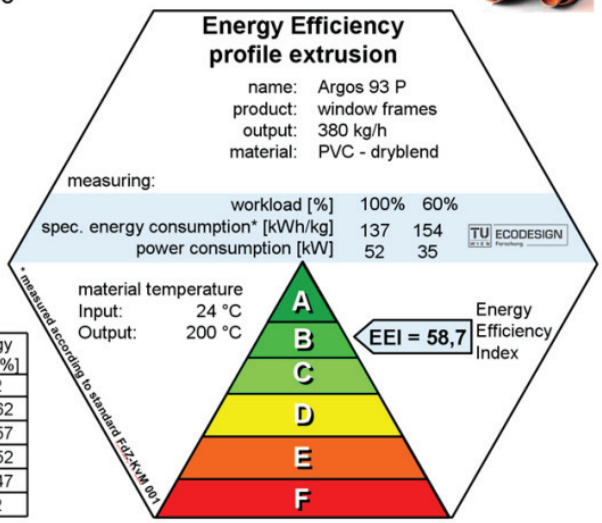
2. Existing approaches - industrial goods

✓ Plastic Processing Machinery – **Extrusion** *[12]* (1)

- measuring-standard: EUROMAP 90
- indication of technical boundary conditions
- specific energy [kWh/kg] and power [kW] consumption for different workloads [%]
- Energy Efficiency Index EEI [%]

Energy class	Type of machine or technology	Energy class [%]
A	BNAT (best not available technology)	> 62
B	BAT (best available technology)	57 – 62
C	State of the art	52 – 57
D	bad state of the art	47 – 52
E	old state of the art	42 – 47
F	Worse tested machine of old state of the art	< 42



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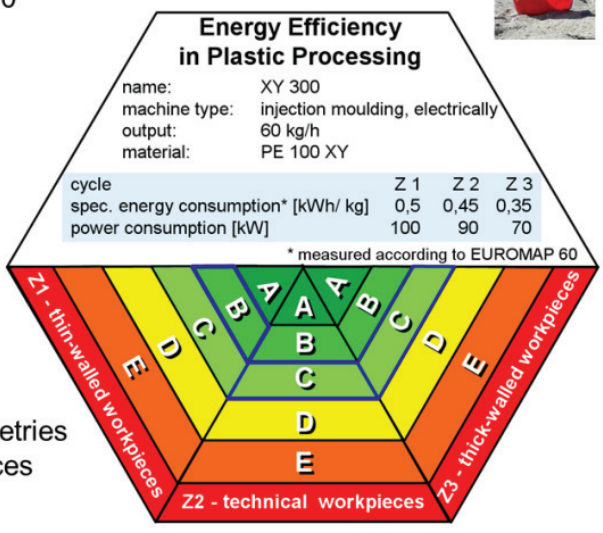
2. Existing approaches - industrial goods

✓ Plastic Processing Machinery - **Injection Moulding** *[12]* (2)

- measuring-standard: EUROMAP 60
- indication of technical boundary conditions
- specific energy [kWh/kg] and power [kW] consumption for different groups of workpieces:
  - Z1 - thin-walled workpieces
  - Z2 - technical workpieces
  - Z3 - thick-walled workpieces

➔ Consideration of specific geometries with typical classes of workpieces



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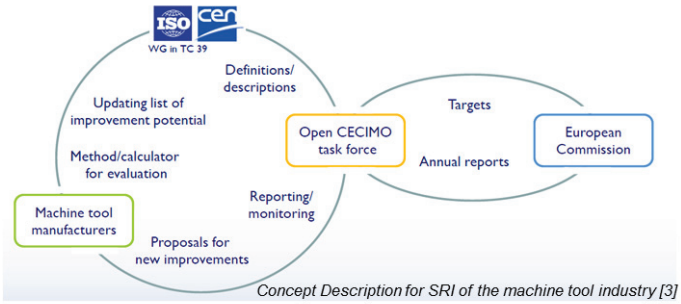
2. Existing approaches - **machine tools**

EU: ECODESIGN Directive 2009/125/EG
Ecodesign of Energy-related Products (ErP), ENTR Lot 5: machine tools

CECIMO Taskforce
Self-Regulation Initiative (SRI) of machine tool manufacturers



Concept Description for SRI of the machine tool industry [3]

***Draft*: ISO 14955: Environmental evaluation of machine tools** *[14]*

conflict of interests: cost efficient products and production

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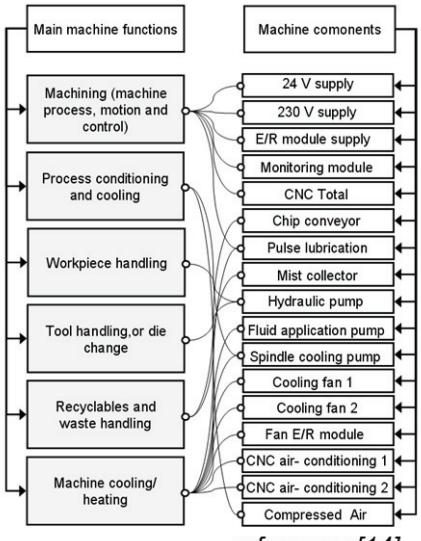
2. Existing approaches - machine tools

Draft: ISO 14955 - "Environmental evaluation of machine tools"

- upcoming standard for metal working machine tools
  ➔ still in progress
- Part 1: Design methodology for energy-efficient machine tools
  - ➔ definition of operating states
  - ➔ assigning components to functions
  - ➔ identify energy-using functions
  - ➔ assigning relevant functions to components
- Part 2: Methods of evaluating energy efficiency of machine tools and machine components
- Part 3 + 4: Test pieces/test procedures and parameters for energy efficiency of metal cutting + forming machine tools (➔ coming up later)



reference: [14]

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2. Existing approaches - machine tools

Energy Efficiency Indicator *EE*

- method of *Kaufeld [15]*
- proposal for technology-independent evaluation
- 15 minute test cycle:
  1. tool change cycle 7,5 min
  2. Manufacturing cycle 3,75 min
  3. Stand-by cycle 3,75 min

$$EE = \frac{number\ of\ tool\ changes \bullet 4}{consumed\ electric\ energy\ E_{vk} \bullet consumed\ compressed\ air\ Q_v \bullet number\ of\ spindles}$$

- correction factors in tool change and manufacturing cycle (E_{vk}) for machine-specific characteristics (geometry, coolant, spindle-speed, nc-axes, dynamic)
- unit: [number/(kW/h • m³/h)]

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3. Methodology for a workshop-orientated evaluation of energy efficiency

Demands for energy labels

Requirements

Reference value / Index
- consistent evaluation criteria
- comparable indicators

Determination of reference value / Index
- theoretical – design of the machine
- practical – gathering at the machine
  → „on the shop floor“

Significance
- Is this the right label for my aim?
- defined case of application/operation (roughing, finishing, …)

Presentation

Evaluation
- Interpretation:
  What conclusion can be drawed?
- Transparency:
  What's considered by the label:
  - the single machine only?
  - the machine in in a certain shop floor?
  - the power generation?

Visualization
- self-explanatory – exclusion of misinterpretations
- relationship to reference value
- quantitative consumption value

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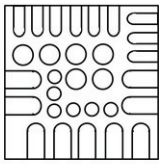
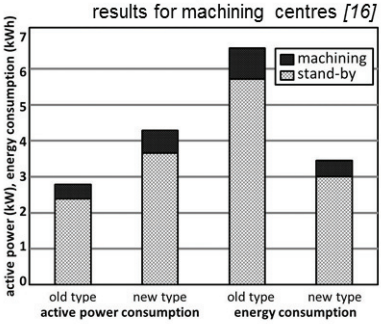
3. Methodology for a workshop-orientated evaluation of energy efficiency

Japanese Standards for metal working machine tools

- JIS TS B 0023: 2010
  „Guidelines - Integrating Environmental Aspects into Design and Development for Machine Tools"
- JIS TS B 0024: 2010
  "Machine Tools - Test Methods for Electric Power Consumption"
  1. Machining centres *[16]*
  2. Numerically controlled turning machines and turning centres
  3. Horizontal grinding wheel spindle and reciprocating table type surface grinding machines
  4. Cylindrical grinding machines
  - electric power consumption in operation modes → moving axes and spindle, machining
  - electric energy consumption → machining test pieces
  - comparison of machine tools of one manufacturer: big ↔ small, old ↔ new, …



test piece and evaluation results for machining centres *[16]*



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3. Methodology for a workshop-orientated evaluation of energy efficiency

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Methodology for a workshop-orientated evaluation of energy efficiency

- Part 3 + 4: Test pieces/test procedures and parameters for energy efficiency of metal cutting + forming machine tools (→ coming up later)

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3. Methodology for a workshop-orientated evaluation of energy efficiency

Target

1) less measuring variables → gathering at the machine → „on the shop floor“
2) data interpretation in relationship to other influencing variables

Procedure/framework

- multistage approach:
  - a) systematization of influencing variables for the energy consumption
  - b) comprehensive data gathering and measuring
  - c) statistical correlation analysis
  - d) show up significant influencing variables
  - e) normalizing on reference value
  - f) Evaluation and comparison with applicable indicators

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3. Methodology for a workshop-orientated evaluation of energy efficiency

a) Systematization of influencing variables

- miscellaneous (machine type, year of manufacture, manufacturing processes)
- size (masses and dimensions for machine, workpieces, workspace)
- quality (positioning accuracy, machining accuracy)
- dynamic (speed, acceleration)
- auxiliary systems (coolant, MQL, automatization modules)
- environmental conditions (forms and quality of needed energy, workshop climate)

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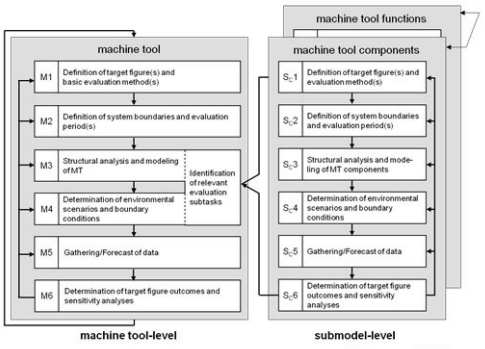
3. Methodology for a workshop-orientated evaluation of energy efficiency

b) Comprehensive data gathering and measuring

Two attempts of a solution within of eniPROD®:

- theoretical – documents, literature
- practical – experimental data from „shop floor“

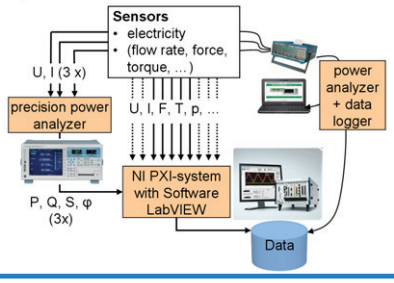
technical and economical analyzing method:



reference [17]

compact mobile measuring system for:

- high dynamic processes
  → milliseconds
- long-time energy consumption
  → days, month



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3. Methodology for a workshop-orientated evaluation of energy efficiency

c) Statistical correlation analyses

- effective dependencies between energy consumption and „potential“ influencing variables
- no evaluation of single components

d) Show up significant influencing variables

- significance of single influencing variables
  ➔ high validity with minimal data gathering and measuring
- investigation of a theoretical explanation for results of c)

e) Normalizing on reference value

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3. Methodology for a workshop-orientated evaluation of energy efficiency

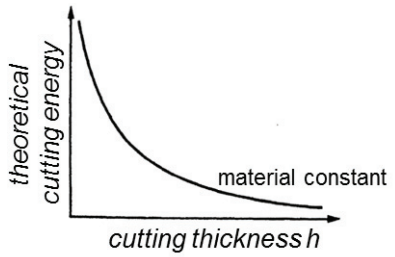
Defining a applicable reference value for cutting machine tools

- theoretical required cutting energy E_{c_th} *[18]:*

$$E_{c\_th} = \frac{P_c}{Q} = k_c \prod K = \frac{k_{c1.1} \prod K}{h^m}$$

- spindle power P_c enables the machining process with a material processed rate Q *[19]*
- specific correction factor K for the manufacturing process
- typical $k_{c1.1}$-values for material classes (Fe, Al, Ti, Ni, CRP, …)

cutting thickness vs. cutting energy *[17]*



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3. Methodology for a workshop-orientated evaluation of energy efficiency

f) Evaluation and comparison with applicable indicators

- Example *[18]*: turning Ck 60, process correction factor $K = 1$

cutting process	cutting thickness h	Specific cutting force k_c	Specific cutting energy E_{c_th}
	[mm]	[N/mm²]	[J/mm³]
roughing	0,80	2220	2,20
finishing	0,20	2850	2,85
precision finishing	0,05	3650	3,65

- Is k_c feasible for normalization?

$$EEI = \frac{theoretical,\ specific,\ normalized\ energy\ requirement}{measured\ specific,\ normalized\ energy\ consumption}$$

- $0 \le EEI \le 1$ (0 % ≤ EEI ≤ 100 %) → similar to efficiency

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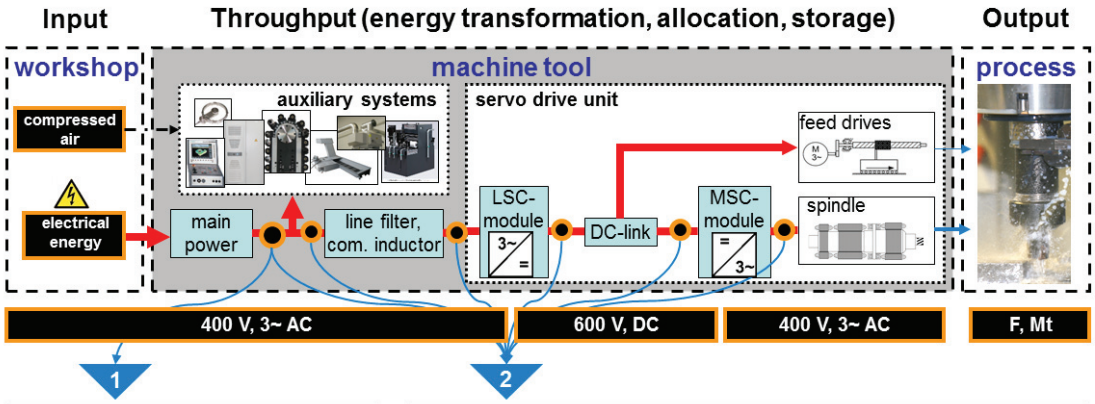
4. Measurements using a mobile systems

Energy flow balancing – from main power supply to spindle



long-time measuring
- time resolution 1-3 s
  → days, weeks

short-time measuring
- high time resolution ≤ 1 ms
  depending on process

- furthermore considered : compressed air ➔ extensions possible

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4. Measurements using a mobile systems

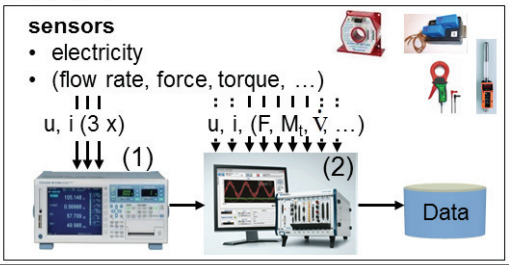
long-time measuring
- time resolution 1-3 s
  → days, weeks
- electrical transducer
- power analyzer
- netbook

➔ easy preparation

short-time measuring
- high time resolution ≤ 1 ms
  depending on process
- different electrical transducer
- precision power analyzer (1)
- NI PXI-system + software LabVIEW (2)

➔ high effort for preparation

➔ enables extensions



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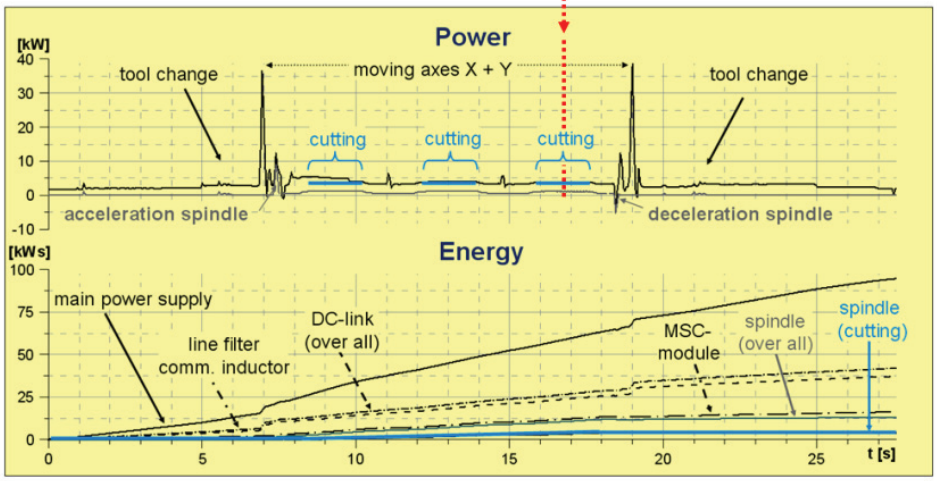
4. Measurements using a mobile systems

Electric measuring – from main power supply to spindle

- milling with coolant, Q=18 cm³/min
- power balance: ca. 14 % of power from main power supply for cutting process



DMG
DMP45V linear

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4. Measurements using a mobile systems

Normalization to a reference value

- existing: numerical relations between characteristics of machine tools *[20, 21]*
- to search for: suitable correction factors and reference values

DMG
DMP45V linear

vertical 3 axis

examples:
comparison of
different milling
centers

StarragHeckert
HEC400D

horizontal 4 axis

Mori Seiki
DuraVertical 5060

horizontal 5 axis

DMG
DMU 125 P duoBLOCK

Heller H2000 *[22]*

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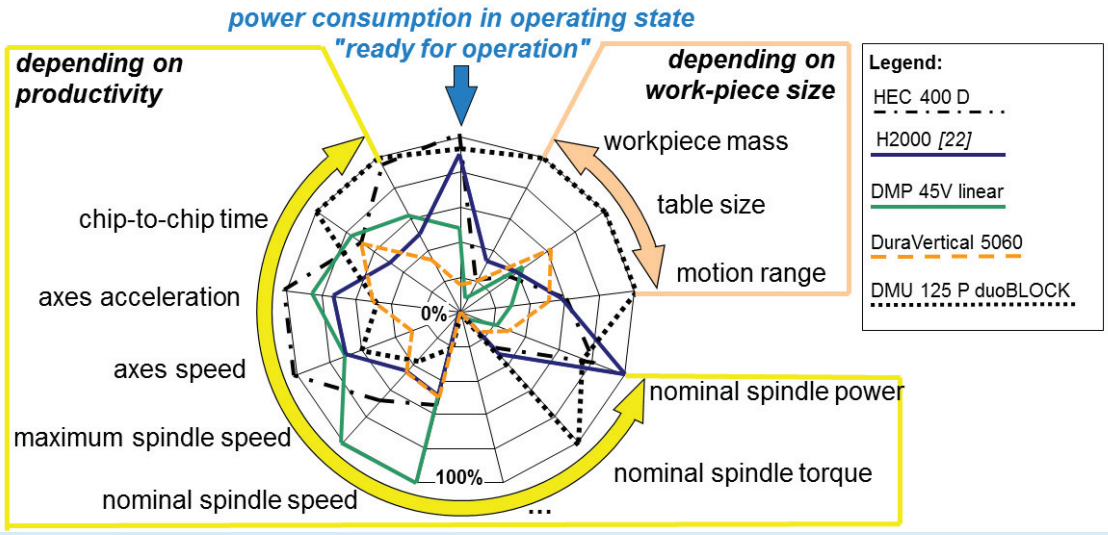
4. Measurements using a mobile systems

Normalization to a reference value

- visualization for some indicators – normalized on max. value of tested machines



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5. Conclusions

- standards and numerous examples for existing energy-labels and indicators → even for the industrial sector
- clear defined reference value needed
- procedure to investigate significant influence values to energy requirement of machine tools by using statistical methods
- proposed reference value:
  theoretical, specific cutting energy k_c for different processes and material classes
- Step 1: Workshop-orientated measuring of energy efficiency

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