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Total Energy Efficiency of Factory-Integrated Machine Tools

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presented by

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To my family.

Acknowledgements

I dedicate this work to my friends from all over the world and in particular to my wonderful family who have made me to who I am today; my mother who taught me gratitude, my father who has planted the seed of the never giving up attitude in me, as well as my brother who has significantly shaped my personality.

Timo Steffen Schudeleit

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Symbols and Acronyms

Latin symbols

Symbol	Unit	Description
A	m^2	Cross-sectional area
C	$\dfrac{W}{m^3}, \dfrac{W}{s}$	Machine-specific coefficient
c_p	$\dfrac{J}{kg\,K}$	Specific heat capacity
e	$\dfrac{J}{m^3}, \dfrac{J}{kg}, \dfrac{J}{piece}$	Specific energy consumption
E	J	Energy
F	N	Force
f_s	Hz	Rated stator frequency
g	$\dfrac{m}{s^2}$	Gravity of Earth
h	m	Height
$i\,,j\,,n$	variable	Fictitious indices
$i(t)$	A	Electric current
$I_{AC,eff}$	A	Effective current of alternating current
I_{act}	variable	Input of the actual system
I_{DC}	A	Direct electric current
I_{ref}	variable	Input of the reference system
k	$\dfrac{m^2}{s^2}$	Machine specific constant
L_m	H	Main field inductance
L_r	H	Rotor inductance
L_s	H	Stator inductance
m	kg	Mass

Symbol	Unit	Description
$\dot{m}$	$\dfrac{kg}{s}$	Mass flow
M	$\dfrac{kg\,m^2}{s^2}$	Momentum
n_p	-	Number of pole pairs
n_{pcs}	-	Number of pieces
n_{ps}	-	Number of pump stages
n_{rev}	$\dfrac{1}{s}$	Number of revolutions
O_{act}	variable	Output of the actual system
O_{ref}	variable	Output of the reference system
p	$\dfrac{kg}{m\,s^2}$	Pressure
P	W	Power
P_I	W	Cable bound supply, i.e. electrical energy (type I)
P_{II}	W	Tube bound supply with inlet measuring only, e.g. compressed air (type II)
P_{III}	W	Tube bound supply with inlet and outlet measuring, e.g. cooling water circuit (type III)
P_{IV}	W	Other functions that are supplied primarily under the use of electrical energy, e.g. exhaust air (type IV)
$P_{AC,eff}$	W	Effective power of alternating current
P_{DC}	W	Power of direct electric current
$\dot{Q}$	W	Heat flow
$Q_{AC,eff}$	W	Reactive power of alternating current
Q_m	$\dfrac{kg}{s}$	Mass material removal rate
Q_{vol}	$\dfrac{m^3}{s}$	Volume material removal rate
R_r	-	Rotor resistance
R_s	-	Stator resistance
S	-	Time share

$S_{AC,eff}$	W	Apparent power of alternating current
t	s	Time
T	s	Time period
$u(t)$	V	Voltage
$U_{AC,eff}$	V	Effective voltage of alternating current
U_{DC}	V	Voltage of direct electric current
v	$\dfrac{m}{s}$	Velocity
$\dot{V}$	$\dfrac{m^3}{s}$	Volume flow
X_m	Ω	Main field reactance
$\overline{X}$	variable	Mean value of a variable
$X_{\sigma 2'}$	Ω	Rotor leakage reactance
$X_{\sigma 1}$	Ω	Stator leakage reactance

Greek symbols

Symbol	Unit	Description
α_{SI}	-	Sufficiency Index
Δ	variable	Difference of two quantities of the same type
ε	-	Energy efficiency ratio
ζ	$\dfrac{J}{m^3}$	Specific fan power
η	-	Efficiency
η_{conv}	-	Energy conversion efficiency
$\eta_{EI/CI}$	-	Relative conversion efficiency
η_{TEEI}	-	Total Energy Efficiency Index
η_{VAEE}	-	Value adding energy efficiency
η_{VAES}	-	Value adding energy share
ϑ	K	Temperature
Θ	kgm^2	Moment of inertia
κ	$\dfrac{J}{m^3}$	Specific compression power
λ_{CI}	variable	Consistency Index
λ_{EEI}	-	Energy efficiency index
λ_{EI}	variable	Efficiency Index
π	-	Circle constant
ρ	$\dfrac{kg}{m^3}$	Density
φ	rad	Phase angle
ω	$\dfrac{rad}{s}$	Angular velocity
$\ddot{\varphi}$	$\dfrac{rad}{s^2}$	Angular acceleration

Indices

Index	Description
AC	Air conditioning system
AC / EA	Combined air conditioning system and exhaust air system
act	Actual system
$brgs$	Bearings
BS	Building shell
CA	Compressed air system
$cnst$	Constant
$conv$	Conversion
$cool$	Cooling
$cycl$	Cyclic
EA	Exhaust air system
EC	Electric power consumption
EEI	Energy efficiency index
EI	Energy intensity
EM	Electric motor
f	Field
fld	Fluid
$hydr$	Hydraulic
IMT	Integrated machine tool integrated
$incp$	Incompressible
inv	Inverter
kin	Kinetic
m	Mass
$mech$	Mechanic
MRR	Material removal rate
MT	Machine tool
n	Norm conditions
nom	Nominal
opt	Optimization
PEF	Primary energy factor

pneu	Pneumatic
pot	Potential
proc	Processing
ref	Reference system
rot	Rotatory
s	State
stby	Standby
stdy	Steady
TBS	Technical building service
tns	Translatory
tot	Total
VA	Value adding
VAEE	Value adding energy efficiency
VAES	Value adding energy share
vol	Volume
WC	Water cooling system

The indexing system is listed in Table 1. If the type of power is classified as electrical, the prefix EC is used. For both power and other values such as flows, pressures, etc. the system type as well as the level of investigation are indicated. For instance, $P_{EC-CA-MT}$ is the electric power consumed (EC) to produce compressed air (system type is the CA system) to operate a MT (level of investigation is MT level).

Table 1: Indexing system

Prefix	System type	Level of investigation
EC (if electric power consumption)	CA	MT, TBS, or IMT
	WC	
	AC	
	EA	
	AC/EA	
	/	
	TBS	MT or BS

Acronyms

AC	Air conditioning
BAT	Best available technology
BS	Building shell
CA	Compressed air
CECIMO	Comité Européen de Coopération des Industries de la Machine-Outil (engl.: European Association of the Machine Tool Industries)
CI	Consistency Index
CO_2	Carbon dioxide
DIN	Deutsches Institut für Normung (engl.: German Institute for Standardization)
EA	Exhaust air
EC	Electricity consumption
EER	Energy efficiency ratio
EI	Efficiency Index
ErP	Energy-related product
ETH	Eidgenössische Technische Hochschule (engl.: Swiss Federal Institute of Technology)
EU28	28 states of the European Union
EuP	Energy-using product
IMT	Integrated machine tool
ISI	Institut Systemtechnik und Innovationsforschung
ISO	International Organization for Standardization
IWF	Institut für Werkzeugmaschinen und Fertigung (engl.: Institute of Machine Tools and Manufacturing)
JSA	Japanese Standards Association
LCA	Life cycle assessment
MEI	Minimum efficiency index
MER	Mandatory ecodesign requirements
MRR	Material removal rate
MT	Machine tool

O	Objective
PEF	Primary energy factor
SCP	Specific compression power
SEC	Specific energy consumption
SFP	Specific fan power
SI	Sufficiency Index
SRI	Self-regulatory initiative
TBS	Technical building service
TCP	Tool center point
TEEI	Total Energy Efficiency Index
VDI	Verein Deutscher Ingenieure (engl.: The Association of German Engineers)
WC	Water cooling

Abstract

Energy efficiency in industry has been underlined as one of the most important challenges of the 21st century by the EU's eco-design directive for energy-related products (2009/125/EC). Aiming to decrease European energy consumption by 20% by 2020 relative to projections, the European initiative Horizon 2020 pushes for standardizing the environmental evaluation of machine tools, which is in the scope of the responsibility of the International Organization for Standardization (ISO). Due to machine tools' complexity and individuality both in design and application, the ISO 14955 series, which aims for the environmental evaluation of machine tools, is still under development.

Existing machine tool models consider the direct electrical energy and compressed air consumption, but do not incorporate the electrical energy consumption related to the technical building service, such as water cooling, air conditioning, or exhaust air treatment. This is essential for setting up a comprehensive energy balance for a machine tool. Within this thesis, a factory-integrated machine tool model is developed by calculating the electrical power demand of the technical building service to operate a machine tool using electrical energy equivalents.

A metric to fully assess the energy efficiency of a factory-integrated machine tool based on its individual components' needs to take into account each component's efficiency and need-based utilization (sufficiency) with reference to an efficiency limit (consistency). Such a metric, which comprises the sustainability strategies efficiency, sufficiency, and consistency, is developed within this thesis and referred to as Total Energy Efficiency Index.

The applicability of both the model and the metric are shown in a practical case study of a grinding machine, serving as a blueprint for future application and modification. All in all, the total energy efficiency of the analyzed factory-integrated machine tool does not exceed 41% for any considered types of production. The machine tool's heat exchanger unit and coolant unit as well as the factory's combined air-conditioning and exhaust air system show based on the performed analysis the highest improvement potentials.

Zusammenfassung

Energieeffizienz in der Industrie wurde durch die Europäische Öko-Design Direktive für energiebezogene Produkte (2009/125/EC) als eine der wichtigsten Herausforderungen des 21. Jahrhunderts herausgestellt. Abzielend darauf, den Europäischen Energieverbrauch bis 2020 um 20% im Vergleich zu Projektionen zu reduzieren, treibt die Europäische Initiative Horizon 2020 die Standardisierung der Umweltbewertung von Werkzeugmaschinen voran, welche sich im Rahmen der Verantwortung der Internationalen Organisation für Standardisierung (ISO) befindet. Aufgrund der Komplexität und Individualität von Werkzeugmaschinen, sowohl im Design als auch in der Anwendung, ist die ISO 14955 Serie, welche auf die Umweltbewertung von Werkzeugmaschinen abzielt, weiterhin in der Entwicklung.

Bestehende Werkzeugmaschinenmodelle berücksichtigen den direkten, elektrischen Energieverbrauch sowie den Druckluftverbrauch, aber integrieren nicht die verbrauchte elektrische Energie, die im Zusammenhang mit der Gebäudetechnik steht, wie der Wasserkühlung, der Klimaanlage oder des Abluftsystems, steht. Dies ist notwendig, um eine umfassende Energiebilanz für eine Werkzeugmaschine aufzustellen. In dieser Thesis wird ein Model einer fabrikintegrierten Werkzeugmaschine entwickelt, indem der elektrische Leistungsbedarf der Gebäudetechnik, um die Werkzeugmaschine zu betreiben, mittels Energieäquivalenten berechnet wird.

Eine Metrik, um die Energieeffizienz einer fabrikintegrierten Werkzeugmaschine auf Basis von ihren individuellen Komponenten komplett bewerten zu können, muss für jede Komponente die Effizienz und die bedarfsgerechte Nutzung (Suffizienz) in Bezug auf ein Effizienzlimit (Konsistenz) berücksichtigen. Eine solche Metrik, welche die Nachhaltigkeitsstrategien Effizienz, Suffizienz und Konsistenz umfasst, ist in dieser Thesis entwickelt und wird als Gesamtenergieeffizienzindex bezeichnet.

Die Anwendbarkeit des Modells sowie der Metrik sind in einer praktischen Fallstudie an einer Schleifmaschine gezeigt, was als Vorlage für zukünftige Anwendungen und Modifikation dienen soll. Insgesamt überschreitet die Gesamtenergieeffizienz der analysierten fabrikintegrierten Werkzeugmaschine 41% für keine der betrachteten Produktionsarten. Die Wärmetauscher- und die Kühlschmiermitteleinheit der Werkzeugmaschine sowie die das kombinierte Klimaanlagen- und Abluftsystem der Fabrik zeigen basierend auf der durchgeführten Analyse die grössten Verbesserungspotentiale.

1. Introduction

Meadows et al. [1] predicted in "The Limits to Growth" the upcoming predicaments of mankind. On the one hand, the five basic elements "population, food production, industrialization, pollution and exploiting of nonrenewable resources" [1] are expected to rise exponentially in the following years. On the other hand, the naturally supported growth is limited by the earth's bio-capacity, which includes material and energy used. The balance between consumption and regrowth is desirable to be ensured by the sustainable development defined by the United Nations as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. The United Nations [3] distinguishes between three interacting dimensions of sustainability, which all need to be considered in sustainable development:

- **Social dimension:** Relationship between services provided by a human being in exchange for societal benefits that are being received.

- **Environmental dimension:** Conservation of the earth's bio-capacity equilibrium by adjusting the resources consumed to the natural regrowth rate and the emissions generated to the natural absorption rate.

- **Economic dimension:** Maintaining and creating of economic conditions in order to meet individual and social needs.

Schaltegger et al. [4] specified the interactions between these dimensions by introducing three concepts (see Figure 1):

- **Socio-efficiency:** Maximize the social benefit while keeping the economic effort low.

- **Eco-justice:** Maximize environmental conservation while keeping the social compromises low.

- **Eco-efficiency:** Maximize the economic benefit while keeping the environmental impact low.
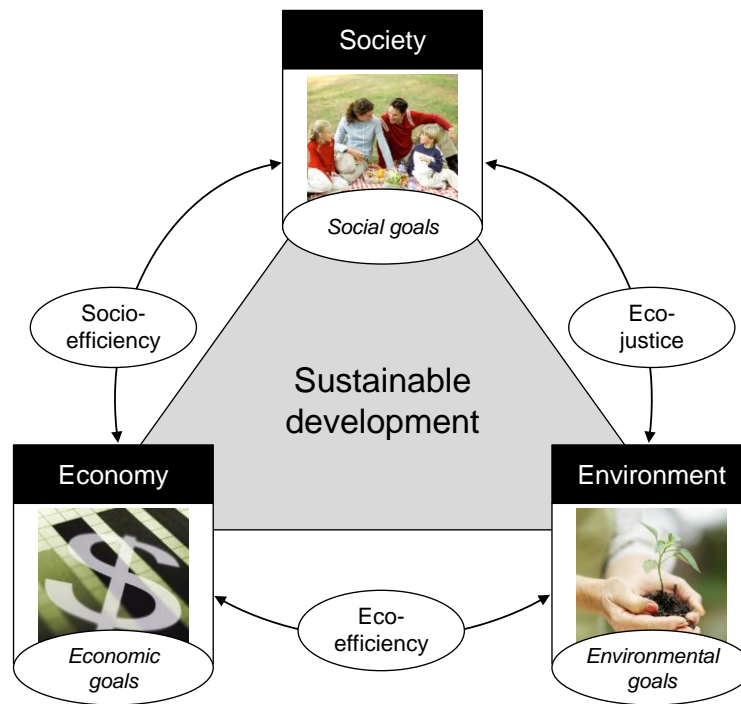
Figure 1: Three dimensions of sustainability: Society, Environment and Economy [3, 4].

In their 30-year update to "The Limits to Growth", Meadows et al. [5] suggested seven guidelines for overcoming today's challenges of this increasingly important issue. One of the seven suggested guidelines for a sustainable society is "use all resources with maximum efficiency" [5] which shall lay the foundation of this thesis.

1.1. Motivation

As industrial electricity consumption contributes to 36.9% [6] of the total electricity consumption in the 28 states of the European Union (EU28) (compare Figure 2), manufacturing industries and machine tool (MT) builders in particular have great influence on the reduction of resources used and CO_2 emitted. The worldwide manufacturing industries' energy saving potential is estimated to be 20% by 2050 [7].

EU28 – Electricity Consumption by Sector 2014

1.7%	0.3%
29.0%	36.9%
29.8%	2.3%

- Industry
- Transport
- Households
- Services
- Agriculture/Forestry
- Others
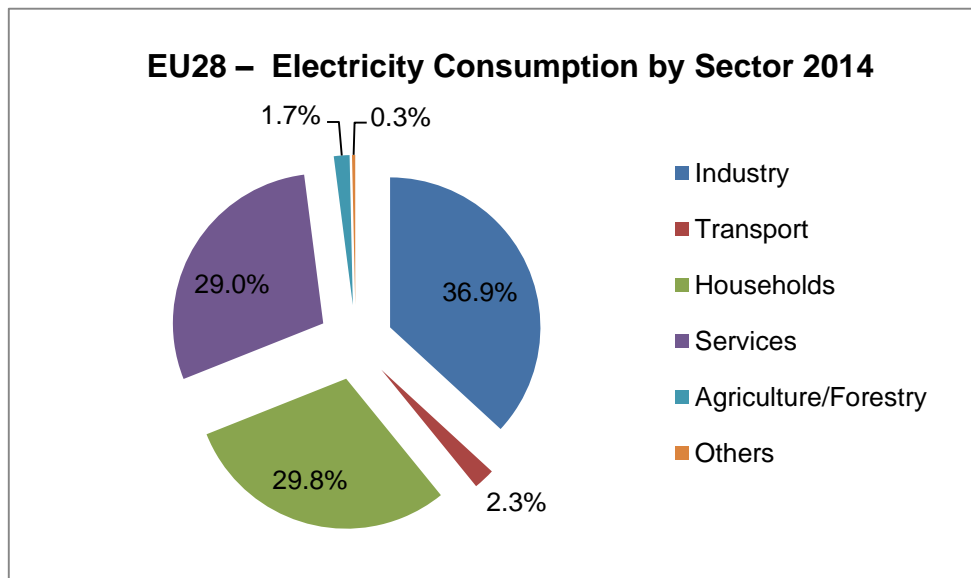
Figure 2: EU28 – Electricity consumption by sector in 2014 [8].

The European directive 2005/32/EC [9] defines the energy-using products (EuPs) that are meant to be regulated, to which MTs belong. The scope has been extended by the European directive 2009/125/EC [10] to energy-related products (ErP). These initiatives and the European directive 2012/27/EU [11] aim to push manufacturers of ErPs to increase their products' energy efficiency by 20% by 2020, compared to projections. Critical ErPs that are subjected to specific initiatives such as incentives, subsidies, and market regulations are defined in order to support accomplishing these objectives. Products must meet the following criteria to be classified as critical [12]:

- significant sales volume,

- significant environmental impact, and

- significant improvement potential.

3

MTs with sale volumes upwards of 300.000 pieces per year in the EU [13] are part of the industrial consumers that collectively contribute to 36.9% [8] of the European electricity consumption, and have an efficiency improvement potential estimated to 25% [14]. Thus, MTs have great influence on the reduction of the energy use as well as the associated CO_2-emissions and are classified as critical products.

The requirements towards production developed over time and new paradigms evolved that are considered to be crucial for maintaining competitiveness. Besides the traditional target variables – costs, time, and quality – new paradigms such as adaptability or innovativeness gained in significance. Müller et al. [15] illustrated the historical development of production systems depicted in Figure 3 and stated energy efficiency to be the most recent paradigm for production systems. In energy intensive industries, the energy costs alone can account for up to 60% of the total production costs [16]. Along those lines, Abele et al. [3] carried out a total cost of ownership calculation and determined the electricity costs of running a MT to be 24% of the operating costs. Thus, energy efficiency can be considered as a complementing aspect to the traditional economic factor costs and can be a promising way to strengthen companies' competitiveness.
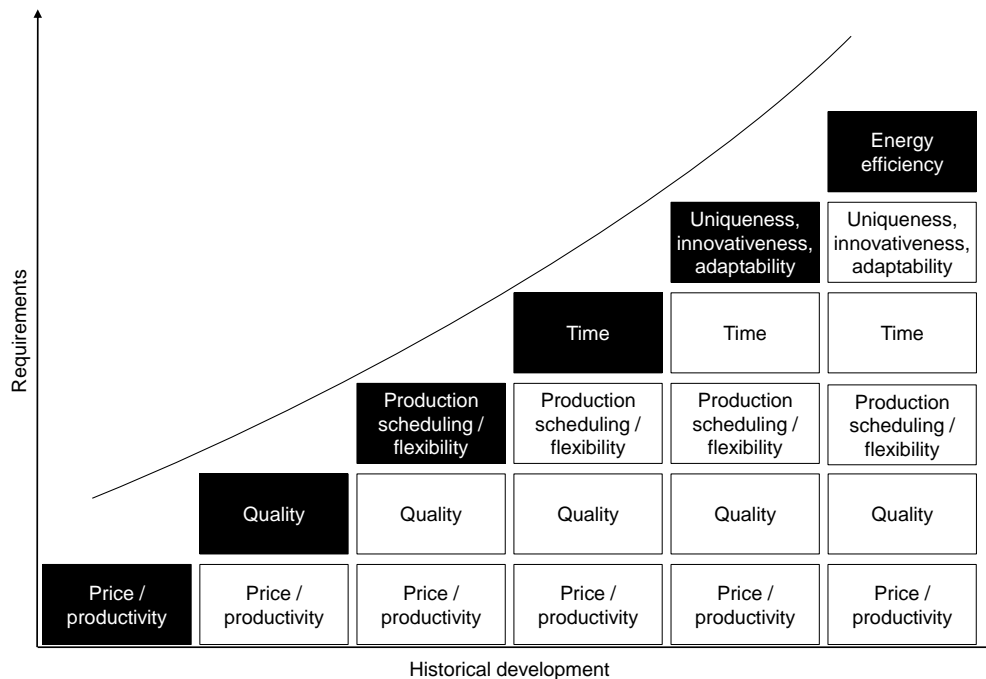
Figure 3: Historical development of paradigms for production systems [15].

Aside from price and productivity, quality has been a major objective in manufacturing for several decades. Quality is negatively influenced by the error of the tool center point (TCP), among other

thermal errors. The electricity consumed by a MT is converted into heat that causes thermal errors and needs to be removed by cooling systems. Ess [17] sees a root cause of thermal errors in the lack of energy efficiency of a MT; due to inefficiencies, more energy is supplied to the MT and converted into heat; the occurring heat transfer impacts the temperature distribution in the solid structures of the MT, leading to mechanical deformation and finally resulting in an error of the TCP.

1.2. Scope

The general life cycle as described in ISO 14040 [18] begins with the raw material acquisition, continues with the production and use of the products, and ends with the waste treatment, the recycling or reuse. The life cycle phase model is valid for any kind of product, such as machines, factory buildings, and consumer goods. Figure 4 depicts the intersecting product life cycle and the manufacturing system life cycle adapted from ISO 20140-1 [19]. The life cycles cross at the product production during operation phase of the manufacturing system.
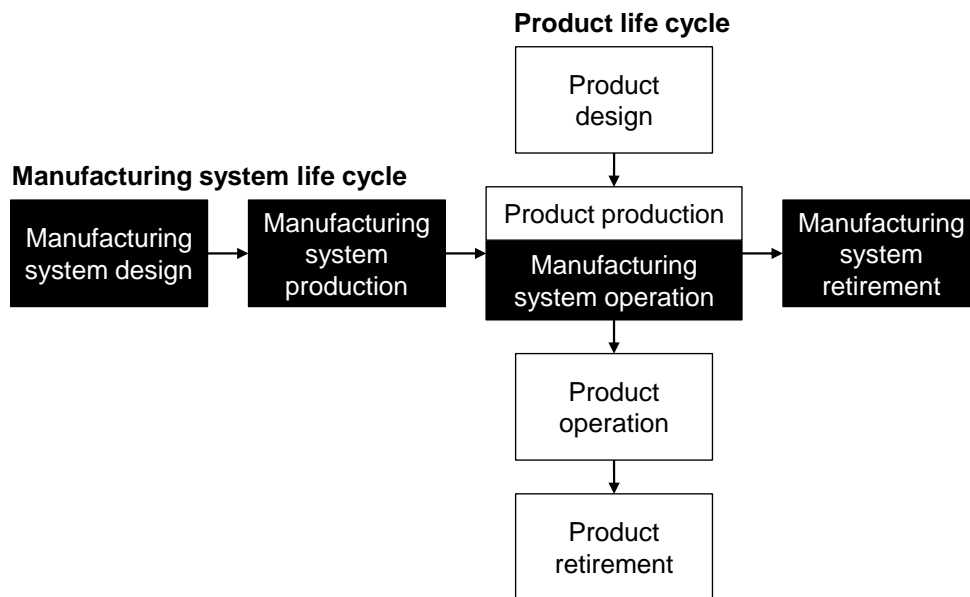
Figure 4: Intersecting product life cycle and manufacturing system life cycle adapted from ISO 20140-1 [19].

Weber and Züst [20] introduced a model for the intersecting life cycles of products and MTs. The model distinguishes between three types of benefits when reducing the environmental impact of MTs and their products:

- **Type I benefit:** simplified MT production, e.g. optimized transportation and efficient assembly through modular structure result in shorter lead times as well as energy savings.

- **Type II benefit:** efficient MT use, e.g. switch-off of the MT during non-operation decreases the energy consumption.

- **Type III benefit:** efficiency of the manufactured product, e.g. high production accuracy of camshafts leads to lower surface friction and results in energy savings.

Züst et al. [21, 22] showed that the environmental impact of a MT is dominated by its use phase. It is consequently comprehensible to shift the focus of attention to this phase and hence on Type II benefits.

Scope 1: Energy efficiency assessment of the use phase of MTs

A manufacturing process describes a physical transformation process of an initial state into a target state. DIN 8580 [23] refers to manufacturing processes as all procedures for the manufacture of geometrically defined solid objects and classifies the manufacturing processes into six main groups (compare Figure 5):

- **Primary shaping:** Manufacturing process of a solid workpiece from shapeless material by creating cohesion, e.g. molding.

- **Forming:** Manufacturing process that plastically changes the shape of a solid workpiece while conserving cohesion, e.g. bending.

- **Separating:** Manufacturing process which reduce cohesion of a solid workpiece partially or eliminates it completely, e.g. milling.

- **Joining:** Manufacturing process to increase cohesion between several geometrically defined and solid workpieces, e.g. welding.

- **Coating:** Manufacturing process to increase cohesion by applying a firmly adhering layer of shapeless material to a workpiece, e.g. varnishing.

- **Material property changing:** Manufacturing process to modify the properties of a workpiece's material without change of shape or cohesion, e.g. hardening.
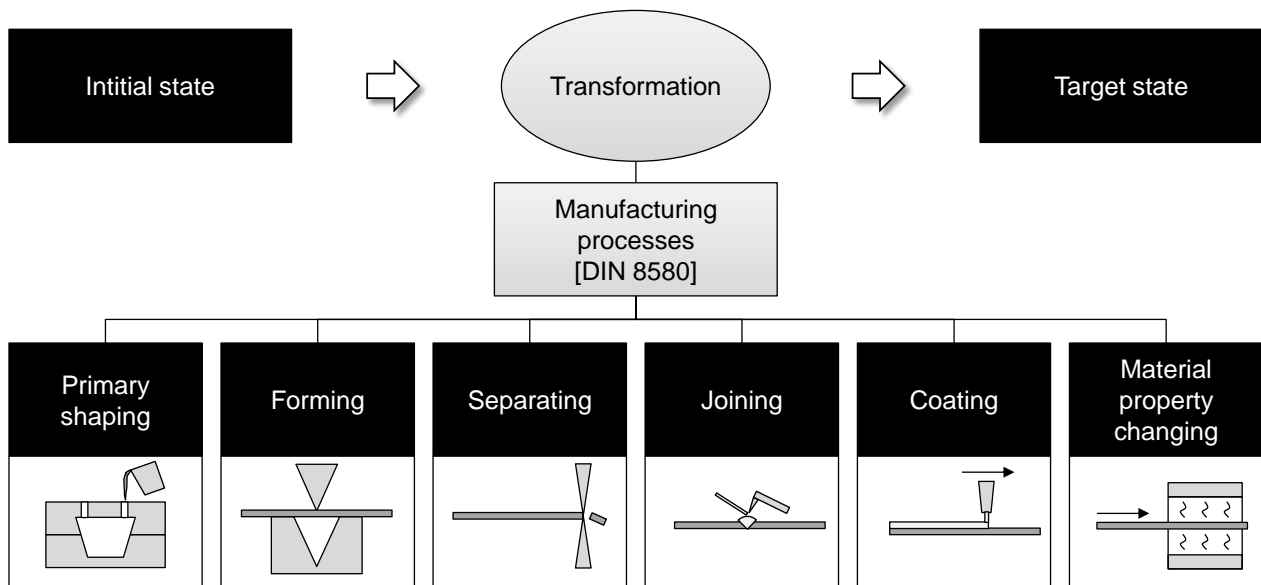
Figure 5: Classification of manufacturing processes according to DIN 8580 [23].

The thesis solely looks at separating manufacturing processes, which will be referred to as manufacturing processes.

Scope 2: Analysis of separating manufacturing processes.

2. Theoretical Background

2.1. Regulations and Standards on Energy Efficiency of MTs

2.1.1. Energy Efficiency Labelling of MTs and Regulatory Initiatives

DIN EN ISO 14020 defines environmental declaration (also referred to as environmental label) as "claim which indicates the environmental aspects of a product or service" [24]. DIN EN ISO 1402x series [24-27] addresses the environmental labelling of products and distinguishes three types of environmental labelling applicable depending on the product type:

- DIN EN ISO 14020: Environmental labels and declarations – General principles

- DIN EN ISO 14021: Environmental labels and declarations – Self-declared environmental claims (Type II environmental labelling)

- DIN EN ISO 14024: Environmental labels and declarations – Type I environmental labelling – Principles and procedures

- DIN EN ISO 14025: Environmental labels and declarations – Type III environmental declarations – Principles and procedures

Directive 2010/30/EU [28] deals with energy efficiency labelling and outlines it as a means to measure the energetic performance of a product and enforce market regulations in order to reach the aforementioned reduction in energy consumption and CO_2-emissions. The energy efficiency directive 2012/27/EU [11] reaffirms both directives 2009/125/EC and 2010/30/EU, and it "establishes a common framework of measures for the promotion of energy efficiency within the Union in order to ensure the achievement of the Union's 2020 20% headline target on energy efficiency and to pave the way for further energy efficiency improvements beyond that date" [11].

Herrmann et al. [29] highlight the correlation between increasing product complexity and the rising difficulty in developing an energy efficiency label. They classified MTs as more complex than components for industry (such as pumps and electric drives), buildings, and cars due to their high variety design and utilization. The resulting difficulty to develop a standardized test procedure is the reason for a lack of energy efficiency labelling for MTs and for alternative approaches being investigated.

On behalf of the European Commission (EC), Schischke at el. [30] and Mudgal et al. [31] jointly conducted a study on how to implement a common framework for enhancing energy efficiency of MTs. They distinguish three strategies different than business-as-usual (in ascending by their estimated improvement potential):

1. Mandatory ecodesign requirements (MER)

2. Self-regulatory initiative (SRI)

3. Best available technology (BAT)

The MER and BAT are respectively rule-based and point-based assessment methods. CECIMO [32, 33] – the European Association of the MT Industries – intends to launch a SRI aiming at the energy efficiency increase of MTs. The SRI concept leaves the evaluation of energy efficiency improvements to the MT manufacturers, who need to report to a supervisory unit. This allows MT manufacturers to implement and assess their MTs individually according to their specialized design and their intended application.

2.1.2. Environmental Evaluation of MTs

The working group ISO/TC 39/WG 12 started in May 2010 to develop the standard series ISO 14955 aiming at the environmental evaluation of MTs. The standard is divided into four main parts:

- ISO 14955-1: Eco-design methodology for machine tools

- ISO 14955-2: Methods for measuring energy supplied to machine tools and machine tool components.

- ISO 14955-3: Principles for testing metal-cutting machine tools with respect to energy efficiency

- ISO 14955-4: Principles for measuring metal-forming machine tools and laser processing machine tools with respect to energy efficiency

ISO 14955-1 [34] is both valid for metal-cutting and metal-forming MTs. The normative part deals with methods for the general energy efficiency evaluation of MTs and the integration of energy efficiency measures into the product development process. The informative appendix contains a list of proven and well-established improvement measures for increasing the energy efficiency of

MTs. The rule-based approach covers the following areas of improvement: overall machine concept, drive units, hydraulic systems, pneumatic systems, electric systems, cooling lubricant system, cooling system, peripheral devices, control systems, and guidance on energy efficient use. The VDMA 34179 [35] outlines the instructions on how to measure the energy and resource demand of MTs based on ISO 14955-1.

2.1.3. Factory Integration of MTs

The MTs integrated into the factory (referred to as IMTs) are emphasized by the ISO 20140 series, which focuses on the manufacturing system evaluation regarding energy efficiency and similar environment influencing factors. ISO 20140-1 [19] deals with the structure of manufacturing systems, boundaries between the units and general energy efficiency enhancing principles as well as environmental evaluation. ISO 20140-2 to ISO 20140-5 have not been published yet. ISO/CD 14955-2 [36] specifies the interconnections of a MT with the technical building service (TBS). Modern MTs are generally integrated into a factory and require different energy and mass flows provided on shop floor level. For an entire integration of a MT into the factory environment, four classes of energy exchange are distinguished by the ISO/CD 14995-2 [36]:

- **Type I:** Cable bound supply, i.e. electrical energy.

- **Type II:** Tube bound supply with inlet measuring only, e.g. compressed air.

- **Type III:** Tube bound supply with inlet and outlet measuring, e.g. cooling water circuit.

- **Type IV:** Other functions that are supplied primarily under the use of electrical energy, e.g. exhaust air.

Hesselbach et al. [37] introduced a factory model that describes the interaction of the factory elements MTs, TBS, building shell (BS), and the environment. Figure 6 illustrates an exemplary model of a MT interacting with the TBS based on Hesselbach et al. [37] and ISO/CD 14955-2 [36]. Energy relevant interfaces are electricity, compressed air, water cooling, exhaust air (forced convection), and air conditioning (natural convection). Services to compensate for external environmental conditions such as illumination, temperature, humidity, etc. are excluded from the consideration.
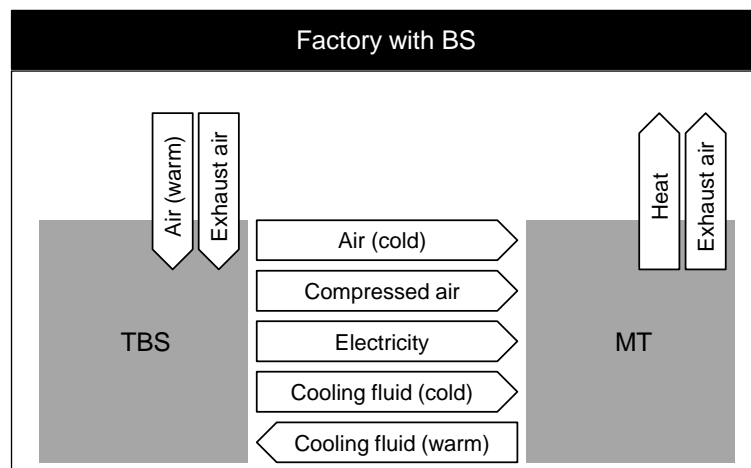
Figure 6: Exemplary interconnection of a MT and the TBS (adapted from Hesselbach et al. [37], ISO 20140-1 [19], ISO/CD 14955-2 [36]).

2.2. Terminology

From the perspective of manufacturing companies, energy is converted from nature to primary energy over to secondary energy to final energy, which is used to realize a targeted energy. The energy conversion chain adapted from Müller et al. [13] and VDI 4661 [59] is illustrated in Figure 7.
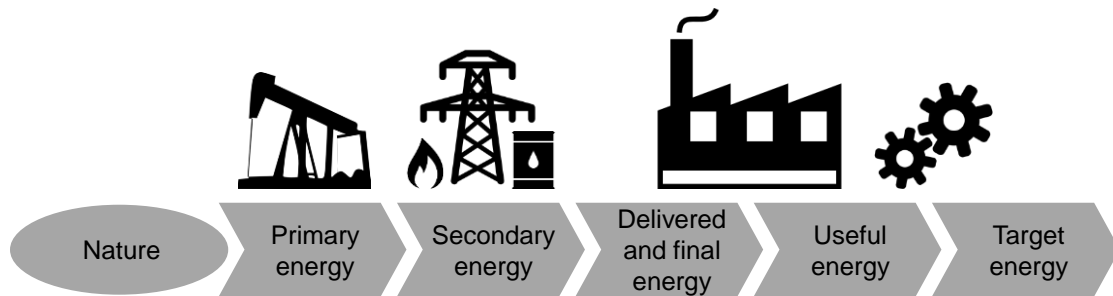
Figure 7: Schematic energy conversion chain adapted from Müller et al. [15] and VDI 4661 [38].

VDI 4661 [38] describes the energy forms for industrial use as follows:

- **Primary energy:** Energy of energy sources or carriers which are found in nature and which have not been converted by technical processes.

- **Secondary energy:** Energy of energy carriers which have been obtained from primary energy by means of one or more conversion operations.

- **Delivered energy:** Energy content of all traded primary and secondary energy sources which the end consumer purchases.

- **Final energy:** Traded energy carriers which are used for generating or converting useful energy.

- **Useful energy:** All technological forms of energy which the consumer ultimately requires.

- **Target energy:** Energy aimed at in an energy-conversion process or a technical energy transformation.

VDI 4661 [38] contains definitions of technical terms relevant in the context of power engineering:

- **Energy conversion:** Energy conversion is a generic term for changing one form of energy into another form of energy.

- **Energy converters:** Energy converters are devices and installations for energy conversion (for example, generators, motors, ovens, lamps).

- **Energy utilization:** Energy utilization is the use of final energy for the generation or conversion of useful energy for the particular purpose of an energy service.

- **Energy demand:** The energy demand is the final energy to be used in order to perform a defined energy service, with a suitable technology being used and for defined boundary conditions.

- **Energy consumption:** Energy consumption is the quantity of particular forms of energy consumed in order to cover energy demands under real conditions.

- **Energy loss:** Energy loss is that part of the supplied energy which escapes form a system and which was not used as intended for the process. An energy loss of this kind can of course be exploited, at least in part, in a different system.

- **Conversion loss:** Conversion loss is the loss of exergy when one form of energy is converted into another. It does appear as an energy loss.

The term efficiency is frequently used in context of the performance evaluation of a system. ISO 9000 defines efficiency as the "relationship between the results achieved and the resources used" [39]. ISO 50001 defines energy efficiency as "ratio or other quantitative relationship between an output of performance, service, goods or energy, and an input of energy" [40] and gives exemplary energy efficiency indicators. Simply stated, improving energy efficiency means to achieve more output with less energy input. ISO 50001 defines the physical entity energy as "the capacity of a system to produce external activity or perform work" [40] and lists forms of energy such as electricity, fuels, steam, heat, and other media. The performed work or energy E is mathematically expressed as the integral of the power P over time t

$$E = \int_{t_0}^{t_1} P(t)\, dt \tag{2.1}$$

More information on the terminology, definitions, and mathematical relations can be found in the literature [38].

2.3. Physical Fundamentals

Energy can exist in various forms and be converted among them. A selection of different types of energy conversions by MT component is listed in Table 2.

Table 2: Component types and energy types.

Component	Input type	Output type
Converter/amplifier	*electrical*	*electrical*
Axis	*electical*	*mechanical*
Electric drive	*electrical*	*mechanical*
Gears	*mechanical*	*mechanical*
Pump	*mechanical*	*hydraulical*
Heat exchanger	*hydraulical*	*thermal*
Compressor, fan, exhaustion	*mechanical*	*pneumatical*

2.3.1. Electrical Power

VDI 4661 [38] contains a brief description of the relevant terms of electrical power. Electrical power of direct current is defined by

$$P_{DC} = U_{DC} \cdot I_{DC} \tag{2.2}$$

with the voltage U_{DC} as measure of the potential and current I_{DC} as measure of the flow of charge. Most MTs are usually supplied with a 400V three-phase alternating current, which requires a distinction in the terminology between apparent power

$$S_{AC,eff} = U_{AC,eff} \cdot I_{AC,eff} \tag{2.3}$$

effective power

$$P_{AC,eff} = U_{AC,eff} \cdot I_{AC,eff} \cdot \cos \varphi \tag{2.4}$$

and the reactive power

$$Q_{AC,eff} = U_{AC,eff} \cdot I_{AC,eff} \cdot \sin \varphi \tag{2.5}$$

derived from the effective voltage

$$U_{AC,eff} = \sqrt{\frac{1}{T} \int_0^T u^2(t)\,dt} \tag{2.6}$$

and the effective current

$$I_{AC,eff} = \sqrt{\frac{1}{T} \int_0^T i^2(t)\,dt} \tag{2.7}$$

with the phase angle φ, the voltage $u(t)$, the current $i(t)$, and the period T. The apparent power is derived by geometrical summation of the effective and reactive power in the electric vector diagram. Hence, the relation is given by

$$S_{AC,eff} = \sqrt{P_{AC,eff}^2 + Q_{AC,eff}^2} \tag{2.8}$$

2.3.2. Mechanical Power

Mechanical work is performed either translatorily or rotatorily. In the former case, the mechanical power is derived by

$$P_{mech,tns} = v(F + ma) \tag{2.9}$$

with the velocity v, the force F, the mass m and the acceleration a. For steady state, the equation is simplified to

$$P_{mech,tns,stdy} = Fv \tag{2.10}$$

Rotational mechanical power is determined by

$$P_{mech,rot} = 2\pi n_{rev}(M + \Theta\ddot{\varphi}) = \omega(M + \Theta\ddot{\varphi}) \tag{2.11}$$

with the rotational speed n_{rev}, the angular velocity ω, the momentum M, the moment of inertia Θ and the angular acceleration $\ddot{\varphi}$. For steady state, the equation is simplified to

$$P_{mech,rot,stdy} = 2\pi n_{rev}M = \omega M \tag{2.12}$$

2.3.3. Hydraulic Power

The Bernoulli equation in pressure form

$$p + \rho_{fld} \left(gh + \frac{1}{2} v_{fld}^2 \right) = const. \tag{2.13}$$

is derived from the Euler equation for momentum conservation and describes the energy conservation of incompressible fluids and steady flow with the pressure p, the density ρ_{fld}, the gravity $g = 9.81 \frac{m}{s^2}$, the height h and the flow speed of the fluid v_{fld}. The Bernoulli equation states that the sum of both dynamic and kinetic energy of a fluid remains constant along the streamline. It is valid for the ideal case of fluid flow, which means incompressible fluids (liquids), for which the density ρ is constant, a steady flow, no volume loss, no temperature change and no friction. If friction shall be taken into account, the Bernoulli equation needs to be extended by the pressure loss $-\Delta p_v$. Neglecting pressure loss and leakages, the power of fluids is composed by the kinetic power share

$$P_{hydr,kin} = \frac{1}{2} \dot{m}_{fld} v_{fld}^2 = \frac{\rho_{fld} \dot{V}_{fld}^3}{2A^2} \tag{2.14}$$

with the mass flow of the fluid $\dot{m}_{fld}$, the fluid volume flow $\dot{V}_{fld}$ and the cross-sectional area A, as well as the potential power share

$$P_{hydr,pot} = \Delta p \dot{V}_{fld} + \dot{m}_{fld} g \Delta h \tag{2.15}$$

with the pressure difference Δp and the height difference Δh between inlet and outlet. The total hydraulic power is derived by

$$P_{hydr} = P_{hydr,kin} + P_{hydr,pot} \tag{2.16}$$

2.3.4. Pneumatic Power

Compressed air is the major form of pneumatic power used in manufacturing. Neglecting pressure loss and leakages as well as the power for elevation of the fluid, the pneumatic power is composed of the kinetic power

$$P_{pneu,\text{kin}} = \frac{1}{2} \dot{m}_{air} v_{air}^2 = \frac{\rho_{air}}{2} \frac{\dot{V}_{air}^3}{A^2} \tag{2.17}$$

and the potential power

$$P_{pneu,pot} = \Delta p \dot{V}_{air} \tag{2.18}$$

leading to the total pneumatic power

$$P_{pneu} = P_{pneu,pot} + P_{pneu,\text{kin}} = \Delta p \dot{V}_{air} + \frac{1}{2} \dot{m}_{air} v_{air}^2 = \Delta p \dot{V}_{air} + \frac{\rho_{air}}{2} \frac{\dot{V}_{air}^3}{A^2} \tag{2.19}$$

with the air mass flow $\dot{m}_{air}$, the velocity of the air mass flow v_{air}, the air density ρ_{air}, the air volume flow $\dot{V}_{air}$, the cross sectional area A, and the pressure difference Δp. The potential power can be neglected for air exhaustion due to the low density of air.

2.3.5. Thermal Power

Transfer heat for cooling purpose is quantified by thermal power. Two general types of heat transfer can be distinguished: forced convection, where the fluids flow is externally generated and natural convection, which is due to flow caused by temperature gradients and the resulting density differences. In reality, both heat transfer types overlap. For active cooling, the forced convection is the decisive quantity. The thermal power extracted from the system by forced convection is determined from the first law of thermodynamics by

$$\Delta \dot{Q} = \dot{Q}_2 - \dot{Q}_1 = c_{p,2} \rho_2 \dot{V}_2 \vartheta_2 - c_{p,1} \rho_1 \dot{V}_1 \vartheta_1 \tag{2.20}$$

with the heat flows $\dot{Q}_j$, the specific heat capacities $c_{p,j}$, the densities ρ_j, the volume flows $\dot{V}_j$ and the temperatures ϑ_j for the inlet $j = 1$ and the outlet $j = 2$. Assuming a constant fluid density ($\rho_2 = \rho_1 = \rho$; $\dot{V}_2 = \dot{V}_1 = \dot{V}$) and a constant specific heat capacity of the fluid ($c_{p,2} = c_{p,1} = c_p$), the heat flow generated by the incompressible fluid heat exchanger is simplified to

$$\Delta \dot{Q}_{incp} = c_p \rho \dot{V} \left(\vartheta_2 - \vartheta_1 \right) \tag{2.21}$$

2.4. Energy Efficiency in Manufacturing

The manufacturing transformation process can be viewed as input-output model of energy and materials as illustrated in Figure 8. Consumables (e.g. lubricants) and energy (e.g. electrical energy) are used for the transformation of raw material and/or semi-finished products to products. The outcomes of the transformation process are emissions (e.g. waste gas or waste heat) and materials (e.g. the final product, waste materials or waste liquids). The input-output model highlights the basic fields of activity that need to be considered for energy and resource efficiency investigations on manufacturing process level.
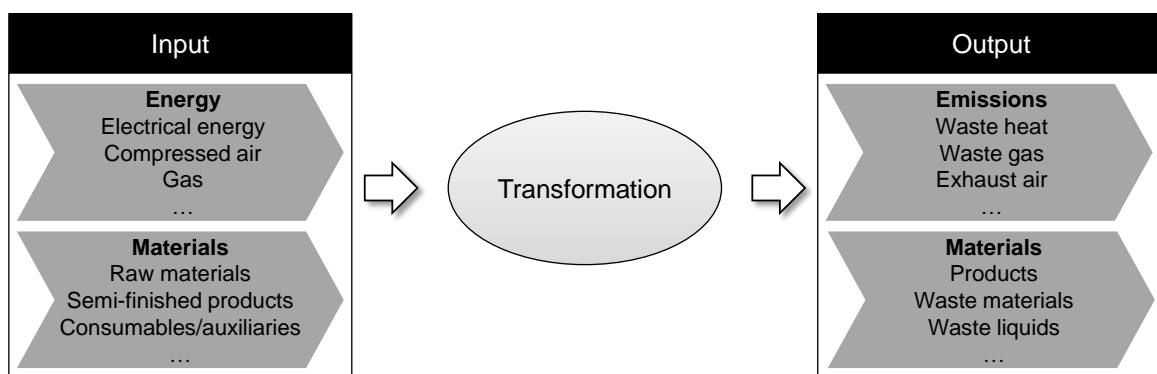
Figure 8: Input-output model of the manufacturing transformation process.

ISO 14995-1 defines a MT as "mechanical device which is fixed (i.e. not mobile) and powered (typically by electricity and compressed air), typically used to fabricate metal components of machines by the selective removal or mechanical deformation of metal" [34]. The MT can be viewed as assembly of multiple components. MT components are "mechanical, electrical, hydraulic, or pneumatic devices of a MT, or a combination" [34]. The structure of a MT built of electrical components is illustrated in Figure 9.
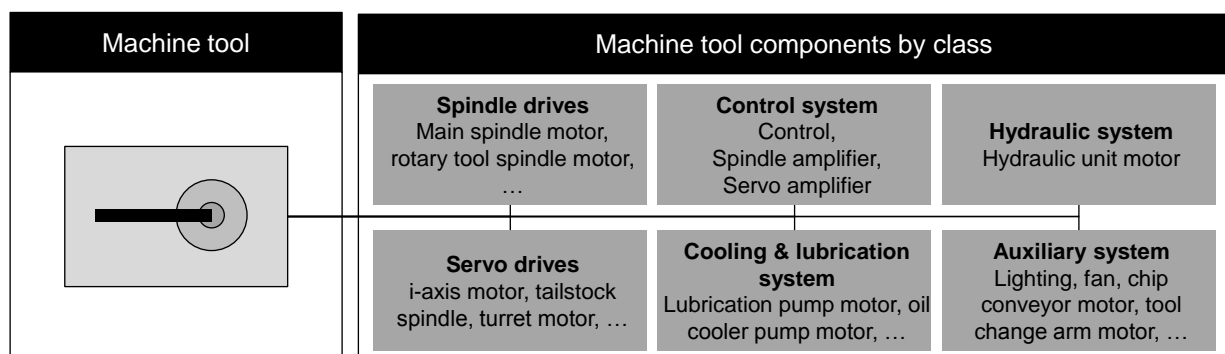
Figure 9: Electrical components in MTs adapted from Li et al. [41].

Li et al. [41] proposed a model for deriving the MT power profile from the component power profiles, as illustrated in Figure 10. Each component of a MT contributes to the power demand in a different manner depending on its characteristic and its utilization. The sum of the component power levels in the respective operational state with the respective MT utilization is aggregated to the total MT power profile.
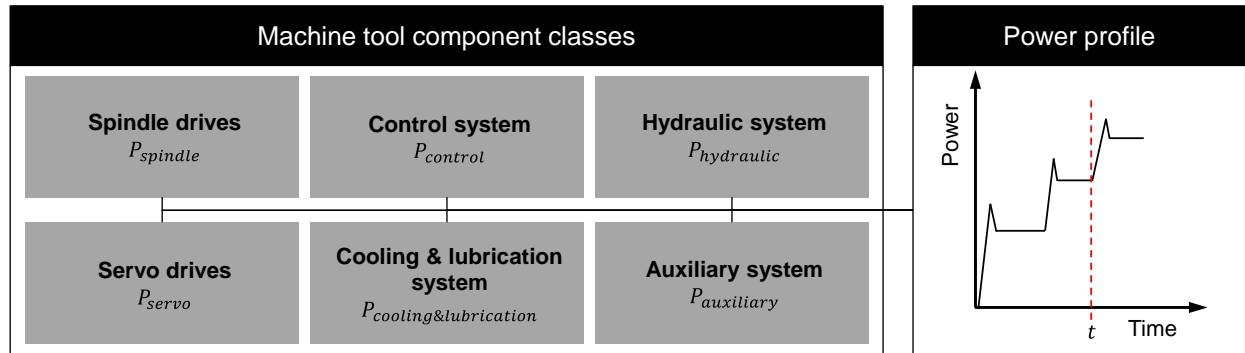
Figure 10: Aggregation of component to the MT power profile adapted from Li et al. [41].

The power profile and the associated energy consumption depend on the operating state of the MT and its utilization (e.g. load). The operating states of a MT are defined by a combination of the MT components' states respectively modules. An exemplary assignment of MT states dependent on MT components' states is listed in Table 3.

Table 3: Exemplary assignment of MT and component states adapted from ISO 14955-1 [34] (excerpt).

Machine operating state	Control system	Hydraulic system	Cooling & lubrication system	Auxiliary system	Servo drives	Spindle drives
off	*off*	*off*	*off*	*off*	*off*	*off*
standby	*on*	*off*	*off*	*on/off*	*off*	*off*
idle	*on*	*on*	*on*	*on*	*not moving*	*moving*
processing	*on*	*on*	*on*	*on*	*moving*	*moving*

Figure 11 illustrates an exemplary power profile and indicates the different power values as well as times for the operating states: off, standby, idle, and processing. The total energy consumption equals the area below the power profile and is calculated by equation (2.1).
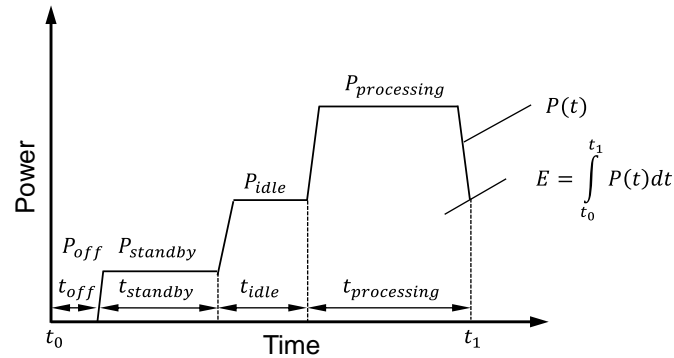
Figure 11: Schematic power profile by machine state.

The objective of improving energy efficiency is to modify the MT by technical and organizational measures in order to decrease the area below the power profile, as illustrated in Figure 12. Technical measures tend to reduce the power level while organizational measures (productivity measures) shorten of cycle times in order to decrease the energy consumption. The latter type of improvement measure goes hand in hand with a cut in cycle time and accordingly a productivity increase.
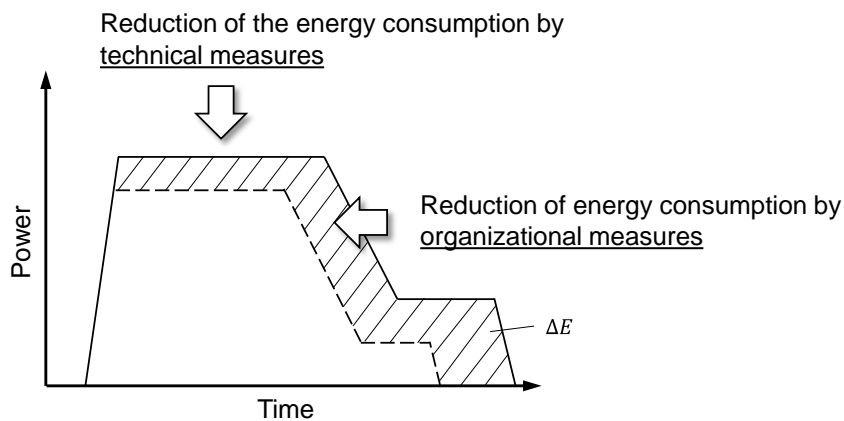
Figure 12: Measures to reduce the energy consumption of MTs adapted from Zein et al. [42] and GE Fanuc [43].

Pears [44] divided the energy use of an actual manufacturing transformation process into a load independent and a load dependent part as illustrated in Figure 13. The load independent part is referred to as energy overhead, which is required to maintain the manufacturing system operational even though no transformation process is performed. The load dependent part increases with the production rate and is characterized by the process energy gradient assuming a linear correlation. An ideal manufacturing transformation process has no energy overhead and

a marginal process energy gradient. Hence, the gap between an actual and an ideal manufacturing transformation can be described as magnitude of the energy overhead and the difference of the process energy gradients. This gap leads to the quantification of energy efficiency as ratio of the energy consumption of an ideal manufacturing transformation process and an actual manufacturing transformation process.
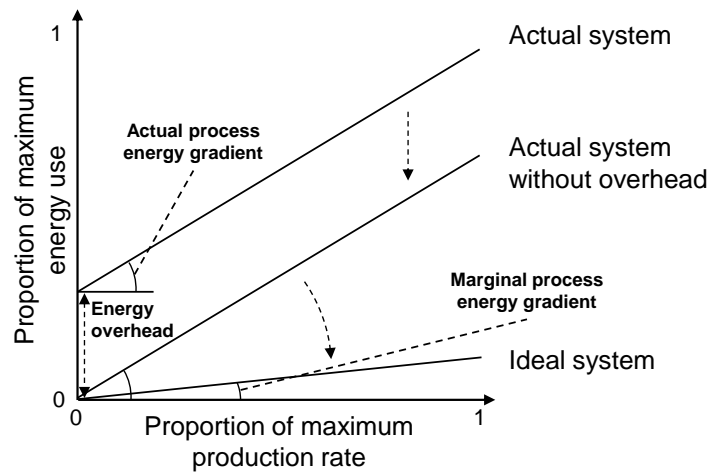
Figure 13: Energy use of an actual compared to an ideal transformation process [44].

The energy use of an ideal manufacturing transformation process serves as reference value to quantify the energy efficiency of an actual manufacturing transformation process. Depending on the context, a different reference can be considered as ideal. According to Zein [45], Seefeldt et al. [46], and VDI 4661 [38], four reference types can be distinguished, namely:

- **Market induced energy limit:** Average level of energy consumption in practice.

- **Economically feasible energy limit:** Lowest level of energy consumption achievable consistent with economic limits.

- **Technically achievable energy limit:** Lowest level of energy consumption realizable with the latest and best feasible technology.

- **Theoretical energy limit:** Lowest possible level of energy consumption limited by physical or chemical laws as stated by VDI 4661 [38].

A comparative illustration of the types of energy limits dependent on the production rate is depicted in Figure 14. Beyond this, other limitations such as costs, company policies, or laws determine the best possible solution.
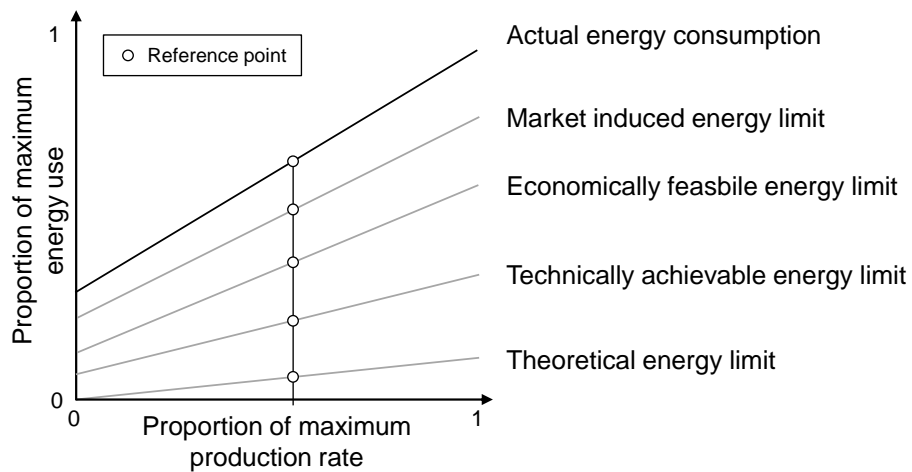
Figure 14: Types of energy process limits adapted from Zein [45].

Three level of investigation-extend can be distinguished according to Schudeleit et al. [47, 48]:

1. **Component level:** Investigation of a component possibly in connection with the MT as superordinate system, e.g. MT spindle.

2. **MT level:** Investigation of a MT built of by multiple components and their interaction.

3. **IMT level:** Investigation of a MT in connection with the technical building service, e.g. air conditioning or water cooling.

All levels of investigation need to be addressed in order to evaluate the energy performance of a MT entirely.

2.5. Classification of Key Figures

Key figures (energy efficiency indicators) are used to quantify and track energy efficiency improvements. Preißler [49] distinguishes single key figures and key figure systems. Single key figures can either be absolute values (single values, sums, differences or mean values) or ratio values (proportions, relationship values, index values). Key figure systems consist of a number of single key figures and can be logical, arithmetic or hybrid systems. While logical systems comprise a set of single key figures without mathematical linking, arithmetic systems combine sets of single key figures using mathematical operations to an aggregated key figure. Hybrid systems are a combination of logical and arithmetic systems. The general classification of key figures is illustrated in Figure 15.
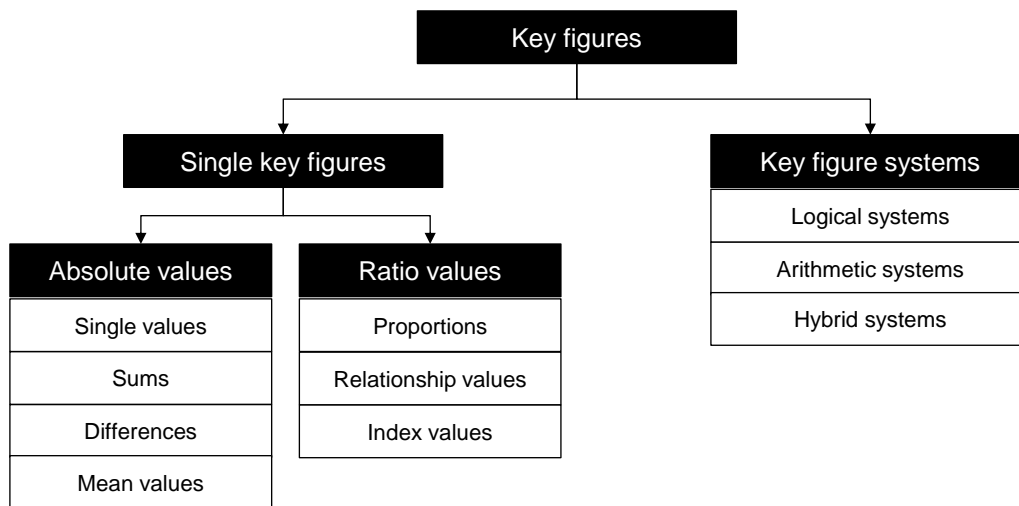
Figure 15: Differentiation of key figures according to Preißler [49].

There are extensive collections of key figures related to energy efficiency available in literature, such as in Bunse et al. [50], ISO/DIS 50006 [51], and Global Reporting Initiative [52]. In order to aggregate single key figures from a lower level such as component level to a higher level such as MT level, different mathematical operations need to be applied.

2.6. Basic Methods for Arithmetic Aggregation of Efficiency Values

Figure 16 depicts three basic types of methods to arithmetically aggregate efficiency values. First, the series connection is obtained, if the first systems output equals the second systems input. Its total system efficiency is derived from the subsystems efficiencies by

$$\eta_{tot,series} = \prod_{i=1}^{n} \eta_i; \qquad i,n \in \mathbb{N} \qquad (2.22)$$

Second, a parallel connection is present, if two or more systems are supplied by one source, and the total system efficiency is derived from the subsystems efficiencies by

$$\frac{1}{\eta_{tot,parallel}} = \sum_{i=1}^{n} \frac{1}{\eta_i}; \qquad i,n \in \mathbb{N} \qquad (2.23)$$

An aggregated connection is characterized by the presence of at least two independent systems that do not have the same source. The total system efficiency of such a system is the mean value weighted by the input power. It is obtained from the subsystems efficiencies and input power values by

$$\eta_{tot,mean} = \frac{\sum_{i=1}^{n} P_i \eta_i}{\sum_{i=1}^{n} P_i}; \qquad i,n \in \mathbb{N} \qquad (2.24)$$
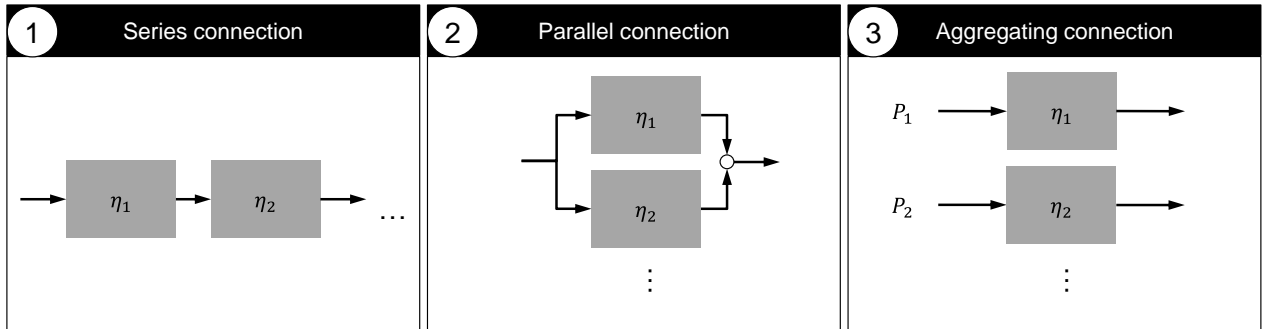
Figure 16: Basic methods for arithmetic aggregation of efficiency values.

3. State of the Art Review and Evaluation

The chapter aims at giving a comparative overview of previously performed research in the area of energy efficiency of MTs and forming the basis identifying a research gap. First, test methods for energy efficiency evaluation of MT are reviewed and evaluated. Second, key figures are compiled from literature, classified and evaluated regarding their feasibility to quantify the energy efficiency of MTs. Third, general research on analyzing and improving energy efficiency of MTs is emphasized.

3.1. Review and Evaluation of Test Methods

Figure 17 illustrates the procedure of MT evaluation. A test method is specified, which determines or at least influences the metering setup as well as the evaluation. The energy-related improvement of MTs bases fundamentally on the application of metering devices for power profiling of electrical energy consumption and measurement of other energy carriers such as compressed air. Kara et al. [53] and Herrmann et al. [54] reviewed commercially available metering devices against their feasibility for MT power profiling, in particular regarding the monitored measurands, output resolutions, communication interfaces, and costs.

Test method → Metering → Evaluation
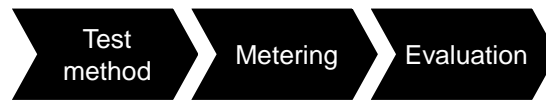
Figure 17: Test, metering, and evaluation procedure.

Saidur [55] introduced a four-step approach towards enabling an incentive program for MTs. First, a test method has to be defined. Second, the test method has to be standardized. Third, an energy efficiency label based on reference values needs to be developed. Fourth, an incentive program can be established. Hence, the development of a standardized test method is mandatory for the energy efficiency labelling and market regulation using incentive programs such as tax concessions or subsidies. Hence, test methods serve as cornerstone for standardization, development an energy efficiency labelling system for MTs, and the launch an incentive program. According to Weiss [56], Wegener et al. [57], and Schudeleit et al. [58], the broad variety of test methods for energy efficiency evaluation of MT can be classified into following test methods:

1. **Reference part method:** Measurement of energy consumption while manufacturing of a reference part.

2. **Reference process method:** Measurement of energy consumption while executing of a reference process.

3. **Specific energy consumption method:** Measurement of energy consumption and determination of the empirical correlation between energy consumption and geometric variables.

4. **Component performance method:** Measurement of energy consumption and component-wise determination of the empirical correlation between energy consumption and load.

Frequently, a mixture of test methods can be observed due to overlapping (e.g. the reference process method implies the manufacture of a reference part). The characteristics of the test methods shall in the following be presented in more detail. Each particular method will be explained including its drawbacks and benefits.

3.1.1. Reference Part Method

The reference part method is a quantification method based on a predefined workpiece. The power profile consumption during processing is metered and serves as comparative value for evaluation purpose for MTs of the same type. The test workpiece imitates a standardized manufacturing task in practice and defines the machine utilization. The stepwise procedure of the reference part method is illustrated in Figure 18.
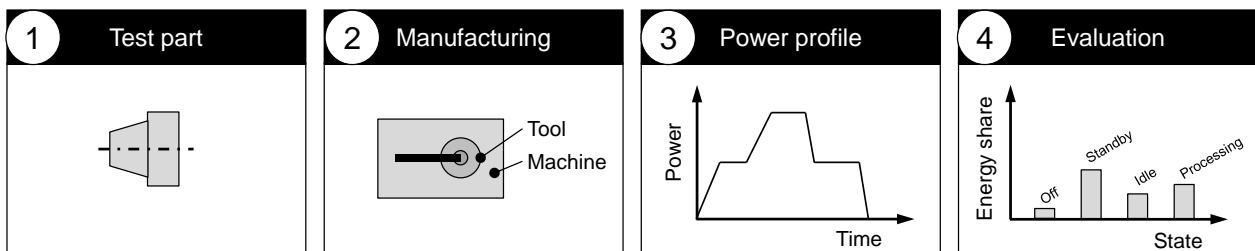
Figure 18: Reference part method.

The manufactured part has to meet a certain specification and has to be within a particular tolerance. The precise geometry (before and after manufacturing) and material of the workpiece, as well as the characteristics of the tool, must be specified in advance. Each test workpiece can only be used for a particular type of MT (e.g. a test workpiece for turning machines and another test workpiece for milling machines).

The Japanese Standards Association (JSA) published the standard series JIS TS B 0024 [59-62] on energy efficiency evaluation using test workpieces. The series suggests test workpieces for various classes of MTs such as machining centers, numerically controlled turning machines and turning centers, horizontal grinding wheel spindle and reciprocating table type surface grinding machines, and cylindrical grinding machines. Figure 19 shows a test workpiece suggested in JIS TS B 0024-1 [59] for numerically controlled milling machines and milling centers. The workpiece is made of S45C steel and measures 120 mm x 120 mm x 50 mm. The test workpieces are used to predefine the machine utilization by its load profile. The measurement result of manufacturing the corresponding test workpiece including the standard machining cycle as an electric power demand profile is depicted in Figure 20. The suggested result quantification method puts emphasis on the processing state, hardly considers the idle times, and neglects the standby times of a MT in practice as well as the factory integration of the MT.
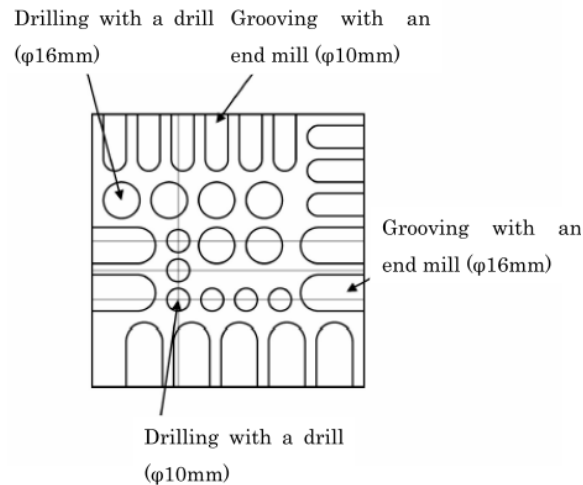
Figure 19: Test workpiece introduced by JIS TS B 0024-1 [59].
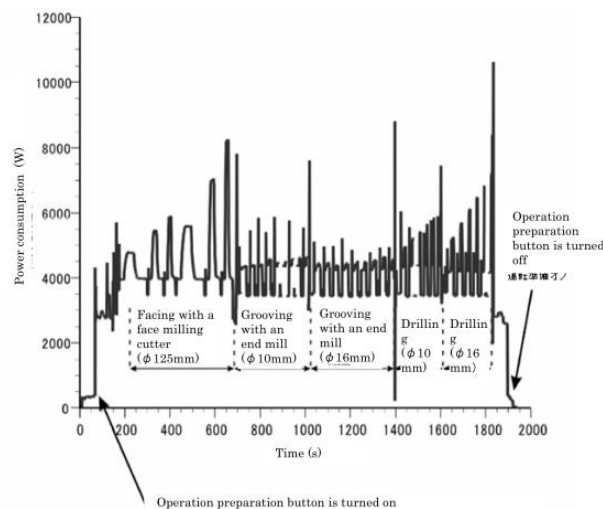
Figure 20: Measured example of power demand by application of JIS TS B 0024-1 [59].

3.1.2. Reference Process Method

A reference process typically includes standby and idle times as well as time for processing in order to replicate a realistic use scenario. It takes into account the impact of the production plan on the machine utilization and therefore on the respective energy consumption. The energy consumption of a MT is measured over a certain time span that exceeds the processing of a single product. The reference process mainly focuses on the entire MT utilization including downtimes (such as during weekends, lunch breaks, change of shift, etc.) rather than on a specific workpiece. The stepwise procedure of the reference process method is illustrated in Figure 21.
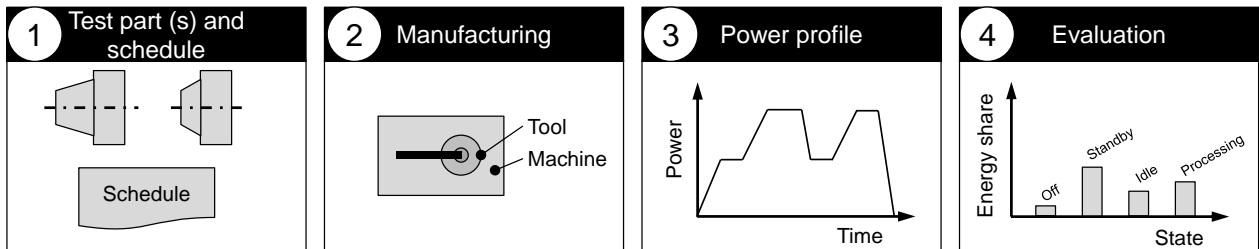
Figure 21: Reference process method.

Figure 22 depicts an exemplary reference process suggested by ISO/CD 14955-2 [36]. The reference process is defined by a shift regime of 4 hours in off state, 4 hours in idle for production state, and 16 hours of processing. Thus, the reference process method is a particular test cycle, which is defined in advance, and contains the predominant MT states such as off, idle for operation and processing.
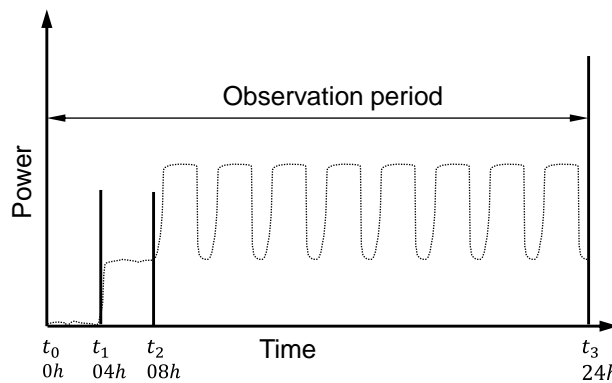
Figure 22: Exemplary reference process adapted from ISO/CD 14955-2 [36].

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Thiede [63] defined power pattern dependent on states and state changes (transitions) in order to simulate the power demand over time for a number of MTs. Kellens [64] used a similar approach and developed a metric that takes into account the influence of a shift regime on the total energy consumption. Kaufeld [65] defined a reference process and aggregates the energy consumption within the different states to a key figure indicating the energy consumption of a MT for the underlying reference process.

3.1.3. Specific Energy Consumption Method

The specific energy consumption method (SEC method) sets the energy consumption in relation to a physical unit of production (e.g. mass, volume, surface, etc.) and determines empirical correlation between both variables. One or more test parts are manufactured in order to cover all operating points from minimum to maximum production rate. The MT is evaluated by determination of an empirical formula that describes the correlation of the energy consumption dependent on the production rate. The SEC method is the scientific approach to enable the comparison of the energetic performance of different MTs for a defined physical unit of production. It enables to determine the energy optimal operating point of a MT. The stepwise procedure of the SEC method in order to evaluate the SEC dependent on the material removal rate (MRR) is illustrated in Figure 23.
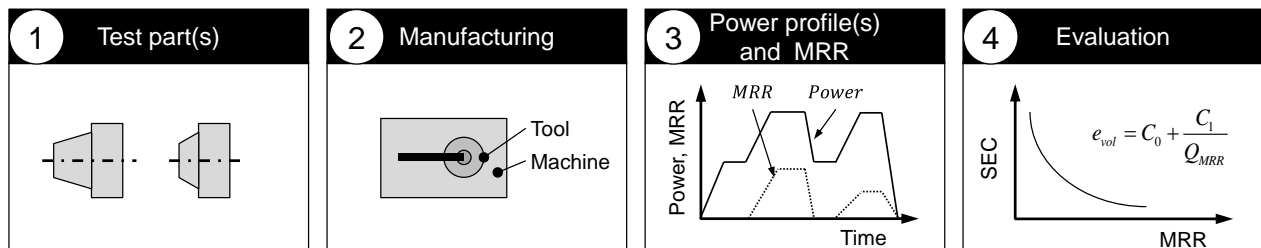
Figure 23: SEC method.

Depending on the manufacturing process and on the product, another physical unit of production can be beneficial due to its impact on the MT's energy consumption. Exemplary manufacturing processes and suitable physical units of production are listed in Table 4.

Table 4: Exemplary manufacturing processes and physical units of production adapted from Erlach and Westkämper [66].

Manufacturing processes according to DIN 8580 [23]	Exemplary manufacturing process	Exemplary physical unit of production
Primary shaping	*molding*	*mass*
Forming	*bending*	*angle*
Separating	*milling, grinding*	*volume, mass, surface*
Joining	*welding*	*length*
Coating	*varnishing*	*surface*
Material property changing	*hardening*	*mass*

For separating processes the volume and mass are crucial physical units of production. Generally, a hyperbolic correlation of SEC with increasing production rate can be observed. In other words, the energy consumption of a MT rises slower than the production rate. Kara and Li [67] expressed the volume SEC as

$$e_{vol} = C_0 + \frac{C_1}{Q_{vol}} \tag{3.1}$$

whereas C_0 and C_1 represent machine-specific coefficients and Q_{vol} is referred to as MRR (volume of material removed per time unit). Gutowski et al. [68] observed a similar correlation for the total power used

$$P = P_0 + k\,Q_m \tag{3.2}$$

with the idle power P_0, the rate of removed mass Q_m and the machine specific constant k. The mass SEC is obtained by

$$e_m = \frac{P_0}{Q_m} + k \tag{3.3}$$

Hence, the energy optimal operating point can frequently be observed at maximum production rate. Sealy et al. [69] compiled an extensive collection of approaches to quantify the SEC and use the information to predict the energy consumption for a given process.

3.1.4. Component Performance Method

MTs are composed of different components such as electric drives, mist collectors, hydraulic systems, system cooling pumps, etc. The component performance method assesses the energy efficiency of a MT by determining the efficiency of its main components. A comparison to another MT with similar functional capabilities is enabled by comparison of the similar components. A load profile is executed for each MT component in order to obtain a component power profile. For a series of load profiles, a component's energy consumption behavior can be mapped multidimensionally by varying parameters such as feed rate, cutting depth, and rotational speed. Similar components can be compared by their characteristic power curves. The efficiency evaluation is based on the comparison of components and enables an assessment independent of the manufacturing process, the tool or the workpiece. The step-by-step procedure of the component performance method is illustrated in Figure 24.
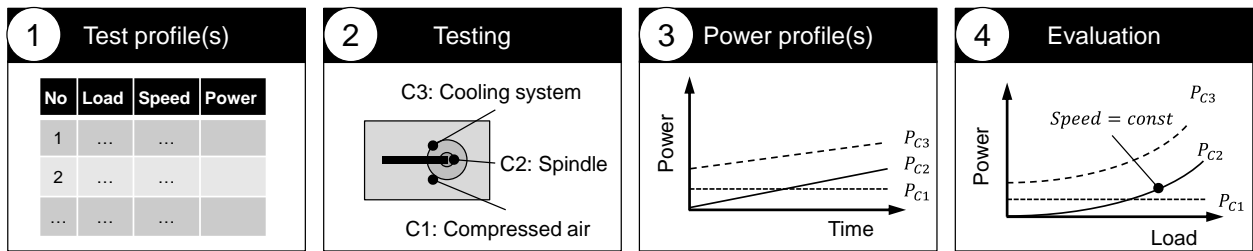
Figure 24: Component performance method.

In literature, a variety of studies using the component performance method can be found. Kellens [64] performed the performance method on MT level by investigating the correlation of the laser cutting power and the required MT energy consumption. Draganescu et al. [70] and Abele et al. [71] mapped the MT spindle efficiency respectively the power demand against torque and rotational speed. Verl et al. [72] put emphasis on the impact of both the depth of cut and the feed rate on the power intake of the MT spindle. Abele et al. [73] focused on the impact of the volume flow at various pressure levels on the power demand of a cooling and lubrication system. Narita et al. [74] investigated the correlation of spindle speed and CO_2-equivalent for high-speed milling.

3.1.5. Comparative Overview of Test Methods

Figure 25 shows an overview of test methods for energy efficiency evaluation of MTs and their role within the evaluation procedure. The selection of the test method determines the procedure of data acquisition as well as the data basis. Whereas the power profile of a single process is metered and recorded for the reference part and the reference process method, the SEC method and the component performance method require a series of processes in order to determine characteristic curves and maps, respectively. The efficiency evaluation is carried out dependent on the data basis. The reference process and the reference part method are due to practical relevance and the lower assessment effort favored during the MT use phase. The component performance and SEC method provide a universal, in-depth analysis of the MT and are appropriate for the MT design.
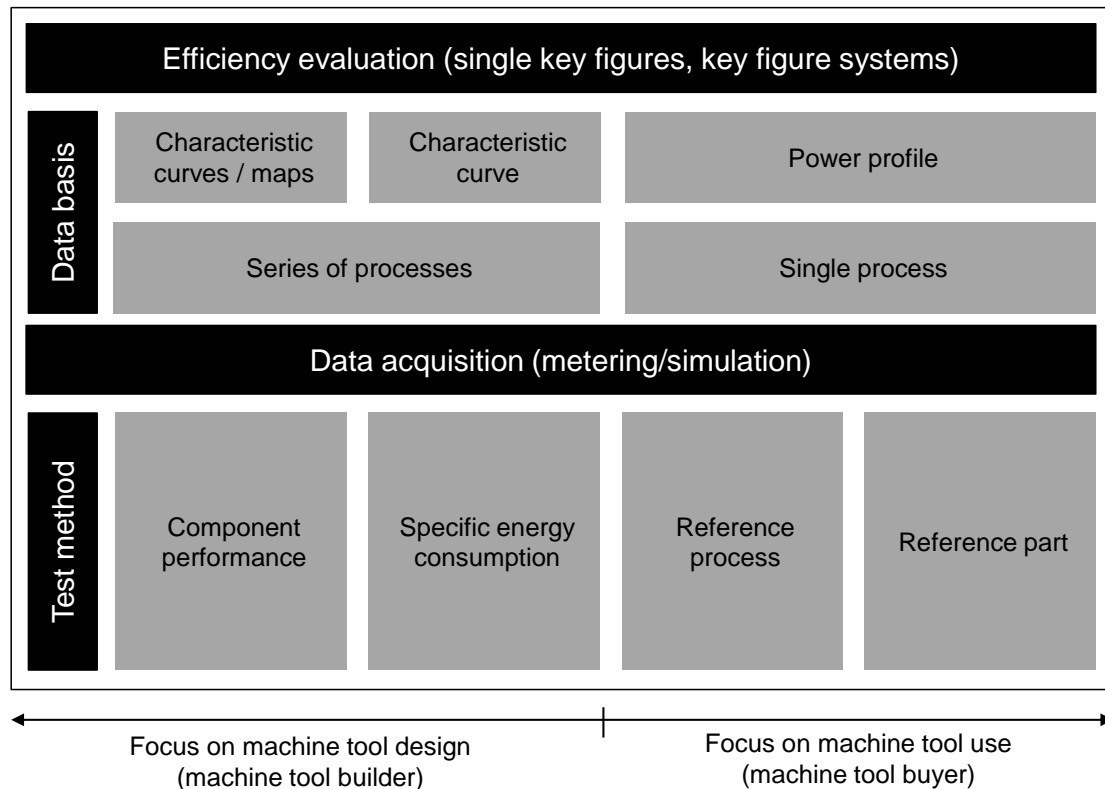
Figure 25: Overview of test methods for energy efficiency evaluation of MTs.

The four presented alternatives for testing the energy efficiency of MTs enable different advantages and comparison options. The alternatives are compared using qualitative criteria. Table 5 lists a comparative overview of the beforehand described energy efficiency test methods according to Schudeleit et al. [58].

Table 5: Comparative overview of test methods based on Schudeleit et al. [58].

Criterion	Reference part method	Reference process method	SEC method	Component performance method
Time required	*Low*	*Medium*	*Medium-high*	*High*
Simplicity of the test method	*Low complexity*	*Low complexity*	*Medium complexity*	*High complexity*
Comparison of MTs	*Yes, with very large restrictions*	*Yes, with larger restrictions*	*Yes, with few restrictions*	*Yes, on component level*
Independence of workpiece and tool	*No*	*No*	*Partly*	*Yes*
Imitation of a realistic use scenario	*Yes, with few restrictions*	*Yes*	*Yes, with larger restrictions*	*No*
Implementation in the design stage	*No, mainly use phase*	*No, mainly use phase*	*Yes*	*Yes*
Evaluation of main operating states	*Partly, processing and idle*	*Yes, all*	*No, only processing*	*No, only indirectly*

All test methods have their own advantages and disadvantages dependent on the scope of the energy efficiency analysis. The remarkable characteristics are therefore outlined without judgement. The effort and complexity for the power profile measurements range from low (reference part method) to medium (SEC method and reference process method) up to high (component performance method). While the reference part method and the reference process method require the metering of a single process over time to achieve a power profile, the SEC method and the component performance method necessitate recording of a series of processes in order to create characteristic curves or maps, respectively. The comparison of different MTs is enabled with strong restrictions (e.g. manufacturability of the same workpiece, the same physical unit of production or similar components) on the reference part and the reference process method. The SEC method and component performance method enable the MT comparison with minor restrictions. In contrast to the reference part method and the reference process method, the SEC method does not require a geometrically predefined workpiece. For the component performance method even the material does not need to be defined. It is the only method that does not require a tool with predefined geometry, predefined adjustments, and predefined material. Both the reference part method and the reference process method reflect a realistic use scenario, but in contrast to the SEC method and the component performance method, are not feasible for application in MT design development. Processing and idle state are included in all test methods, whereas the SEC method does not distinguish between the states in which the physical unit of production equals zero (i.e., off, standby, and idle state). The reference process directly considers the non-operating states (off, standby, and idle state).

In conclusion, each method has its particular advantages and disadvantages for application in practice. Weiss [56] highlights both the variety of workpieces manufactured on a MT and the different utilization of the MT dependent on the industrial application as reasons for why no consensus has been found regarding an unified test piece or method. For the design of an energy efficient MT for versatile application focus, the component performance method is, according to Schudeleit et al. [58], the most meaningful one due to its independency on workpiece and tool.

3.2. Review and Evaluation of Key Figures

In the following, typical key figures to quantify the energy efficiency of MTs are reviewed and evaluated. Key figures derived from literature are assigned to one of the key figure types introduced in chapter 2.5. In order to assess the key figures' suitability to express the MT efficiency, each key figure is checked against the three sustainability strategies as distinguished by Schaltegger et al. [4] in order to foster on environmental improvements in the context of sustainability:

1. **Efficiency:** Optimization of the **transformation procedure** in order to minimize the waste of energy (e.g. improve efficiency of an engine). Improvement of the conversion efficiency (e.g. run electric components at the highest point of efficiency).

2. **Sufficiency:** Minimization of energy losses due to **frugality of the system** itself (e.g. engine shutdown in standby). Requirement-based dimensioning and need-based utilization/control (e.g. control of the cooling fluid volume flow).

3. **Consistency:** Reduction of the energy losses by **selection of the optimal system** (e.g. water cooling instead of air cooling). Selection of the best technology in order to accomplish the task considering both effectiveness and boundary conditions (e.g. legal restrictions or energy efficiency limits of the technological standard such as technically available or economically feasible).

In summary, sustainability improvements can be made by selecting the optimal system that is only used when needed and runs at the highest point of efficiency. The sustainability strategies applied to MTs consist of selecting the optimal set of components that are only used when needed and exactly to the degree they are needed.

3.2.1. Single Key Figures

MT builders are system integrators who combine self-made and purchased components to the final MT. Using efficient components (e.g. highly efficient drives) does not ensure the need-based utilization (e.g. operation of a cooling pump only when and to the exact degree it is needed), and vice versa. Patterson et al. [75], Bunse et al. [50], Bogdanski et al. [76], ISO/DIS 50006 [51], International Energy Agency [77], VDI 4070 [78], Global Reporting Initiative [52], ISO 14031 [79], and Zhou et al. [80] collected a great number of sustainability-related indicators, which are summarized, sorted by their key figure type according to Preißler [49], and evaluated

against the three improvement strategies stated above. The review results are listed in Table 6, where the filled circle (●) indicates fulfillment and the empty cycle (○) indicates non-fulfillment of the respective improvement strategy.

Table 6: Evaluation of energy efficiency indicators.

Key figure type	Energy efficiency indicator class	Symbol and formula example	Efficiency	Consistency	Sufficiency
Single values	*Absolute amount of energy (in a time span)*	$E_{2015} = E_{input,2015}$	○	○	○
Sums	*Total amount of energy (in a time span)*	$E_{tot,2015} = \sum_{i=1}^{n} E_{i,2015}$	○	○	○
Differences	*Energy saving (in a time span)*	$\Delta E_{2014-2015} = E_{2014} - E_{2015}$	○	○	○
Mean values	*Mean power demand*	$\overline{P} = \dfrac{1}{T}\int_{0}^{T} P(t)dt$	○	○	○
Relationship values	*Energy intensity*	$e_{EI} = \dfrac{E_{input}}{n_{pcs}}$	●	○	○
	SEC	$e_m = \dfrac{E_{input}}{\Delta m} == \dfrac{P_{input}}{Q_m}$ $e_{vol} = \dfrac{E_{input}}{\Delta V} = \dfrac{P_{input}}{Q_{vol}}$	●	○	○
	Energy efficiency ratio	$\varepsilon = \dfrac{\dot{Q}_{output}}{P_{input}}$	●	○	○
Proportions	*Energy conversion efficiency*	$\eta_{conv} = \dfrac{E_{output}}{E_{input}}$	●	○	○
	Value adding energy share	$\eta_{VAES} = \dfrac{E_{input,VA}}{E_{input,tot}}$	○	○	●
	Value adding energy efficiency	$\eta_{VAEE} = \dfrac{E_{output,VA}}{E_{input,tot}}$	●	○	●
Index values	*Energy efficiency index*	$\lambda_{EEI} = \dfrac{E_{ref}}{E_{act}}$	●	●	○

Efficiency analysis of components is considered to be state of the art and can be quantified by relationship values, proportions, and index values. The proportional indicator 'value adding energy share' possesses the sufficiency property. The consistency attribute is only covered by the index value 'energy efficiency index'. All in all, it can be deduced that none of the single key figures comprises all characteristics of the three improvement strategies. However, this is necessary in order to take into account all possible types of energy losses. Hence, an open issue is derived in the field of combining efficiency, consistency, and sufficiency as measures for the need-based utilization and dimensioning of efficient components.

3.2.2. Key Figure Systems

In combination with an aggregation method, the key figures become a key figure system referred to as metric. Key figure systems combine characteristics of all single key figures that are aggregated. Since logical key figure systems conglomerate single key figures without mathematical linking, the review focus is limited to arithmetic systems either in pure form or embedded in a hybrid system. Kuhrke [81] and Thiede [63] developed metrics to estimate the electrical energy consumption of a MT dependent on the MT utilization over time. A similar approach has been chosen by Mori et al. [82], who investigated the impact of process parameters on the energy consumption and the SEC for the cases of drilling, face/end milling, and deep hole machining. Duflou et al. [83] proposed a metric to calculate the SEC for laser cutting, bending, injection molding, and selective laser sintering dependent on the MT utilization over time. Guo et al. [84] investigated the impact of the cutting speed and feed on the SEC. The model also distinguishes the SEC caused by the value adding variable power demand and the non-value adding constant power demand. Branham et al. [85] and Gutowski et al. [68, 86] used the first and second law of thermodynamics to quantitatively describe manufacturing systems and illustrated the calculation of the "degree of perfection" as popularized by Szargut et al. [87]. Similarly, Renaldi et al. [88, 89] investigated the different parts of exergy loss within a system and distinguished three exergy efficiency indicators (degree of perfection according Szargut et al. [87], the utilizable exergy coefficient, the efficiency of removal according to Branham et al. [85]). Zein [45] determined performance limits of MTs such as the technical efficiencies of a number of grinding machines. ElMaraghy et al. [90] used the same concept and proposed a metric to analyze and benchmark the energy efficiency of manufacturing lines using efficiency values and relating them to benchmark values. Stark et al. [91] developed an energy efficiency factor taking into account two indices for base load reference and processing load reference,

respectively, which aim at making MTs comparable. Giacone and Mancò [92] use the energy consumption, the SEC and the useful energy efficiency in order to analyze the energy efficiency of industrial processes in correlation with the production rate mathematically. Schlosser et al. [93] developed a calculation procedure to estimate the energy consumption per part based on a process measurement and summing the direct energy consumed by the main MT functions and the indirect energy consumed by the peripherals. Kellens [64] and Kaufeld [65] defined an energy efficiency metric based on a predefined and a non-predefined reference process, respectively. Rajemi et al. [94] carried out an optimization to find the cutting parameters that lead to the minimum MTs energy consumption. Narita et al. [74, 95] as well as Desmira et al. [96] developed metrics to estimate the environmental burden of MT operation. Cao et al. [97] developed a metric for calculating the carbon efficiency of a MT over its life-cycle. Gontarz et al. [98] developed an indicator in order to evaluate the potential of retrofitting a component. Kuznetsow et al. [99] developed a metric to evaluate and compare the energy efficiency of technological processes considering efficiency, productivity and accuracy. The metric addresses efficiency as well as consistency aspects. The review results are listed in Table 7.

Table 7: Comparative overview of key figure systems.

Source	Type of Key Figure System	Efficiency	Consistency	Sufficiency
Kuhrke [81], Thiede [63], Mori et al. [82]	*arithmetic systems of single values, sums, mean values, relationship values, and proportions*	●	○	○
Duflou et al. [83]	*arithmetic system of single values, sums, differences, relationship values, and proportions*	●	○	○
Guo et al. [84]	*arithmetic system of single values, sums, and relationship values*	●	○	○
Branham et al. [85], Gutowski et al. [68, 86], Renaldi et al. [88, 89]	*arithmetic systems of single values, sums, differences, relationship values, proportions, and index values*	●	●	○
Zein [45], ElMaraghy et al. [92]	*arithmetic systems of single values, sums, differences, mean values, relationship values, proportions, and index values*	●	●	○
Stark et al. [91]	*arithmetic system of single values, sums, differences, proportions, and index values*	●	●	○
Giacone and Mancò [92]	*arithmetic system of single values, sums, differences, mean values, relationship values, and proportions*	●	○	●
Schlosser et al. [93]	*arithmetic system of single values, sums, mean values, relationship values, and proportions*	●	○	○
Kellens [64], Kaufeld [65]	*arithmetic systems of single values, sums, mean values, and relationship values*	●	○	○
Rajemi et al. [94]	*arithmetic system of single values, sums, differences, relationship values and proportions*	●	○	●
Narita et al. [74, 95], Desmira et al. [96]	*arithmetic systems of single values, sums, differences, relationship values, and proportions*	●	○	○
Cao et al. [97]	*arithmetic system of single values, sums, differences, relationship values, and proportions*	●	○	○
Gontarz et al. [98]	*arithmetic system of single values, sums, differences, and proportions*	●	○	●
Kuznetsow et al. [99]	*arithmetic system of single value, sums, proportions, and index values*	●	●	○

The literature review of key figure systems reveals that an efficiency measure is included by all metrics presented in research papers. About half of the research papers include either a consistency or sufficiency measure in their metrics. None of the reviewed metrics combine all sustainability measures, which are necessary to quantify the entire improvement potential. Hence, there is a gap in research in the field of combining efficiency, sufficiency, and consistency. The performance indicators feasible to quantify efficiency, sufficiency, and consistency are relationship values, proportions, and index values, which cannot easily be aggregated by summing. None of the approaches shows how to aggregate the energy efficiency of components to MT level and beyond.

3.3. Review and Evaluation on Enhancing Energy Efficiency of Machine Tools

Enhancing energy efficiency aims at taking into account all influencing factors in order to reduce the MTs energy consumption during the use phase. Beyond the use phase itself, the MT design phase and the MT configuration have an effect on the MTs energy consumption during the usage. The energy consumption of MTs during their use phase can be influenced by the MT design and the configuration as well as the use itself. The knowledge about the MT use and the ability to modify the MT for enhanced energy efficiency strongly depend on the life cycle perspective. This interconnection is illustrated in Figure 26.
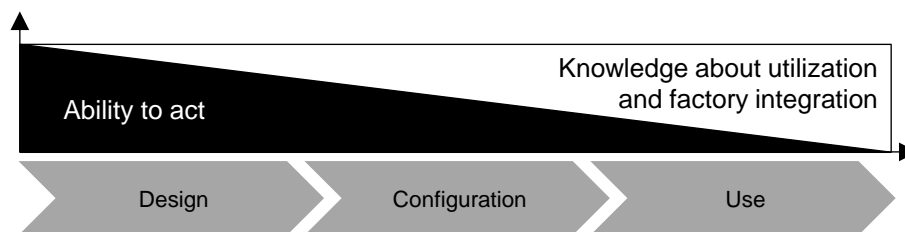
Figure 26: Schematic relationship of ability to act and knowledge depending on the action phase.

The ability to influence the energy efficiency of a MT, which is prominent in the design phase, decreases during the configuration due to the compilation of the MT components according to the users' needs and are relatively low during the use phase. In contrast to that, the knowledge about the MT use increases from the design phase up to the use phase due to increasing data availability. The design phase is the counterpart to the use phase because of the modest data basis and the maximal ability to act. The design phase is referred to as phase that comprises all phases before the customer specification process (configuration) and thus the planning, conceptual design, detailed design and testing phase according to ISO/TR 14062 [100].

A balance between ability to act and knowledge of use can be found in the configuration phase, which allows tailoring products such as MTs according to customers' needs and is mostly realized by a modular structure. Configuration is the compilation of a set of predefined modules, taking into account restrictions for assembly [101]. Among other things, the configuration of MTs implies the selection of tool functionalities and their dimension, which are both critical to the energy efficient use of MTs. Configuration is part of the mass-customization movement, popularized by Pine [102], which is stated by Salvador et al. [103] and Ehrlenspiel et al. [104] as an approach that satisfies an increasing demand for customized products, while keeping costs to a minimum. The mass-customization demands for flexible manufacturing systems; configuration is one aspect of flexibility. The configuration aims at clarifying the customer requirements (gain in knowledge about the MT utilization and integration) and meeting these requirements best possibly within the range of possibility given by the MT modularization (drop of ability to act). Knowledge gained from previous configuration activities and investigation of the use phase can be applied to future MT design and configuration activities.

All in all, each phase has its challenges. The design phase allows a great ability to impact the structure as well as functionalities of the MT. The configuration phase offers a compromise between the ability to act and the information about the MT use due to the MT builders' flexibility to select modules and the buyers' knowledge about the planned MT utilization. The use phase allows a detailed investigation of the MT's utilization and integration into the factory environment. Research on the action phases design, configuration, and use is presented in the following.

3.3.1. Energy Efficiency of Machine Tools in Design Phase

The application of a MT is versatile and making assumptions about the typical utilization of a MT is challenging. In the design stage, information on the MT utilization is mostly estimated and therefore insufficient in accuracy and detail. Diaz et al. [105] created an approach to estimate the power demand of non-controlled MT components during design phase in order to minimize the constant power demand of the MT. Seow and Rahimifard [106] presented a comprehensive review of approaches to integrate energy aspects into the design phase. ISO 14955-1 [34] states fields of action for integrating energy efficiency into the design process. Approaches such as Eco-Design and Life Cycle Assessment (LCA) put holistic, life cycle oriented design into practice. These approaches benefit from a high level of flexibility during the design phase, e.g. by embedding eco-design guidelines into the design process, and are based on predictive assumptions due to the limited information basis. DIN EN ISO 14044 [107] describes LCA as an approach to quantify the environmental footprint of a product over its entire life cycle, from raw materials to disposal or recycling as environmental measure, e.g. as CO_2-equivalent. The uncertainty for estimating the use phase is highest for products with dominating use phase and versatile application, such as MTs. Among others, Chen et al. [108], Diaz et al. [109], and Kellens et al. [110, 111] applied LCA to MTs. In all cases, assumptions about the dominant use phase had to be made, hazarding the consequences of uncertainty. On the basis of these approaches, a MT can be optimized for a defined product and manufacturing process. However, the optimization of the MT design in general, e.g. using universal metrics for the design evaluation regarding energy efficiency, has not been considered.

3.3.2. Energy Efficiency of Machine Tools in Configuration Phase

Configuration enables to customize the MT with its components to the individual needs of the MT buyer and requires a modular design kit for realization. Two basic types of configuration approaches according to the customer perception shall be distinguished: preference-oriented and need-oriented decision-making.

- **Preference-oriented:** The MT builder provides all information needed to define a set of MT components units, taking into account interfaces, limitations, component descriptions and other supportive information. The customer chooses between a set of options based on subjective perception, experiences, values and views. A car configurator is an example for a mainly preference-oriented configurator.

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- **Need-oriented:** The MT builder inquires objective customer needs in order to configure the most suitable MT using a defined set of components with their interfaces and limitation. The MT builder intends to predict the future use as accurately as possible (including a change of products produced, resale, etc.) based on customer information. The configuration of an elevator is an example for a mainly need-oriented configuration.

In order to tailor MTs according to customers' needs and preferences, a configuration procedure ought to combine both configuration types timely decoupled, as illustrated in Figure 27.
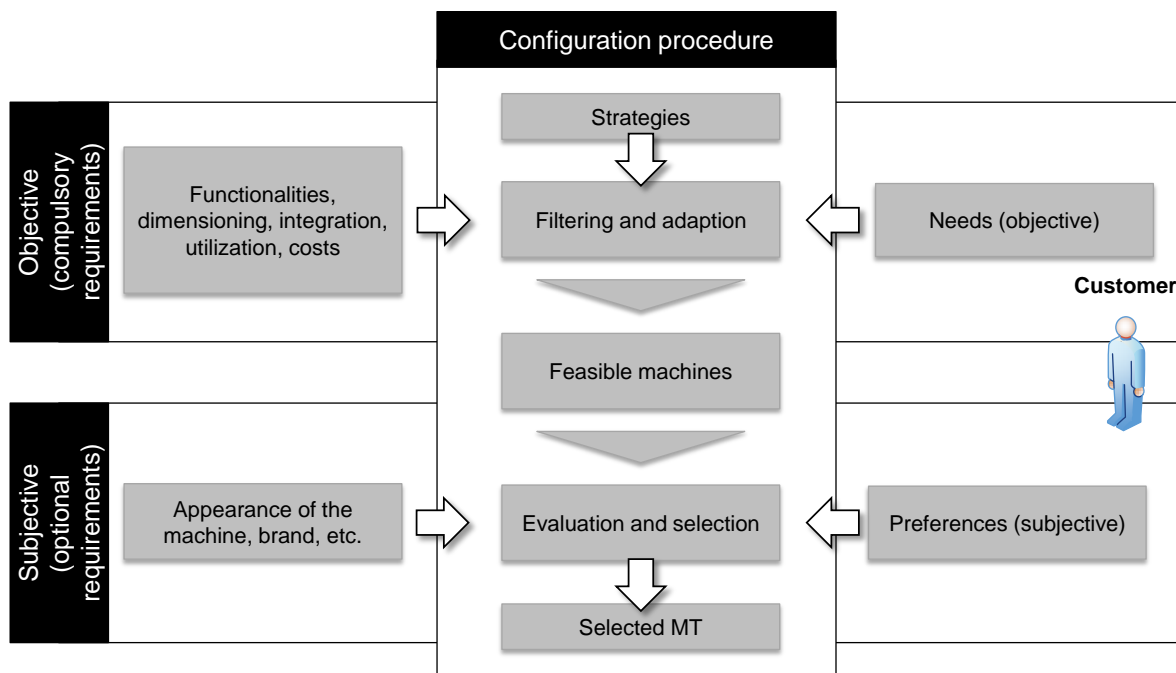
Figure 27: Ideal configuration procedure.

A MT shall objectively be configured by taking into account its functionalities (e.g. five axis machining), the dimension of components (e.g. exhaust air system), the integration into the factory environment (e.g. local versus external compressed air supply), the utilization (e.g. job shop production), and costs. Objective customers' needs are used to identify the most feasible MT type and configure the MT according to the specification as well as filtering and adaption techniques based on machine builder experiences. The outcome of the objective part of the procedure is a MT matched to the customers' needs and feasible to fulfill the specified requirements. The preference-oriented part puts emphasize on the marketing side and considers aspects that are not related to the machine use, but favored by the customer (e.g. color of the machine housing). In order to foster on energy efficiency, decisions on aspects that are relevant to the energy consumption shall be drawn as need-oriented (objective) as possible.

Schmitt et al. [112] underline the importance of need-oriented dimensioning to foster on energy efficiency in production and indicate over-dimensioning as a limiting factor for optimization activities. Brecher et al. [113, 114] see poor information about the actual energetic needs before MT purchase as reason for the occurring over-dimensioning of MTs in practice. Schäfer [115] states that a total safety margin of 1.3 to 2 is fully sufficient to ensure all theoretically possible load conditions of a MT. However, this safety factor is taken into consideration more than once and thus accumulated, which might lead to components twice as large as actually necessary and result in efficiency losses of up to 50%. Abele et al. [116] came to the same result of about 50% energy saving potential of an entire MT due to configuration.

Approaches to reduce over-dimensioning of MT components are presented in literature, e.g. for pneumatic components [117], drives of auxiliary components [118], or the spindle drive gearbox design [119], but not for the complete MT. Case studies conducted by Schischke et al. [30] show that the optimization of single components or modules is less effective to increase the energy efficiency of MTs than a need-based matching of the entire system. Beyond the need-oriented dimensioning, further improvements are to be expected by the reduction of standby losses of MTs through implementation of functionalities to control auxiliary components such as exhaust air extraction, compressed air use, and coolant supply. Gontarz et al. [120] presented a four-step approach, which contains the main required steps from data acquisition using a multichannel power metering system (1) towards the modular design kit system for energy intensive components (4), as depicted in Figure 28. The experience gained from acquired and evaluated power data is used to create standards that can be applied in the MT optimization procedure. Proven optimization decisions are then comprised in a configuration logic (3), which represents a set of component combinations in order to configure a MT based on best practice experiences. The highest stage can be achieved by taking into account the configuration logic in the product design phase in order to develop a modular design kit system for energy intensive components.
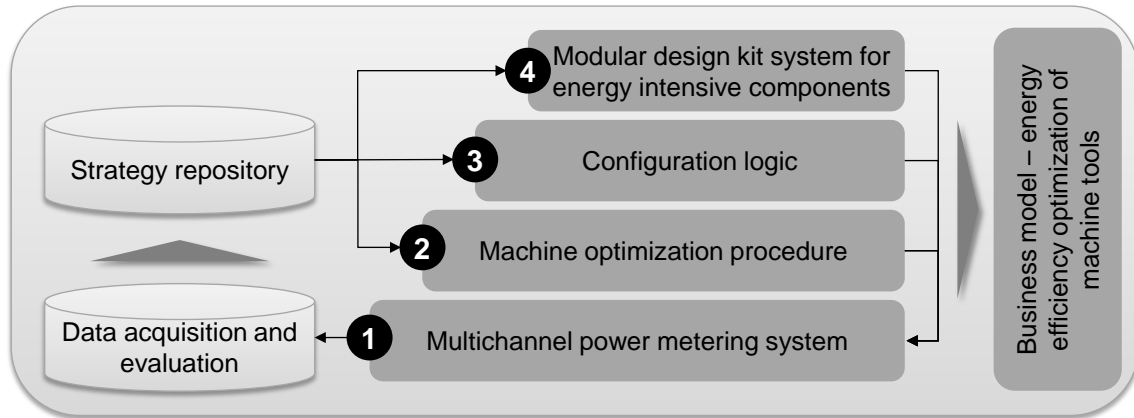
Figure 28: Four-step approach towards energy efficiency optimization through MT configuration according to Gontarz et al. [120].

At present, the configuration of MTs is based on the selection of possible process characteristics such as rated speed or maximum torque as well as main functionalities as five-axis machining. The key to allow the MT builder to foster energy efficiency in configuration phase is to investigate the machining process, the machine utilization, and the production environment. The knowledge about the intended application of the MT can be integrated into the configuration procedure on top of the traditional decision variables and serve to improve the MT design in the long term.

3.3.3. Energy Efficiency of Machine Tools in Use Phase

Gutowski et al. [121] stated the component level as the required level of detail for investigation of the energy efficiency of MTs and for development of appropriate improvement measures. Gontarz et al. [122] addressed this identified need for detailed investigation by development of a multichannel metering device allowing power profiling on component level in order to enable an in-depth investigation of machine components.

Desmira et al. [96] introduced a mathematical approach to determine the environmental burden caused by the electric consumption conditional upon the cutting conditions for the case of high-speed milling. Liu et al. [123] set up power demand models of MTs and used them to simulate the energy consumption of a manufacturing system depending on the production schedule. Thiede [63], Schlechtendahl et al. [124], Mousavi et al. [125], and Yan et al. [126] developed state models of MTs that can be linked to a production line capable of estimating a factory's expectable power profile based on a production schedule. Beck et al. [127] made an approach to take into account the heat flow to the air conditioning system, which removes the dissipated heat from the factory, but did not consider the resulting power demand.

Abele et al. [128] carried out an ABC-analysis in order to identify the typical energy critical components of MTs. The topic of energy efficiency improvement measures for MTs is well-covered inter alia by an axiomatic approach by Zein et al. [42], a sustainability strategy framework by Herrmann [129], the machine parameter optimization by Diaz et al. [130], the improvement measure categories by Kellens [64], and a comprehensive collection of improvement measures listed in ISO 14955-1 [34]. Improvement measures on installed MT level generally require technological modifications. Züst et al. [131] have shown that technological modifications during MT use mostly do not pay off for a considerable period of time. Thus, the industrial implementation of such measures is prevented and the identified improvement potential cannot be exploited.

3.3.4. Evaluation of Existing Approaches

A state of the art review of existing approaches to foster on energy efficiency of MTs enables the identification of a research gap. In order to gain a comprehensive overview of the state of research in energy efficiency evaluation of MTs, the previously presented research is compared using assessment criteria (completeness criteria are aimed to be fulfilled and characterization criteria help classifying the work). In order to foster on energy efficiency of MTs holistically, the following four assessment criteria are chosen:

- **Completeness criterion "Level of evaluation" (component, MT, IMT):** The degree of data aggregation predefines the achievable depth of analysis for deriving improvement measures. Data acquired on component level can be aggregated to higher level such as the MT level or IMT level. Due to data loss, a reverse action (disaggregation) is impossible.

- **Completeness criterion "Operating states" (off, standby, idle, processing):** A MT can be in different operational states. In each state another combination of components is turned on or operating. Main operational machine states are the off state, standby state, idle state, and processing state. The investigation by operational states is determined in the ISO 14955-1 [34] as mandatory for a MT energy efficiency assessment.

- **Characterization criterion "Test method" (reference part, reference process, SEC, component performance):** The energy consumption of a MT is impacted by the utilization and the manufacturing environment. A MT is designed for an extensive

set of utilization cases determined by the manufacturing process and the product to be manufactured. Various test methods have been developed to emulate realistic use scenarios (reference part, reference process) to ensure the comparability of different use scenarios (specific energy consumption) or different MTs (component performance). Each test method has its own advantages and disadvantages. The test method (also referred to as type of result quantification) describes the procedure and boundaries that are used for the performance test.

- **Characterization criterion "Life cycle perspective" (design, configuration, use):** As the major share of energy consumption and therefore the environmental contribution of a MT is dominated by its use phase, the previous phases as well as the use phase enable implementation of improvement measures. Each of the phases is important in order to exploit the energy saving potentials holistically and past research can be classified according to its life cycle perspective.

Table 8 assesses the approaches to foster on energy efficiency against the before presented criteria in a comparative manner. The dominating research focus lies on the analysis on MT level, rather than on simultaneously investigating the interrelation of components, the MT, and the factory. The main operating states of a MT are clearly covered by research with great focus on the processing. The comparative overview of approaches to foster on energy efficiency reveals that the use phase is the primarily considered life cycle phase. Although comprehensive research has been carried out in the field of optimizing MTs during their use phase, a gap can be observed between the identified improvement measures in use phase and the ones being economically feasible for implementation. To address this issue, novel design procedures, guidelines, tools, etc. have been developed in order to integrate energy efficiency of MTs to the design phase. Existing approaches lack validity due to limited data availability about future use. The configuration phase finds a compromise to address the shortcomings of existing solutions. Even though configuration is forecasted by the United States National Research Council [132] to be one out of six key competitive factors in manufacturing, the configuration of MTs is frequently neglected and its importance for energy efficiency optimization is underestimated. However, a research gap cannot be identified for this phase. Similarly, the more use-oriented test methods (reference part method and reference process method) are more frequently addressed by literature than the more design-oriented methods (SEC method and component performance method). A combination focusing on the evaluation from component to IMT level, covering all operating states could not been found in literature.

Table 8: Comparative overview of approaches to foster on energy efficiency.

Source	Completeness criteria							Characterization criteria						
	Level of evaluation			Operating states				Life cycle perspective			Test method			
● fulfilled ○ not fulfilled	Component	MT	IMT	Off	Standby	Idle	Processing	Design	Configuration	Use	Reference Part	Reference Process	SEC	Component Performance
Diaz et al. [105]	●	●	○	○	○	●	●	●	○	●	●	○	○	○
Seow and Rahimifard [106]	○	●	●	○	○	●	●	●	○	○	●	○	○	○
ISO 14955-1 [34]	●	●	○	●	●	●	●	●	○	●	○	●	○	○
DIN EN ISO 14044 [107]	○	●	●	●	●	●	●	●	○	●	○	●	○	○
Chen et al. [108]	○	●	○	○	○	●	●	●	○	●	●	○	○	○
Diaz et al. [109]	○	●	○	○	○	●	●	●	○	●	●	○	○	○
Kellens et al. [110, 111]	○	●	○	○	○	●	●	●	○	●	●	○	○	○
Schmitt et al. [112]	●	●	○	●	●	●	●	○	○	●	○	●	○	○
Brecher et al. [113, 114]	○	●	○	●	●	●	●	○	○	●	○	●	○	○
Schäfer [115]	●	○	○	○	○	○	●	○	●	○	○	○	○	●
Abele et al. [116]	●	●	○	○	●	●	●	○	●	●	○	○	○	●
Harris et al. [117]	●	○	○	○	○	○	●	○	○	●	○	○	○	●
Riemer et al. [118]	●	○	○	○	○	○	●	○	○	●	○	○	○	●
Salgado and Alonso [119]	●	○	○	○	○	○	●	○	○	●	○	○	○	●
Schischke et al. [30]	●	●	○	●	●	●	●	●	●	●	○	●	○	○

Table 8: Comparative overview of approaches to foster on energy efficiency (continuation).

Source	Completeness criteria							Characterization criteria						
	Level of evaluation			Operating states				Life cycle perspective			Test method			
● fulfilled ○ not fulfilled	Component	MT	IMT	Off	Standby	Idle	Processing	Design	Configuration	Use	Reference Part	Reference Process	SEC	Component Performance
Gontarz et al. [120]	●	●	○	○	○	○	●	○	●	●	●	○	○	○
Gutowski et al. [121]	●	●	○	○	○	○	●	○	○	●	●	○	○	○
Gontarz et al. [122]	●	●	○	○	○	●	●	○	○	●	○	●	○	○
Desmira et al. [96]	●	●	○	○	○	●	●	○	○	●	○	○	●	○
Liu et al. [123]	○	●	○	●	●	●	●	○	○	●	○	●	○	○
Thiede [63]	○	●	●	●	●	●	●	○	○	●	●	○	○	○
Schlechtendahl et al. [124]	○	●	○	●	●	●	●	○	○	●	○	●	○	○
Mousavi et al. [125]	○	●	●	●	●	●	●	○	○	●	○	●	○	○
Yan et al. [126]	○	●	○	●	●	●	●	○	○	●	○	●	○	○
Beck et al. [127]	●	●	●	●	●	●	●	○	○	●	●	○	○	○
Abele et al. [128]	●	○	○	○	○	●	○	○	○	●	○	○	○	●
Zein et al. [42]	○	●	○	○	○	●	●	●	○	●	○	●	○	○
Herrmann [129]	○	●	●	○	○	○	○	●	○	●	○	○	○	○
Diaz et al. [130]	○	●	○	○	○	○	●	○	○	●	○	○	●	○
Kellens [64]	○	●	○	●	●	●	●	●	○	●	○	●	●	○
Züst et al. [131]	●	●	○	●	●	●	●	○	○	●	○	●	○	○
Gontarz et al. [133]	●	●	○	●	●	●	●	●	○	●	○	●	○	○

4. Research Gap, Objectives and Thesis Structure

4.1. Research Gap

The review of key figures and key figure systems revealed that research lacks a metric combining efficiency, consistency, and sufficiency as measures for the need-based utilization / dimensioning of efficient components and enabling their aggregation from MT component level to IMT level. The technical implementation requires a metric to quantify the energetic performance of an IMT. The following key findings are derived from the state of the art review and evaluation:

- The component performance method is identified (compare Chapter 3.1.5) as most feasible method for the evaluating the design of a MT regarding energy efficiency. Most publications apply the reference part method, the reference process method, or the SEC method. The component based approach is hardly researched, but should build the backbone of the metric developed in this thesis.

- A significant lack of quantifying sufficiency and consistency in energy efficiency performance metrics is identified. Most publications use only efficiency as improvement strategy to quantify the energetic performance. None of the analyzed metrics quantifies all three types of improvement strategies for energy efficiency enhancement.

- Most publications focus on analysis and improvements during use phase. A smaller number of publications consider design and configuration as means to foster on energy efficiency. However, no lack of integration of energy efficiency into the configuration phase can be observed.

- Most publications address all main operating machine states. No lack of research can be observed in this field.

- A lack of approaches that perform investigations on IMT level as well as on the combination of all three previously presented levels can be observed. None of the reviewed publications shows a comprehensive evaluation comprising the energy efficiency of the components, the resulting energy efficiency of the MT, and the resulting energy efficiency of the IMT.

4.2. Objectives

This thesis aims at filling the research gap by developing a metric to foster on MTs' energy efficiency holistically. Following objectives (O) shall be met by the developed metric:

- **O1:** Include the domains efficiency, consistency, and sufficiency in the energy efficiency quantification.

- **O2:** Enable applicability to subsystems level, such as MT component and the TBS component level.

- **O3:** Enable aggregability to system level, such as MT and IMT level.

- **O4:** Enable identifying the subsystems with the highest improvement potential for the entire system.

The application of the metric in practice should serve as proof of concept. The metric with these characteristics shall serve as preparatory work for the development of a not yet defined energy efficiency rating system for MTs and may contribute to the further development of the ISO 14955 series. The thesis framework, highlighting the interrelations of the building, is illustrated in Figure 29. The IMT (1) needs to be assessed based on the sustainability strategies (2) efficiency, consistency, and sufficiency using a metric (3). The gained results of the metric application can then by applied to the life cycle phases (4) design, configuration, and use.
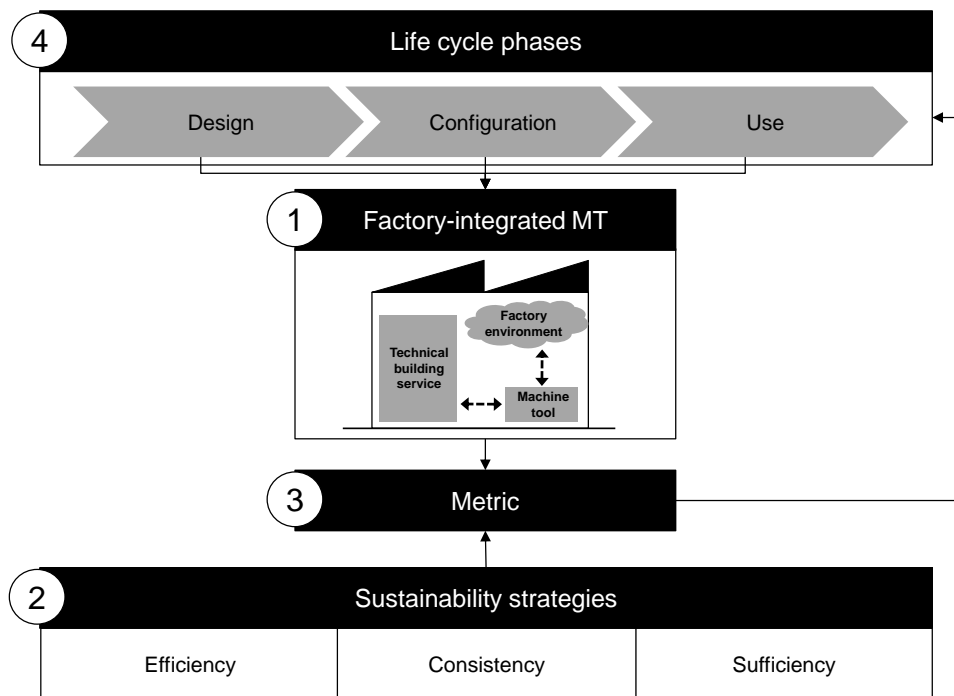
Figure 29: Thesis framework consisting of the IMT (1), the sustainability strategies (2), the metric (3), and the life cycle phases (4).

4.3. Thesis Structure

The approach for the proposed research topic can be divided into seven phases, illustrated in Figure 30. The topic of sustainable manufacturing is first introduced. Based on the definition of sustainable development, the concept of the three pillars approach to foster on such development is explained. This leads to the major strategies to achieve improvements in the context of sustainability that provide the backbone for the metric development. The theoretical background research contains fundamental information about current regulations and standards as well as the terminology and the physical fundamentals for this thesis. Moreover, basics of energy efficiency in manufacturing are summarized. The theoretical background ends with the introduction of key figure types and the basics methods to aggregate efficiency values. Existing work in energy efficiency evaluation of MTs is reviewed and evaluated in order to identify a research gap and deduce the thesis objectives.

1	Introduction
2	Theoretical Background
3	State of the Art
4	Research Gap and Objectives
5	Metric Development
6	Metric Application
7	Discussion, Conclusion, and Outlook

Figure 30: Thesis structure.

A metric for MT energy efficiency assessment is developed in three steps. First, a model for quantifying the power demand of an IMT is proposed. Second, a metric is developed, which comprises the sustainability strategies sufficiency, efficiency, and consistency. Third, the metric is specified for application to the IMT model. The concept is applied in practice for a grinding machine Rollomatic 628 XS located in the IWF-lab at ETH Zurich. Finally, the thesis results are critically discussed, conclusions are drawn, and future research perspectives are outlined.

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5. Metric Development

First, a model for quantification of the electrical power demand of a IMT is developed based on Schudeleit et al. [47]. Second, a metric concept is developed to quantify the energy efficiency with respect to the need-based utilization (sufficiency) and the possible degree of efficiency (consistency) according to Schudeleit et al. [48]. Third, the metric concept is applied to the MT components, the entire MT, and the TBS components in order to enable the total energy efficiency quantification of the IMT. Fourth, the possible impact of energy efficiency improvements on the total savings of primary energy is shown.

5.1. Model Development

The power demand of the MT (direct power demand) and associated power demand of the TBS due to MT operation (indirect power demand) need to be taken into account. The total electrical power consumption caused by the IMT is derived by

$$P_{EC-IMT} = P_I + P_{II} + P_{III} + P_{IV} = P_{EC-MT} + P_{EC-TBS-MT} \tag{5.1}$$

with the electric power consumption of the MT $P_I = P_{EC-MT}$ and the electrical power share of the TBS to operate the MT $P_{EC-TBS-MT} = P_{II} + P_{III} + P_{IV}$. The roman indices refer to the types of energy exchange defined by ISO/CD 14955-2 [36]. The MT is subdivided into MT components, which collectively contribute to the power demand of the MT. The TBS components are modeled likewise. Finally, the TBS component models are linked to the MT model in order to obtain the IMT model.

5.1.1. Electrical Power Demand of a Machine Tool

The MT power profile is created by the superposition of the MT component power profiles. When the component state is changed, a transition period is passed through, in which electric power peaks occur, as depicted in Figure 31. Each power peak leads to an increase in power demand and hence a higher energy consumption. If the transition period T_{tns} is small compared to the steady period T_{stdy}, transient states in power demand can be neglected, leading to

$$\overline{P} \approx \overline{P}_{stdy} = \frac{1}{t_3 - t_2} \int_{t_2}^{t_3} P(t)\,dt \tag{5.2}$$
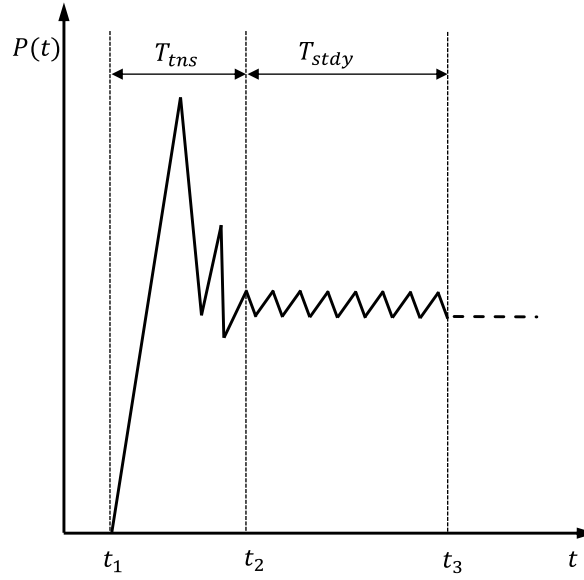
Figure 31: Electric power peaks due to state transition.

According to Schudeleit et al. [134], each MT component's power demand behavior can be assigned to one of three characteristic power profile classes as illustrated in Figure 32 and described below: constant power consumers, cyclic power consumer, and variable power consumers.
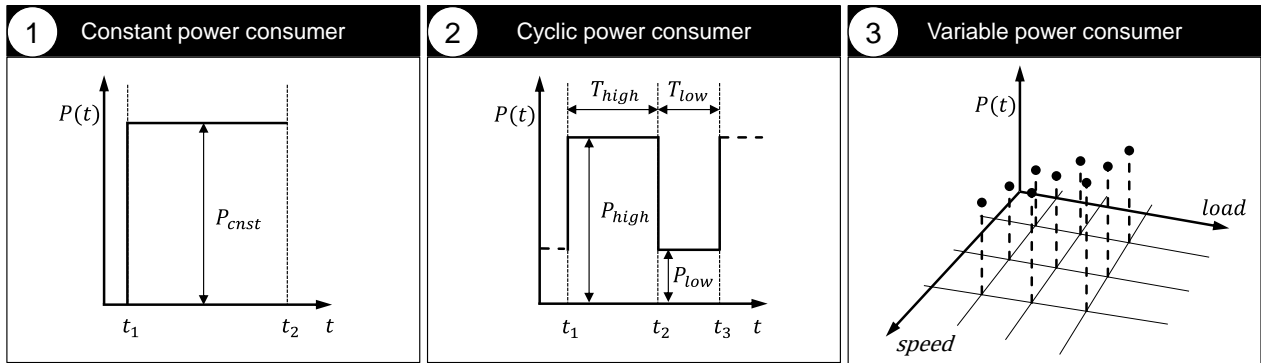
Figure 32: Characterization of power consumers: constant (1), cyclic (2), and variable (3).

Components are classified as constant power consumers (1), if their power demand remains at a constant level within each component state. The consumer is switched on at the time t_1 until the observation ends at the time t_2. An ideal constant consumer is modelled by P_{cnst}.

Components are classified as cyclic power consumers (2), if their power level depends on the component state and/or the time, but not on the load. The cyclic power consumer type is turned on and off periodically, e.g. by the machine control unit. The cyclic power consumer type can be

modelled by four values, whereas transient behavior is neglected. The component power demand switches to the upper power state P_{high} at time t_1 and remains constant for the time period T_{high} until the power demand is switched to the lower state P_{low} at time t_2. The power demand remains there for the time period T_{low} until the entire pattern repeats at the time t_3. Similar to the constant power consumer, transient states are neglected for the same reason. The average power of a cyclic consumer is derived by

$$P_{cycl} \triangleq \frac{T_{high} \cdot P_{high} + T_{low} \cdot P_{low}}{T_{high} + T_{low}} \tag{5.3}$$

Since the time periods in upper and lower state might vary, an observation of more than one cycle is recommended. In this case, the average power of cyclic consumer is derived by the average value of multiple cycles.

Components are classified as variable power consumers (3), if their power demand depends on the manufacturing process represented by a speed variable (e.g. velocity, rotational speed, volume flow) and load variable (e.g. force, torque, pressure). Hence, variable power demand behavior can only be observed during processing. The variable power consumer type has non-constant and non-cyclic power demand behavior in the processing state. The power demand characteristic of a variable consumer is entirely described by a power map. Different combinations of the speed and the load variable must be applied to the component in order to fully describe the components power demand behavior.

The component consumer type and/or the values to describe the power demand behavior might change with the operational state of the MT and the utilization during this state. Hence, a component can be classified as constant consumer during one machine state and as cyclic or variable consumer in another machine state. ISO 14599-1 [34] lists a number of exemplary machine states that can be observed. However, four main machine states can be distinguished:

- **Off:** The main switch is turned off and compressed air is disabled.

- **Standby:** Compressed air is enabled. The main switch is turned on and the control is operating. CNC code can be programmed.

- **Idle:** The main switch is turned on, the control is operating, and most functional units are started. The axis and spindle can be moved.

- **Processing:** The main switch is turned on, the control is operating, and most functional units are started. The coolant unit and the spindle are operating.

Table 9 depicts the principle classification of components in consumer types at different operational states. The characteristic power profile of the MT component consumer types accumulate to the MT consumer type, as indicated in the last row of the table.

Table 9: Exemplary list of consumer types of components at the machine states.

Component name	Off	Standby	Idle	Processing
A	constant	constant	constant	variable
B	-	-	cyclic	cyclic
C	-	constant	constant	constant
…	…	…	…	…
MT	constant	constant	cyclic with constant share	variable with constant and cyclic share

The difference between the MT's total power demand and the sum of the MT components power demand indicates the uncertainty due to unmeasured components. ISO 14955-1 [34] prescribes to meter each consumer causing at least 10% of the entire MT's power demand collectively contributing to at least 80% of the entire MT's power demand in each machine state. Hence, a difference of less than 20% is required for the validity of the study. The uninvestigated components are excluded from the entire study. Hence, the MT power demand is assigned to be the sum of the power demands of all considered components i within the machine state s

$$\sum_{i=1}^{n} P_{EC-MT,i,s} \triangleq P_{EC-MT,s} = P_I \qquad (5.4)$$

5.1.2. Electrical Power Demand of the Technical Building Service

MTs and the TBS mainly interact through following four interfaces (compare Chapter 2.1.3):

- compressed air (CA) system (type II)

- water cooling (WC) system (type III)

- air conditioning (AC) system (type IV)

- exhaust air (EA) system (type IV)

Moreover, the baseload energy consumption of the factory, which is needed to maintain constant conditions (humidity, temperature, etc.) irrespective of the external climate are not assigned to the MTs and are similarly as in Bogdanski et al. [135] assigned to the factory baseload. The total electric power demand of the TBS in order to operate a number of MTs is derived by

$$P_{EC-TBS} = P_{EC-CA-TBS} + P_{EC-WC-TBS} + P_{EC-AC-TBS} + P_{EC-EA-TBS} \tag{5.5}$$

with the equivalent electrical power demand of the CA system $P_{EC-CA-TBS}$, the WC system $P_{EC-WC-TBS}$, the AC system $P_{EC-AC-TBS}$ and the EA system $P_{EC-EA-TBS}$. The CA system demands $P_{EC-CA-TBS}$ to produce CA with the pneumatic volume flow of $\dot{V}_{CA-TBS}$ at a defined pressure level p_{CA-TBS} above the norm pressure p_n. The WC system and the AC system consume the electrical power $P_{EC-WC-TBS}$ and $P_{EC-AC-TBS}$ to transport the heat flows $\Delta\dot{Q}_{WC-TBS}$ and $\Delta\dot{Q}_{AC-TBS}$ out of the factory building. The EA system demands the electrical power $P_{EC-EA-TBS}$ to filter and transport the air volume flow $\dot{V}_{EA-TBS}$ with the speed v_{EA-TBS} together with the heat flow $\Delta\dot{Q}_{EA-TBS}$ to the AC system. The energetic performance of TBS systems is described by following electrical energy equivalents:

- specific compression power (SCP) for CA flows κ

- energy efficiency ratio (EER) for heat flows ε

- specific fan power (SFP) for EA flows ζ

The performance values quantify the electrical power demand needed to realize a CA supply, heat intake and respectively volume flow as following

$$P_{EC-CA-TBS} = \kappa_{CA-TBS} \dot{V}_{CA-TBS} \frac{p_{CA-TBS}}{p_n} \frac{\vartheta_n}{\vartheta_{CA-TBS}} \tag{5.6}$$

$$P_{EC-WC-TBS} = \frac{\Delta\dot{Q}_{WC-TBS}}{\varepsilon_{WC-TBS}} \tag{5.7}$$

$$P_{EC-AC-TBS} = \frac{\Delta\dot{Q}_{AC-TBS}}{\varepsilon_{AC-TBS}} \tag{5.8}$$

$$P_{EC-EA-TBS} = \frac{\Delta \dot{Q}_{EA-TBS}}{\varepsilon_{EA-TBS}} + \zeta_{EA-TBS} \cdot \dot{V}_{EA-TBS} \tag{5.9}$$

Equation (5.6) assumes the validity of the ideal gas law

$$\frac{\dot{V}_{CA-TBS} \, p_{CA-TBS}}{\vartheta_{CA-TBS}} = \frac{\dot{V}_n \, p_n}{\vartheta_n} = const. \tag{5.10}$$

with the norm volume flow $\dot{V}_n$ at norm pressure $p_n = 1 bar$ and norm temperature $\vartheta_n = 293.15K$ according to ISO 8778 [136]. Combining equation (5.5) with the equations (5.6), (5.7), (5.8), and (5.9) leads to

$$P_{EC-TBS} = \kappa_{CA-TBS} \dot{V}_{CA-TBS} \frac{p_{CA-TBS}}{p_n} \frac{\vartheta_n}{\vartheta_{CA-TBS}} + \frac{\Delta \dot{Q}_{WC-TBS}}{\varepsilon_{WC-TBS}} + \frac{\Delta \dot{Q}_{AC-TBS}}{\varepsilon_{AC-TBS}} + \frac{\Delta \dot{Q}_{EA-TBS}}{\varepsilon_{EA-TBS}} + \zeta_{EA-TBS} \cdot \dot{V}_{EA-TBS} \tag{5.11}$$

5.1.3. Electrical Power Demand of a Factory-integrated Machine Tool

The total electrical power demand of the IMT is derived by

$$P_{EC-IMT} = P_{EC-MT} + P_{EC-CA-MT} + P_{EC-WC-MT} + P_{EC-AC-MT} + P_{EC-EA-MT} \tag{5.12}$$

with the electrical power demand of the MT P_{EC-MT} as well as the equivalent electrical power demand of the CA system $P_{EC-CA-MT}$, the WC system $P_{EC-WC-MT}$, the AC system $P_{EC-AC-MT}$, and the EA system $P_{EC-EA-MT}$ in order to operate a single MT. Figure 33 illustrates the linking of both previously described approaches to a model for the energetic linking of a MT with the TBS.
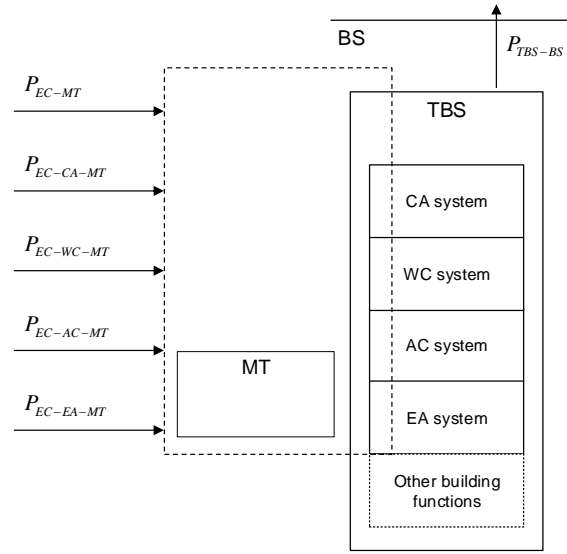
Figure 33: Electrical power demand model of an IMT.

In order to link the MT and the TBS, the power balance of services supplied to a single MT need to be considered and determined as illustrated in Figure 34. The MT's electric power demand P_{EC-MT} and the CA power described by its volume flow $\dot{V}_{CA-MT}$ and pressure level Δp_{CA-MT} above the nominal pressure p_n enter the system. The heat flow to the WC system $\Delta \dot{Q}_{WC-MT}$, the heat flow to the EA system $\Delta \dot{Q}_{EA-MT}$, the kinetic power of the EA system described by the air density ρ_{air}, the air volume flow $\dot{V}_{EA-MT}$, the flow velocity v_{EA-MT}, and the heat flow to the AC $\Delta \dot{Q}_{AC-MT}$ leave the system.
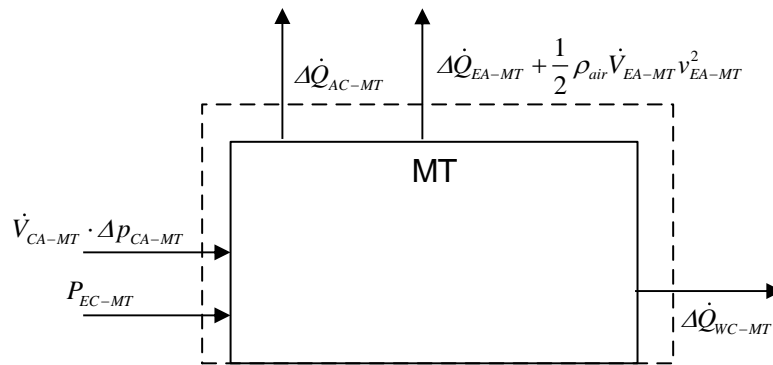
Figure 34: Services supplied to operate a MT.

Assuming a single MT in the factory environment, neglecting the impact of weather conditions, leakages, and pressure loss in media supply systems leads to

$$\dot{V}_{CA-TBS} = \dot{V}_{CA-MT} \tag{5.13}$$

$$p_{CA-TBS} = p_{CA-MT} \tag{5.14}$$

$$T_{CA-TBS} = T_{CA-MT} \tag{5.15}$$

$$\Delta\dot{Q}_{WC-TBS} = \Delta\dot{Q}_{WC-MT} \tag{5.16}$$

$$\Delta\dot{Q}_{AC-TBS} = \Delta\dot{Q}_{AC-MT} \tag{5.17}$$

$$\Delta\dot{Q}_{EA-TBS} = \Delta\dot{Q}_{EA-MT} \tag{5.18}$$

$$\dot{V}_{EA-TBS} = \dot{V}_{EA-MT} \tag{5.19}$$

Combining the equations (5.13), (5.14), (5.15), (5.16), (5.17), (5.18), and (5.19) with the equations (5.6), (5.7), (5.8), (5.9) leads to the power demand of the TBS components due to a single MT operation

$$P_{EC-CA-MT} = \kappa_{CA-TBS}\dot{V}_{CA-MT}\frac{p_{CA-MT}}{p_n}\frac{\vartheta_n}{\vartheta_{CA-MT}} \tag{5.20}$$

$$P_{EC-WC-MT} = \frac{\Delta\dot{Q}_{WC-MT}}{\varepsilon_{WC-TBS}} \tag{5.21}$$

$$P_{EC-AC-MT} = \frac{\Delta\dot{Q}_{AC-MT}}{\varepsilon_{AC-TBS}} \tag{5.22}$$

$$P_{EC-EA-MT} = \frac{\Delta\dot{Q}_{EA-MT}}{\varepsilon_{EA-TBS}} + \zeta_{EA-TBS}\cdot\dot{V}_{EA-MT} \tag{5.23}$$

and combined with equation (5.12) results in the total power demand of the IMT

$$P_{EC-IMT} = P_{EC-MT} + \kappa_{CA-TBS}\dot{V}_{CA-MT}\frac{p_{CA-MT}}{p_n}\frac{\vartheta_n}{\vartheta_{CA-MT}} + \frac{\Delta\dot{Q}_{WC-MT}}{\varepsilon_{WC-TBS}} + \frac{\Delta\dot{Q}_{AC-MT}}{\varepsilon_{AC-TBS}} + \frac{\Delta\dot{Q}_{EA-MT}}{\varepsilon_{EA-TBS}} + \zeta_{EA-TBS}\cdot\dot{V}_{EA-MT} \tag{5.24}$$

5.2. Concept of the Total Energy Efficiency Index

The presented approach to quantify the energy efficiency of MTs comprises the demand-oriented component utilization (sufficiency of components), the component conversion efficiency (efficiency of components), and the component conversion efficiency of a reference system (consistency of components) according to Schudeleit et al. [48]. The occurring losses related to insufficiencies, inefficiencies, and inconsistencies accumulate to the overall loss in energy referred to as efficiency gap, as illustrated in Figure 35. The ratio of the reference system's demand and the actual system's demand build the overall energy efficiency, which is referred to as Total Energy Efficiency Index (TEEI).
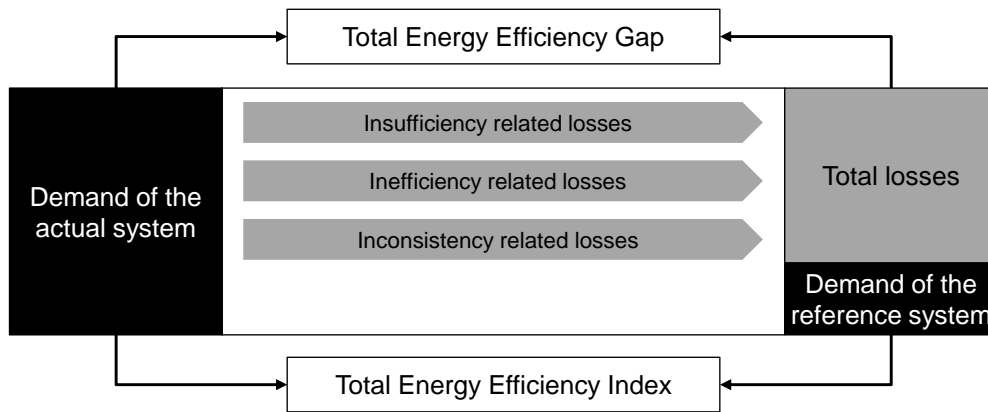
Figure 35: Total energy efficiency gap due to sufficiency, efficiency, and consistency losses as well as the TEEI according to Schudeleit et al. [48].

The novelty of the concept is that the energy efficiency key figure of a system is divided into three parts, which can relatively simple be determined individually. Three key figures are introduced in order to quantify the component sufficiency, efficiency, and consistency, namely:

- Sufficiency Index (SI), calculated based on demand assessment or empirical studies,

- Efficiency Index (EI), calculated based on measurements, and

- Consistency Index (CI), calculated based on measurements, efficiency standards or labels.

The key figures are finally aggregated to the TEEI, which is a general metric that can universally be used for evaluating the energy efficiency of MT or TBS components. In any case, the TEEI can be aggregated from lower to higher level, e.g. from MT component level to MT level or from TBS component level to TBS level. Figure 36 illustrates the relations between an actual system and reference system, which can be real or ideal. The SI focuses on the comparison of the

outputs of the reference and the actual system, whereas the EI and the CI quantify the conversion efficiency and the productivity of each system, respectively. The TEEI compares the input of the actual system with the input a reference system would need to perform the same task.
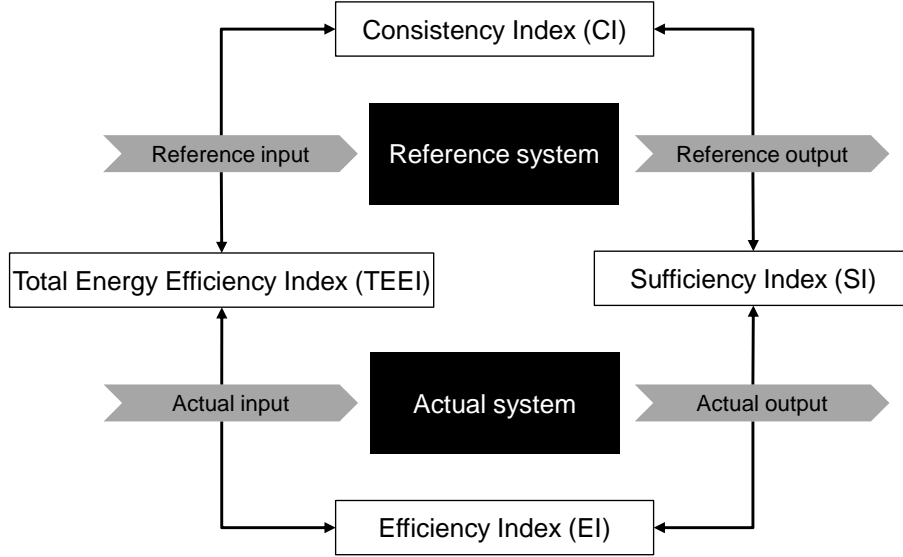
Figure 36: Illustration of the sustainability indices.

5.2.1. The Sufficiency Index

The SI compares the output supplied by an ideal reference system with the one of the actual system. Hence, losses due to incorrect dimensioning and inappropriate component utilization, such as air extraction during long idle times or a compressed air use beyond the required one, is taken into account by this index. The SI of a component is defined by

$$\alpha_{SI} = \frac{O_{ref}}{O_{act}}; \qquad \alpha_{SI} \in [0,1] \tag{5.25}$$

with the output of the reference system O_{ref} and the output of the actual system O_{act}. α_{SI} is a dimensionless, percentage scaled key figure. The reference output is the minimum output required to fulfill the manufacturing task. An actual output less than the reference output indicates under-dimensioning, which might cause a lack of safety, or harm the system to perform the manufacturing task. In this case, $\alpha_{SI} = 1$ is assigned and the dimensioning is highlighted as a potential improvement measure.

5.2.2. The Efficiency Index

The EI quantifies the power intake in order to achieve a desired result and is generally defined as

$$\lambda_{EI} = \frac{O_{act}}{I_{act}}; \qquad \lambda_{EI} \in \mathbb{R}^+ \tag{5.26}$$

with the input of the actual system I_{act}. The EI and its unit depend on the type of transformation process as well as on the technological standard of the evaluated system. For energy transforming processes, the EI is the conversion efficiency of the system and a dimensionless, percentage scaled key figure. Input and output do not necessarily have to have the same unit, in which case EI is referred to as the productivity of the actual system.

5.2.3. The Consistency Index

In order to quantify the maximum energy saving potential of a component, the EI needs to be related to a reference value, the index introduced as CI. In this way, the losses due to inappropriate component selection (ineffectiveness and lack of technological standard) are taken into account. The CI refers to an efficiency limit, such as the most suitable and BAT. The CI is determined by

$$\lambda_{CI} = \frac{O_{ref}}{I_{ref}}; \qquad \lambda_{CI} \in \mathbb{R}^+ \tag{5.27}$$

with the input of the reference system I_{ref}. The reference output is the same minimum output as used for the SI.

5.2.4. The Total Energy Efficiency Index in General

The TEEI is a metric that comprises all sustainability strategies and refers to the system with the highest sufficiency, efficiency, and consistency in order to quantify the actual energy efficiency gap. It measures to which degree an actual system matches a reference system that would fulfill the given task best with respect to the given boundary conditions (e.g. technology limits, economic restrictions, etc.). In reality, the design decisions cannot be decoupled. To overcome this issue, the indices for sufficiency, efficiency, and consistency are aggregated to a compiled index referred to as TEEI

$$\eta_{TEEI} = \alpha_{SI} \cdot \frac{\lambda_{EI}}{\lambda_{CI}} = \alpha_{SI} \cdot \eta_{EI/CI} = \frac{I_{ref}}{I_{act}}; \qquad \eta_{TEEI}, \eta_{EI/CI} \in [0,1] \qquad (5.28)$$

with the relative conversion efficiency $\eta_{EI/CI}$, which cannot exceed one. η_{TEEI} is simply the ratio of the power input of an ideal reference system and the power input of the actual system. The procedure of successively calculating α_{SI}, λ_{EI}, and λ_{CI} in order to finally summarize the indices to η_{TEEI} ensures that all possible types of energy losses are considered.

5.2.5. Classification and Simplification of System Types

For mathematical specifications of the inputs and outputs of the indices (α_{SI}, λ_{EI}, and λ_{CI}), the components are classified by their system type as follows:

- **Input systems:** The desired result of the system is a physical input, while electricity is consumed. An example for an input system is a cooler with a heat flux entering the system boundary.

- **Output systems:** The desired result of the system is a physical output, while electricity is consumed. An example for an output system is an electric motor with mechanical power exiting the system boundary.

- **State systems:** The desired result of the system is a state, while electricity is consumed. If the state is desired, the output of reference and the actual system are both the state quantified by $O_{ref} = O_{act} = 1$, which leads to $\alpha_{SI} = 1$. Otherwise, α_{SI} is equated to zero. An example for a state system is a control unit.

- **Passive systems:** The desired result of the system is a physical output caused by a physical non-electric input. The SI of a passive system is determined and comprised by the SI of the superordinate input or output system, which converts electricity to a non-electric input for the type passive system. Hence, SI of the passive system is equated to $\alpha_{SI} = 1$. The physical input can be mechanically, hydraulically, pneumatically, or thermally. An example for a passive system is a transmission.

It is dependent on the desired degree of detail whether a component is composed of a combination of different systems or not. For example, a pump unit can be viewed as output

system with electric input and hydraulic output or as a combination of an output system and a passive system, which would be an electric motor and a pump. The electric motor's mechanical output power is converted by the pump into a hydraulic output.

The value of α_{SI} has to be determined explicitly for the input and output systems. A decision tree, depicted in Figure 37, is used to reduce the calculation effort by following assumptions:

- Systems that are switched off do not demand power and are therefore excluded from the study for the respective state.

- Systems that are unnecessarily switched on in a certain state are fully insufficient in this state. Hence, $\alpha_{SI} = 0$ is derived. η_{TEEI} equals zero for this case and no calculation of λ_{EI} or λ_{CI} is required.

- Systems that are necessarily switched on and automatically (not manually or by time) demand controlled in a certain state are fully sufficient in this state. Hence, $\alpha_{SI} = 1$ is derived and λ_{EI} as well as λ_{CI} need to be calculated.

- Systems that are necessarily switched on, but not automatically demand controlled require a detailed assessment of α_{SI}, λ_{EI} as well as λ_{CI}. For a constant state, a constant α_{SI} will be derived.
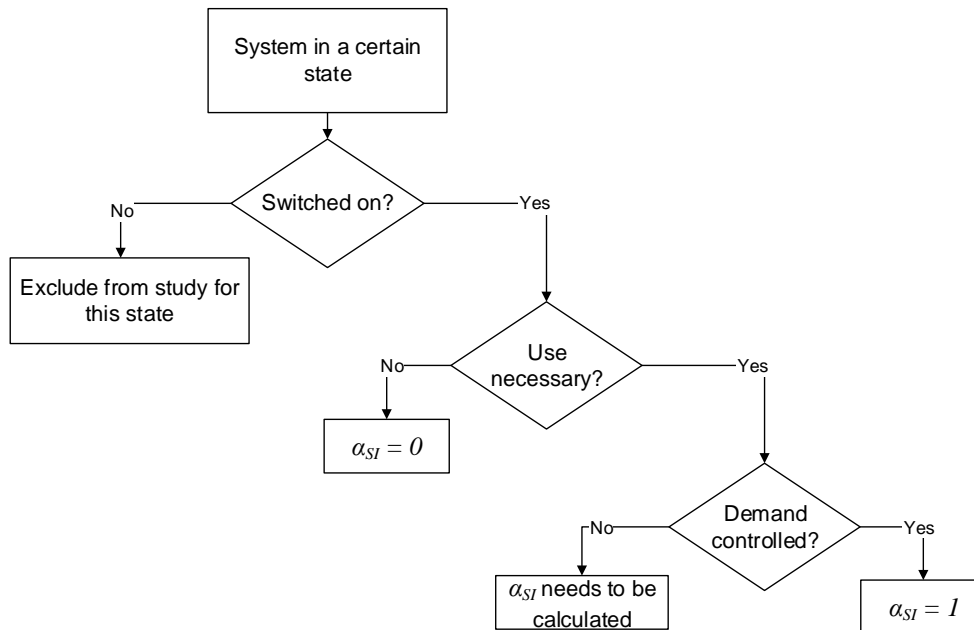
Figure 37: Sufficiency tree for SI determination of input and output systems.

5.3. The Total Energy Efficiency Index in Manufacturing

The beforehand presented concept is in the following specified for the application in manufacturing. The methodology follows a three-step procedure:

1. The TEEIs on MT component level are derived and aggregated to the MT TEEI.

2. The calculation of the TEEIs of the TBS components is shown.

3. Both TEEI models are combined to the TEEI model of the IMT.

5.3.1. The Total Energy Efficiency Indices of the Machine Tool Components and the Machine Tool

Specifying the generalized equation (5.28) for each component i and the machine state s leads to the MT component TEEI

$$\eta_{TEEI,i,s} = \alpha_{SI,i,s} \frac{\lambda_{EI,i,s}}{\lambda_{CI,i,s}} = \alpha_{SI,i,s} \cdot \eta_{EI/CI,i,s}; \qquad i = 1,...,n \tag{5.29}$$

The metric can universally be aggregated from lower to higher level, e.g. MT component to MT level. When all $\eta_{TEEI,i,s}$ are computed, the TEEI on MT level $\eta_{TEEI,MT,s}$ is derived by

$$\eta_{TEEI,MT,s} = \frac{\sum_{i=1}^{n} \left(P_{EC-MT,i,s} \cdot \eta_{TEEI,i,s} \right)}{\sum_{i=1}^{n} P_{EC-MT,i,s}}; \qquad i = 1,...,n \tag{5.30}$$

An exact $\eta_{TEEI,MT,s}$ can only be calculated, if all energy consuming components of a MT are included in the study. If some components are not investigated in more detail due to their low power share, $\eta_{TEEI,MT,s}$ is an approximation.

5.3.2. The Total Energy Efficiency Indices of the Technical Building Service Components

The SIs of the TBS components are determined by their use by the MT within each state s, whereas the EIs and CIs of the TBS components are independent of the machine states based on the assumption that a MT does not change the operational point of the respective TBS component. Decreases in sufficiency of CA supply are caused by insufficient use on MT level in each state, and are derived by

$$\alpha_{SI,CA-MT,s} = \frac{\dot{V}_{CA-MT,s,ref}}{\dot{V}_{CA-MT,s,act}} \tag{5.31}$$

Assuming a constant pressure level and constant temperature, $\lambda_{EI,CA-TBS}$ and $\lambda_{CI,CA-TBS}$ are derived by

$$\lambda_{EI,CA-TBS} = \frac{1}{\kappa_{CA-TBS,act}} \tag{5.32}$$

$$\lambda_{CI,CA-TBS} = \frac{1}{\kappa_{CA-TBS,ref}} \tag{5.33}$$

and lead combined with equation (5.31) to the total energy efficiency index of the CA system

$$\eta_{TEEI,CA-MT,s} = \alpha_{SI,CA-MT,s} \cdot \frac{\lambda_{EI,CA-TBS}}{\lambda_{CI,CA-TBS}} = \frac{\dot{V}_{CA-MT,s,ref}}{\dot{V}_{CA-MT,s,act}} \cdot \frac{\kappa_{CA-TBS,ref}}{\kappa_{CA-TBS,act}} \tag{5.34}$$

Assuming no leakages (loss in volume flow) of the WC system leads to

$$\alpha_{SI,WC-MT,s} = 1 \tag{5.35}$$

The $\lambda_{EI,WC-TBS}$ and $\lambda_{CI,WC-TBS}$ of the WC system are defined by energy efficiency ratios of the actual and the reference system

$$\lambda_{EI,WC-TBS} = \varepsilon_{WC-TBS,act} \tag{5.36}$$

$$\lambda_{CI,WC-TBS} = \varepsilon_{WC-TBS,ref} \tag{5.37}$$

which lead combined with equation (5.35) to

$$\eta_{TEEI,WC-MT,s} = \alpha_{SI,WC-MT,s} \cdot \frac{\lambda_{EI,WC-TBS}}{\lambda_{CI,WC-TBS}} = \frac{\varepsilon_{WC-TBS,act}}{\varepsilon_{WC-TBS,ref}} \tag{5.38}$$

In order to maintain a constant temperature level in the factory using the AC system, all in the factory dissipated heat needs to be removed by the actual system respectively the reference system, which leads to

$$\alpha_{SI,AC-MT,s} = \frac{\Delta \dot{Q}_{AC-MT,act}}{\Delta \dot{Q}_{AC-MT,ref}} = 1 \tag{5.39}$$

Neglecting the impact of weather conditions and using the energy efficiency ratios as performance measure, following subordinate indices can be derived

$$\lambda_{EI,AC-TBS} = \varepsilon_{AC-TBS,act} \tag{5.40}$$

$$\lambda_{CI,AC-TBS} = \varepsilon_{AC-TBS,ref} \tag{5.41}$$

These equations combined lead to the TEEI of the AC system

$$\eta_{TEEI,AC-MT,s} = \alpha_{SI,AC-MT,s} \cdot \frac{\lambda_{EI,AC-TBS}}{\lambda_{CI,AC-TBS}} = \frac{\varepsilon_{AC-TBS,act}}{\varepsilon_{AC-TBS,ref}} \tag{5.42}$$

Since, the EA system volume flow is normally not controlled, insufficiency is caused by more air changes than required by e.g. legal regulations. The SI of the EA system is obtained by

$$\alpha_{SI,EA-MT,s} = \frac{\dot{V}_{EA-MT,s,ref}}{\dot{V}_{EA-MT,s,act}} \tag{5.43}$$

Two basic cases can be distinguished regarding the characteristic of an EA system:

1. Free cooling: The heat is released out of the factory to the environment, directly or with heat recovery. In this case, the EA system is a simple air suction, leading to an efficiency benchmark of the fan by

$$\lambda_{EI,EA-TBS} = \frac{1}{\zeta_{EA-TBS,act}} \tag{5.44}$$

$$\lambda_{CI,EA-TBS} = \frac{1}{\zeta_{EA-TBS,ref}} \tag{5.45}$$

$$\eta_{TEEI,EA-MT,s} = \alpha_{SI,EA-MT,s} \cdot \frac{\lambda_{EI,EA-TBS}}{\lambda_{CI,EA-TBS}} = \frac{\dot{V}_{EA-MT,s,ref}}{\dot{V}_{EA-MT,s,act}} \cdot \frac{\zeta_{EA-TBS,ref}}{\zeta_{EA-TBS,act}} \tag{5.46}$$

2. A system linked to an AC or a WC system: The EER of the EA system equals the one of the AC system respectively the WC system and is assigned to them for efficiency evaluation. The performance of the combined AC system is described by

$$\lambda_{EI,EA-TBS} = \varepsilon_{EA-TBS,act} = \frac{\Delta \dot{Q}_{EA-TBS,act}}{P_{EC-EA-TBS,act}} \tag{5.47}$$

$$\lambda_{CI,EA-TBS} = \varepsilon_{EA-TBS,ref} = \frac{\Delta \dot{Q}_{EA-TBS,ref}}{P_{EC-EA-TBS,ref}} \tag{5.48}$$

with $P_{EC-EA-TBS,act}$ and $P_{EC-EA-TBS,ref}$ including both the power demand for cooling and the EA suction, leading to

$$\eta_{TEEI,EA-MT,s} = \alpha_{SI,EA-MT} \cdot \frac{\lambda_{EI,EA-TBS}}{\lambda_{CI,EA-TBS}} = \frac{\dot{V}_{EA-MT,s,ref}}{\dot{V}_{EA-MT,s,act}} \cdot \frac{\varepsilon_{EA-TBS,act}}{\varepsilon_{EA-TBS,ref}} \tag{5.49}$$

5.3.3. The Total Energy Efficiency Indices of the Integrated Machine Tool

The TEEI of the IMT is derived by the ratio of the power demand of the reference and the actual system by

$$\eta_{TEEI,IMT,s} = \frac{P_{EC-IMT,s,ref}}{P_{EC-IMT,s,act}} = \frac{1}{P_{EC-IMT,s,act}} \begin{pmatrix} P_{EC-MT,s,act} & \eta_{TEEI,MT,s} & + P_{EC-CA-MT,s,act} & \eta_{TEEI,CA-MT,s} \\ +P_{EC-WC-MT,s,act} & \eta_{TEEI,WC-MT,s} + P_{EC-AC-MT,s,act} & \eta_{TEEI,AC-MT,s} \\ +P_{EC-EA-MT,s,act} & \eta_{TEEI,EA-MT,s} \end{pmatrix} \tag{5.50}$$

In order to predict the MT's average total energy efficiency in practice, the distribution of machine states over time needs to be considered. The average total energy efficiency index of the IMT weighted by the power demand in each state is determined by

$$\bar{\eta}_{TEEI,IMT} = \frac{\sum_s \left(\eta_{TEEI,IMT,s} \cdot P_{EC-IMT,s,act} \cdot S_s \right)}{\sum_s \left(P_{EC-IMT,s,act} \cdot S_s \right)} \tag{5.51}$$

with the time share in each state S_s. The distribution of machine states over a time period strongly depends on the type of production. Table 10 lists an assumed distribution over time of machine states by type of production.

Table 10: Assumed distribution over time of machine states by type of production.

Series type	S_{off}	S_{stby}	S_{idle}	S_{proc}
Small series	20%	20%	20%	40%
Medium series	10%	15%	15%	60%
Large series	0%	15%	15%	70%

5.3.4. Calculation of the Optimization Potential and Analysis

The optimization potential in terms of power and efficiency is derived from the previously calculated TEEIs. The possibly saved power demand is derived from the difference of the power demand between the actual and the reference IMT by

$$\Delta P_{EC-IMT,s} = P_{EC-IMT,s,act} - P_{EC-IMT,s,ref} = P_{EC-IMT,s,act}\left(1 - \eta_{TEEI,IMT,s}\right) \tag{5.52}$$

In order to improve the energy efficiency of an IMT, following three step-procedure is applied:

1. Calculation of the improvement potential of the MT, its components, the CA system, EA system, WC system, and AC system.

2. Ranking according to their improvement potential and selection of the most promising systems.

3. Detailed system analysis to derive individual improvement measures.

A decrease in power demand of the MT causes an additional decrease in power demand of the TBS systems responsible for cooling, namely the WC, the AC and the EA system. A MT's impact to increase the TEEI of the IMT is derived by

$$\eta_{TEEI,opt,MT,s} = \frac{\Delta P_{EC-MT,s} + \Delta P_{EC-WC-MT,s} + \Delta P_{EC-AC-MT,s} + \Delta P_{EC-EA-MT,s}}{P_{EC-IMT,s,act}} \tag{5.53}$$

The decrease in power demand of the WC, the AC and the EA system resulting from the MT improvement are derived by

$$\Delta P_{EC-MT,s} = P_{EC-MT,s,act}\left(1 - \eta_{TEEI,MT,s}\right) \tag{5.54}$$

$$\Delta P_{EC-WC-MT,s} = P_{EC-WC-MT,s,act}\left(1 - \eta_{TEEI,MT,s}\right) \tag{5.55}$$

$$\Delta P_{EC-AC-MT,s} = P_{EC-AC-MT,s,act} \left(1 - \eta_{TEEI,MT,s}\right)$$

(5.56)

$$\Delta P_{EC-EA-MT,s} = P_{EC-EA-MT,s,act} \left(1 - \eta_{TEEI,MT,s}\right)$$

(5.57)

with an assumed, constant distribution of heat flux between the systems. The equations (5.53) to (5.57) combined result in the optimization potential of the MT to improve the TEEI of the IMT

$$\eta_{TEEI,opt,MT,s} = \frac{P_{EC-MT,s,act} + P_{EC-WC-MT,s,act} + P_{EC-AC-MT,s,act} + P_{EC-EA-MT,s,act}}{P_{EC-IMT,s,act}} \left(1 - \eta_{TEEI,MT,s}\right)$$

(5.58)

The MT component's impact on improving the IMT is derived by

$$\eta_{TEEI,opt,MT,i,s} = \frac{\begin{pmatrix} P_{EC-MT,s,act} & + P_{EC-WC-MT,s,act} \\ + P_{EC-AC-MT,s,act} & + P_{EC-EA-MT,s,act} \end{pmatrix}}{P_{EC-IMT,s,act}} \frac{P_{EC-MT,i,s,act}}{P_{EC-MT,s,act}} \left(1 - \eta_{TEEI,i,s}\right)$$

(5.59)

$\eta_{TEEI,opt,MT,i,s}$ indicates the potential on percentage scale by which the power demand of an IMT within machine state s can be reduced by improving component i. Hence, a preselection of critical components to be optimized can be carried out. The optimization potential of the CA system, the WC system, the AC system, and the EA system are derived as follows:

$$\eta_{TEEI,opt,CA,s} = \frac{P_{EC-CA-MT,s,act} \left(1 - \eta_{TEEI,CA-MT,s}\right)}{P_{EC-IMT,s,act}}$$

(5.60)

$$\eta_{TEEI,opt,WC,s} = \frac{P_{EC-WC-MT,s,act} \left(1 - \eta_{TEEI,WC-MT,s}\right)}{P_{EC-IMT,s,act}}$$

(5.61)

$$\eta_{TEEI,opt,AC,s} = \frac{P_{EC-AC-MT,s,act} \left(1 - \eta_{TEEI,AC-MT,s}\right)}{P_{EC-IMT,s,act}}$$

(5.62)

$$\eta_{TEEI,opt,EA,s} = \frac{P_{EC-EA-MT,s,act} \left(1 - \eta_{TEEI,EA-MT,s}\right)}{P_{EC-IMT,s,act}}$$

(5.63)

Based on the ranking according to optimization potential, the most critical MT components and parts of the TBS system can be selected. In order to derive the cause of a low $\eta_{TEEI,IMT}$, a mapping as depicted in Figure 38 is carried out. The graph depicts $\eta_{EI/CI}$ as measure for the degree of achieved efficiency against the α_{SI} as measure for the need-based utilization / dimensioning. The angle bisector indicates a balanced score of efficiency and need-based utilization / dimensioning. Below the angle bisector, a lack of need-based utilization / dimensioning can be observed. Above the angle bisector a lack of component efficiency (of the MT or TBS) is indicated. The TEEI is visualized by the greyish area, which is aimed at being maximized. The curves show sets of points with the same TEEI ($\eta_{TEEI} = const.$). Hence, the goal is to move each component (of the MT or TBS) to the equi-TEEI curve with the largest distance possible to the origin. Each MT or TBS component can be added to the map and interpreted as follows:

1. Improvement in need-based utilization / dimensioning leads to an increase in sufficiency.
2. Optimization of the efficiency to consistency ratio leads to a gain in component efficiency.
3. The full improvement potential can only be exploited by taking both dimensions $\eta_{EI/CI}$ and α_{SI} into account.

To sum up, the proposed method recommends to calculate each component's optimization potential based on the three sustainability indices (SI, EI, and CI) and to improve the components with the highest optimization potential in their weaker domain first. A lack in need-based utilization / dimensioning or a lack in efficiency can be detected and suitable improvement measures can directly be derived.
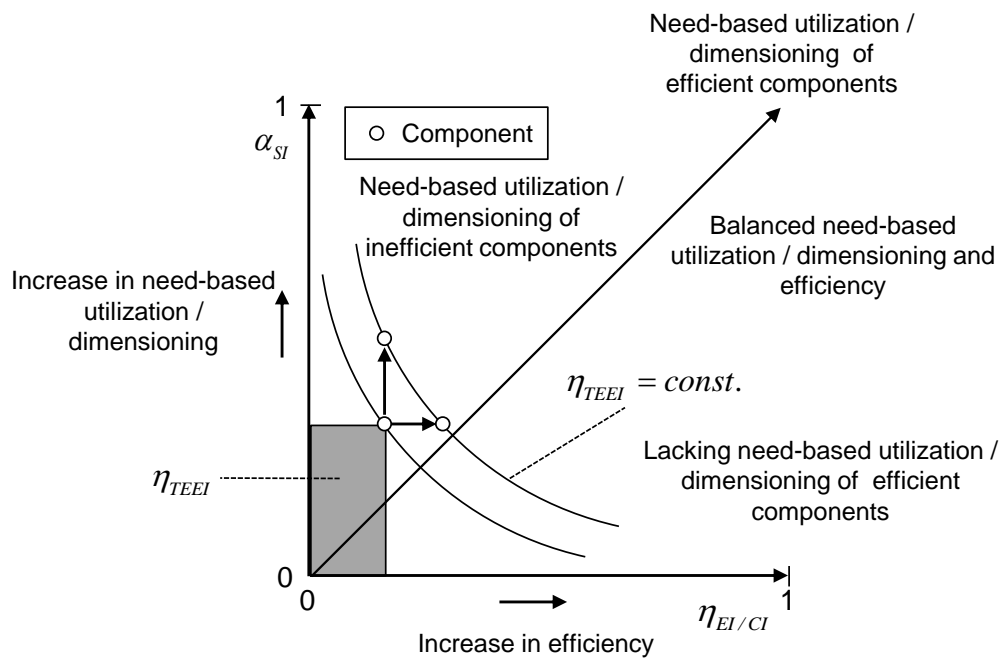
Figure 38: Dependence of the TEEI on α_{SI} and $\eta_{EI/CI}$.

5.4. Leveraging the Impact of Energy Efficiency

A way to leverage the impact of an IMT's efficiency is to extend the system boundary and take into account the energy conversion chain. A schematic energy conversion chain adapted from Müller et al. [15] is depicted in Figure 39. It shows the TEEI of the IMT as well as the one for the conversion from primary to delivered energy.
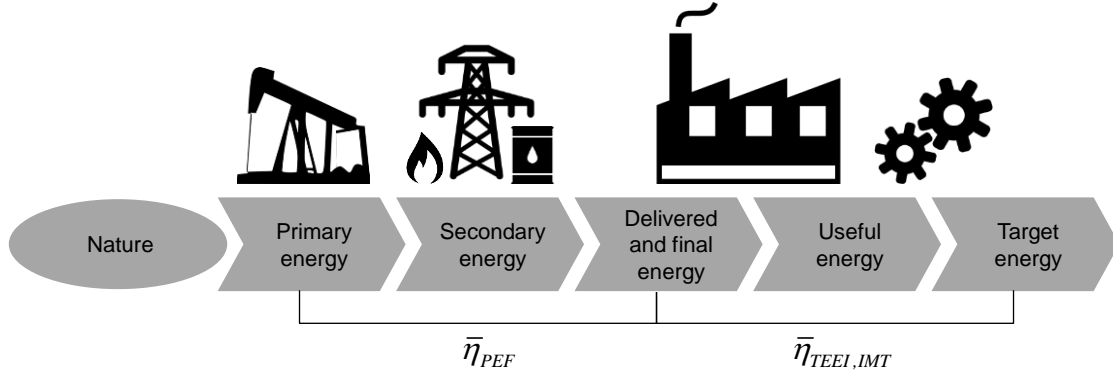
Figure 39: Schematic energy conversion chain adapted from Müller et al. [15] and VDI 4661 [38].

With target energy being the power demand of an ideal IMT, the total efficiency of the energy conversion chain is derived by

$$\bar{\eta}_{TEEI,tot} = \bar{\eta}_{PEF} \cdot \bar{\eta}_{TEEI,IMT} \tag{5.64}$$

with the primary energy efficiency $\bar{\eta}_{PEF}$ obtained from the primary energy factor (PEF). DIN EN 15603 defines the PEF as the "ratio of final energy and primary energy including extraction, processing, storing, transportation, generation, conversion, transmission and distribution as well as all other required steps in order to deliver the energy to the building where it is used" [137]. The PFE depends on the energy mix. The Directive 2012/27/EU [11] specified the average PFE value for the EU28 electricity by $\bar{\varepsilon}_{PEF} = 2.5$ leading to a conversion efficiency of

$$\bar{\eta}_{PEF} = \frac{1}{\bar{\varepsilon}_{PEF}} = \frac{1}{2.5} = 40\% \tag{5.65}$$

and resulting in

$$\bar{\eta}_{TEEI,tot} = \bar{\eta}_{PEF} \cdot \bar{\eta}_{TEEI,IMT} = 0.4 \cdot \bar{\eta}_{TEEI,IMT} \tag{5.66}$$

which associates the leverage of energy efficiency improvements of an IMT being 2.5 and leading to $2.5 kWh$ savings in primary energy for every delivered kWh saved.

6. Metric Application: A grinding case

The methodology of the case study is illustrated in Figure 40. First, the system boundary is defined. Based on this, the analysis of the MT is carried out. Relevant operational machine states as well as the relevant components are defined. Subsequently, the sustainability indices SI, EI, CI, and TEEI are determined for each relevant MT component and the MT. A similar procedure is performed for the analysis of the TBS. Reference values are when possible taken from international standards and efficiency labels. The TEEIs of the IMT are calculated based on this. Finally, the calculation of the optimization potential and the analysis to enhance energy efficiency of the IMT are conducted.

6.1	Definition of the System Boundary

6.2	Analysis of the Machine Tool

- Operational State Definition and Component Selection
- Sufficiency Indices of MT Components
- Efficiency Indices of MT Components
- Consistency Indices of MT Components
- Total Energy Efficiency Indices of the MT Components and the MT

6.3	Analysis of the Technical Building Service

- Metering of Power Exchange between MT and TBS
- Sufficiency Indices of TBS Components
- Efficiency Indices of TBS Components
- Consistency Indices of TBS Components
- Total Energy Efficiency Indices of the TBS Components

6.4	Total Energy Efficiency Indices of the Integrated Machine Tool

6.5	Optimization Potential and Analysis

Figure 40: Methodology of the case study.

6.1. Definition of the System Boundary

The previously developed TEEI metric is applied to a 6-axis grinding machine Rollomatic 628 XS depicted in Figure 41. The case study MT is located in a lab at ETH Zurich.

Figure 41: 6-axis grinding machine Rollomatic 628 XS.

The MT equipped with a decentralized EA unit, which filters the air of the machine room before releasing it to the lab, and a heat exchanger unit, which exchanges heat between the cooling lubricant and the centralized WC system. Moreover, the MT is supplied by a centralized CA system. The TBS of the particular building of ETH Zurich combines the AC and EA including ventilation, which is responsible to remove both the convective heat flux and the heat of the MT's decentralized EA unit out of the lab. Figure 42 illustrates the services supplied to the MT by the TBS, which is composed of a CA system, a WC system, and a combined AC/EA system. Other building functions are not taken into account.
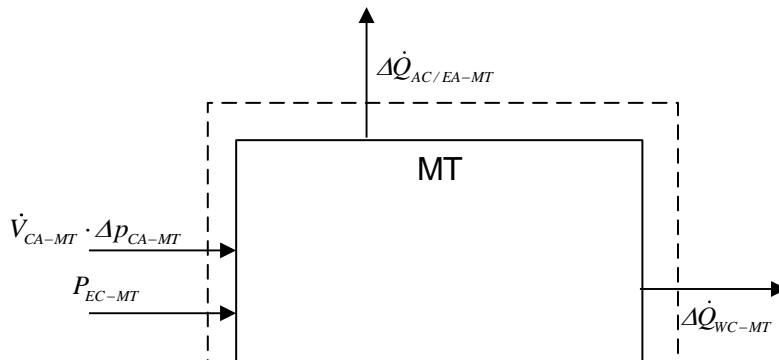
Figure 42: Interfaces between the MT and the factory environment.

6.2. Analysis of the Machine Tool

6.2.1. Operational State Definition and Component Selection

The case study focuses on following main machine states:

- **Off:** The main switch is turned off and compressed air is disabled.

- **Standby:** Compressed air is enabled. The main switch is turned on and the control is operating. CNC code can be programmed.

- **Idle:** The main switch is turned on, the control is operating, and most functional units are started. The axis and spindle can be moved.

- **Processing:** The main switch is turned on, the control is operating, and most functional units are started. The coolant is at maximum flow rate. The spindle is rotating at 10.000 rpm (maximum rotational speed of the spindle) without material cutting (air cut), since this is the operational speed with the highest power demand that can be hold until a thermal equilibrium between MT and TBS is reached. Any other remarkable utilization (e.g. duty cycle type according to IEC 60034-1 [138] or DIN IEC/TS 60034-30-2 (VDE V 0530-30-2) [139]) can only serve the purpose, if each manufacturing condition can be hold or repeated until thermal steady state conditions are achieved.

The ISO 14955-1 [34] prescribes to meter each consumer causing at least 10% of the entire MT's power demand collectively contributing to at least 80% of the entire MT's power demand in each machine state. The analysis of the MT therefore focuses on following electric consumers of the MT:

- Heat exchanger unit (input system)
- Spindle unit (output system)
- Coolant unit (output system)
- EA unit (output system)
- Control unit (state system)
- Hydraulic unit (state system)

The electrical power metering is carried out with the multi-channel metering device. Table 11 lists the metered power levels of the selected components, the sum of the components' power demands, the total MT's power demand and the share of explicitly metered components. The selection of the components meets the requirements stated in ISO 14955-1 [34].

Table 11: Power level of components by machine state.

i	$P_{EC-MT,i,s,act}$	Off	Standby	Idle	Processing
1	Heat exchanger unit	$0W$	$0W$	$561W$	$564W$
2	Spindle unit	$0W$	$0W$	$0W$	$238W$
3	Coolant unit	$0W$	$0W$	$1016W$	$2163W$
4	EA unit	$0W$	$0W$	$105W$	$105W$
5	Control unit	$0W$	$151W$	$158W$	$159W$
6	Hydraulic unit	$0W$	$0W$	$181W$	$181W$
	$\sum_{i=1}^{6} P_{EC-MT,i,s,act}$	$0W$	$151W$	$2021W$	$3464W$
	$P_{EC-MT,s,act}$	$0W$	$151W$	$2408W$	$4014W$
	$\dfrac{\sum_{i=1}^{6} P_{EC-MT,i,s,act}}{P_{EC-MT,s,act}}$	100%	100%	84%	86%

6.2.2. Sufficiency Indices of Machine Tool Components

All MT components that are switched off in a respective state have a negligible power demand and are based on Figure 37 in Chapter 5.2.5 excluded from the study for the respective state. Hence, the off state can completely be neglected for the study of the MT. In standby state, only the control unit needs to be taken into account for the MT evaluation. Vice versa, only the spindle unit is excluded from the study during idle state. In processing state, all components need to be taken into account. The heat exchanger unit's operation is only required after processing due to thermal inertia and only for a comparable short time. However, the heat exchanger unit is constantly operating in idle state, but does not exchange heat with the connected cooling water provided by the WC system, which leads to

$$\alpha_{SI,1,idle} = 0 \tag{6.1}$$

During processing, the operation of the heat exchanger unit is required. Moreover, the heat changer unit's heat exchange with the WC system is controlled, which leads to

$$\alpha_{SI,1,proc} = 1 \qquad (6.2)$$

The volume flow of the cooling fluid, which is exchanged with the machine tank, and the possible caused loss are taken into account by the EI in comparison to the CI of the heat exchanger unit. The spindle unit is necessarily switched on and automatically demand controlled in processing state, which leads to

$$\alpha_{SI,2,proc} = 1 \qquad (6.3)$$

The cooling unit demands electrical power during idle state. However, neither the spindle unit nor the workpiece are cooled which leads to

$$\alpha_{SI,3,idle} = 0 \qquad (6.4)$$

For the spindle cooling and the process cooling, a total coolant volume flow of $\dot{V}_{3,proc,act} = 4.42 \frac{m^3}{h}$ has been measured. Based on the assumption that the entire electrical power consumed by the spindle is finally converted into heat, which needs to be removed for thermally stable operation, the reference coolant flow is calculated according to Meister [140] by

$$\dot{V}_{3,proc,ref} = \frac{\Delta \dot{Q}_{3,proc,ref}}{c_{p,3} \rho_3 \Delta \vartheta_{3,proc,ref} E_3} \qquad (6.5)$$

with the reference cooling power $\Delta \dot{Q}_{3,proc,ref}$, the cooling fluid's specific heat capacity $c_{p,3}$, and density ρ_3, as well as its temperature difference between inlet and outlet $\Delta \vartheta_{3,proc}$ and the geometric factor E_3 in order to take into account the nozzle design. The specific heat capacity of the coolant Blasogrind HC 5 is specified by the manufacturer [141] by $c_{p,3} = 2000 \, J/(kgK)$ at $20°C$. Together with the measured density of $\rho_3 = 847 \frac{kg}{m^3}$, the measured temperature difference $\vartheta_{3,proc,act} \triangleq \vartheta_{3,proc,ref} = 0.53 \, K$, and the geometric factor for optimal nozzle design $E_3 = 0.9$ according to Meister [140] leads to

$$\dot{V}_{3,proc,ref} = \frac{238W}{2000\dfrac{J}{kg \cdot K} \cdot 847\dfrac{kg}{m^3} \cdot 0.53K \cdot 0.9} \approx 1.06\frac{m^3}{h} \tag{6.6}$$

and the SI of the coolant unit

$$\alpha_{SI,3,proc} = \frac{\dot{V}_{3,proc,ref}}{\dot{V}_{3,proc,act}} = \frac{1.06\dfrac{m^3}{h}}{4.42\dfrac{m^3}{h}} \approx 0.24 \tag{6.7}$$

The Rollomatic 628 XS is equipped with a decentralized EA unit with electro-filter, mounted on the top of the MT. During the machine states idle and processing, an average EA volume flow is derived by

$$\dot{V}_{4,idle,act} = \dot{V}_{4,proc,act} = v_{4,act} \cdot A_4 = 2.31\frac{m}{s} \cdot (0.23 \cdot 0.26)m^2 \approx 497\frac{m^3}{h} \tag{6.8}$$

with the EA flow speed $v_{4,act}$ and the suction surface A_4. The operation of the EA system is only needed during processing state. The time share, during which the EA is needed during idle state, is marginal and leads to

$$\dot{V}_{4,idle,ref} = 0\frac{m^3}{h} \tag{6.9}$$

$$\alpha_{SI,4,idle} = 0 \tag{6.10}$$

Figure 43 depicts a recommendation by VDI 3802-2 [142] for the extraction volume flow dependent on the cabin volume. The minimum specified air quantity for an effective cabin size of $2m^3$ and oil coolant is derived by

$$\dot{V}_{4,proc,ref} \approx 800\frac{m^3}{h} \tag{6.11}$$
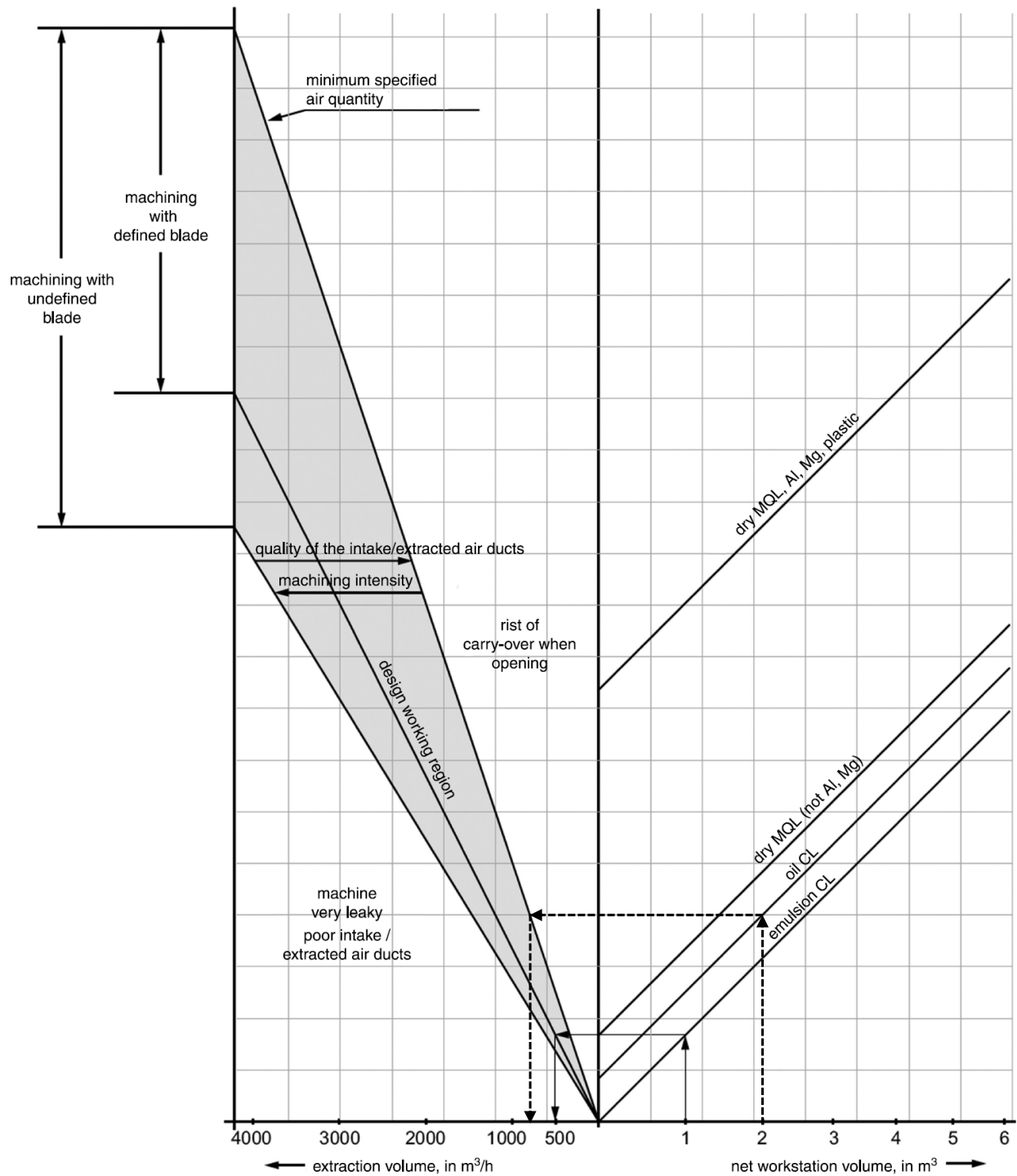
Figure 43: Design of extraction volume flows in MTs according to VDI 3802-2 [142] (dashed arrows for Rollomatic 628 XS).

Since following relationship applies

$$\dot{V}_{4,proc,act} < \dot{V}_{4,proc,ref} \tag{6.12}$$

the EA unit is classified as under dimensioned, leading for the processing state by definition (compare equation (5.25)) to

$$\alpha_{SI,4,proc} = 1 \tag{6.13}$$

The specifications in chapter 5.2.5 lead for the control unit to

$$\alpha_{SI,5stby} = \alpha_{SI,5,idle} = \alpha_{SI,5,proc} = 1 \tag{6.14}$$

The hydraulic unit is a combination of an electric motor, which determines the degree of sufficiency for the entire hydraulic unit, and a gear pump. The main functions of the hydraulic unit are workpiece handling and tool handling. None of the functions is used during idle or processing state (as defined), which leads to

$$\alpha_{SI,6,idle} = \alpha_{SI,6,proc} = 0 \tag{6.15}$$

A pressure accumulator can be used for static hydraulic functions such as workpiece clamping, which leads to $\dot{V}_{6,proc,act} \gg \dot{V}_{6,proc,ref}$ and the same result for the SIs as long as no dynamic functions such as tool changes are performed. The SIs of MT components by machine state are summarized in Table 12.

Table 12: SIs of components by machine state.

i	$\alpha_{SI,i,s}$	Off	Standby	Idle	Processing
1	Heat exchanger unit	/	/	0	1
2	Spindle unit	/	/	/	1
3	Coolant unit	/	/	0	0.24
4	EA unit	/	/	0	1
5	Control unit	/	1	1	1
6	Hydraulic unit	/	/	0	0

6.2.3. Efficiency Indices of Machine Tool Components

The $\lambda_{EI,i,s}$ only have to be calculated for MT components and states with $\alpha_{SI,i,s}$ different than zero, namely the EIs of all MT components in processing state except of for the hydraulic unit. Moreover, the control unit needs to be analyzed in addition for standby and idle state. Electrical power is demanded by the electric motor and the control of the heat exchanger in order to transfer heat from the MT to the cooling water cycle operated by the WC system. Assuming a constant specific heat capacity of water $c_{p,1} = 4182 \dfrac{J}{kg \cdot K}$ and a constant water density $\rho_1 = 988 \dfrac{kg}{m^3}$, the heat flow due to WC is derived by

$$\dot{Q}_{1,proc,act} = c_{p,1} \cdot \rho_1 \cdot \dot{V}_{1,proc,act} \cdot \vartheta_{1,proc,act} = 4182 \cdot 988 \cdot 4.417 \cdot 10^{-4} \cdot 1.24 W = 2263W \tag{6.16}$$

with the water volume flow $\dot{V}_{1,proc,act} = 1.59 \dfrac{m^3}{h} \approx 4.417 \cdot 10^{-4} \dfrac{m^3}{s}$ as well as the water's temperature difference between inlet and outlet $\Delta \vartheta_{1,proc,act} = 1.24 \ K$. The EI of the heat exchanger unit during processing state is derived by

$$\lambda_{EI,1,proc} = \frac{\dot{Q}_{1,proc,act}}{P_{EC-MT,1,proc,act}} = \frac{2263W}{564W} \approx 4.01 \tag{6.17}$$

The spindle efficiency is calculated based on the assumption that the relative conversion efficiency is independent of the operational state

$$\eta_{EI/CI,2} = \frac{\lambda_{EI,2,proc}}{\lambda_{CI,2,proc}} \triangleq const. \tag{6.18}$$

The nominal operational point $P_{nom,2,EM,act} = 7000W$ at $n_{nom,2,EM,act} = 3880 \min^{-1}$ is chosen to calculate the relative conversion efficiency of the spindle. The conversion efficiency of the spindle unit is composed of the efficiency of the electric motor (EM) and the inverter. The EM's efficiency is modelled for the nominal operational point according to Züst [143] and Krause et al. [144] by

$$\eta_{nom,2,EM,act}^{-1} = \frac{\omega_{f,2,EM,act}}{n_{p,2,EM,act} \cdot \omega_{nom,2,EM,act}}$$

$$+ \frac{R_{r,2,EM,act} \cdot R_{s,2,EM,act}}{L_{m,2,EM,act}^2 \cdot \left(\omega_{f,2,EM,act} - n_{p,2,EM,act} \cdot \omega_{nom,2,EM,act}\right) \cdot n_{p,2,EM,act} \cdot \omega_{nom,2,EM,act}} \tag{6.19}$$

$$+ \frac{R_{s,2,EM,act}}{R_{r,2,EM,act}} + \frac{L_{r,2,EM,act}^2}{L_{m,2,EM,act}^2} \cdot \frac{\omega_{f,2,EM,act} - n_{p,2,EM,act} \cdot \omega_{nom,2,EM,act}}{n_{p,2,EM,act} \cdot \omega_{nom,2,EM,act}}$$

with the rotor resistance $R_{r,2,EM,act} = 0.412$, the stator resistance $R_{s,2,EM,act} = 0.510$, and the number of pole pairs $n_{p,2,EM,act} = 2$ derived from manufacturer's data. The rotor inductance is calculated with the stator leakage reactance $X_{\sigma 1,2,EM,act} = 1.33\Omega$ and the rated stator frequency $f_{s,2,EM,act} = 134 Hz$ by

$$L_{r,2,EM,act} = \frac{X_{\sigma 1,2,EM,act}}{f_{s,2,EM,act} \cdot 2\pi} = \frac{1.33\Omega}{134 Hz \cdot 2\pi} = 1.58 \cdot 10^{-3} H \tag{6.20}$$

Similarly, the stator inductance is derived with the rotor leakage reactance $X_{\sigma 2',2,EM,act} = 1.49\Omega$ by

$$L_{s,2,EM,act} = \frac{X_{\sigma 2',2,EM,act}}{f_{s,2,EM,act} \cdot 2\pi} = \frac{1.49\Omega}{134 Hz \cdot 2\pi} = 1.77 \cdot 10^{-3} H \tag{6.21}$$

The main field inductance is calculated with the main field reactance $X_{m,2,EM,act} = 32.6\Omega$ by

$$L_{m,2,EM,act} = \frac{X_{m,2,EM,act}}{f_{s,2,EM,act} \cdot 2\pi} = \frac{32.6\Omega}{134 Hz \cdot 2\pi} = 38.72 \cdot 10^{-3} H \tag{6.22}$$

The nominal angular velocity of the rotor is derived by

$$\omega_{nom,2,EM,act} = 2\pi \cdot n_{nom,2,EM,act} = 2\pi \cdot \frac{3880}{60s} \approx 406 s^{-1} \tag{6.23}$$

The angular velocity of the field $\omega_{f,2,EM,act}$ is calculated numerically and leads to

$$\eta_{nom,2,EM,act} = 97.2\% \tag{6.24}$$

Applying the models from Züst et al. [143] and van der Broeck et al. [145, 146], the losses caused by the inverter and the bearings are numerically derived by

$$P_{nom,2,inv,act} \approx 0.16W \qquad (6.25)$$

$$P_{nom,2,brgs,act} \approx 82.90W \qquad (6.26)$$

leading to

$$\lambda_{EI,2,proc} = \eta_{nom,2,EM,act} \frac{P_{nom,2,EM,act}}{P_{nom,2,EM,act} + P_{nom,2,brgs,act} + P_{nom,2,inv,act}} \\ \approx 97.2\% \frac{7000W}{7000W + 82.90W + 0.16W} \approx 96.0\% \qquad (6.27)$$

The coolant unit serves two functions: spindle cooling and process cooling. The installed pump is a multistage centrifugal pump, which is powered by an electric motor. In processing state a total volume flow of $\dot{V}_{3,proc,act} = 4.42\frac{m^3}{h}$ has been measured, which results with an electric power demand of $P_{EC-MT,3,proc,act} = 2163W$ in

$$\lambda_{EI,3,proc} = \frac{\dot{V}_{3,proc,act}}{P_{EC-MT,3,proc,act}} = \frac{4.42\frac{m^3}{h}}{2163W} = 5.67 \cdot 10^{-7} \frac{m^3}{J} \qquad (6.28)$$

The EI of the EA unit is derived from the electrical power demand $P_{EC-MT,4,proc,act} = 105W$ and the volume stream $\dot{V}_{4,proc,act} = 497\frac{m^3}{h}$ by

$$\lambda_{EI,4,proc} = \frac{\dot{V}_{4,proc,act}}{P_{EC-MT,4,proc,act}} = \frac{497\frac{m^3}{h}}{105W} = 1.31 \cdot 10^{-3} \frac{m^3}{J} \qquad (6.29)$$

The control unit is a state system and its EIs by state are derived by

$$\lambda_{EI,5,stby} = \frac{1}{P_{EC-MT,5,stby,act}} = \frac{1}{151W} \qquad (6.30)$$

$$\lambda_{EI,5,idle} = \frac{1}{P_{EC-MT,5,idle,act}} = \frac{1}{158W} \tag{6.31}$$

$$\lambda_{EI,5,proc} = \frac{1}{P_{EC-MT,5,proc.act}} = \frac{1}{159W} \tag{6.32}$$

The MT component EIs by machine state are summarized in Table 13.

Table 13: EIs of components by machine state.

i	$\lambda_{EI,i,s}$	Off	Standby	Idle	Processing
1	Heat exchanger unit	/	/	/	4.01
2	Spindle unit	/	/	/	0.96
3	Coolant unit	/	/	/	$5.67 \cdot 10^{-7} \frac{m^3}{J}$
4	EA unit	/	/	/	$1.31 \cdot 10^{-3} \frac{m^3}{J}$
5	Control unit	/	$\frac{1}{151W}$	$\frac{1}{158W}$	$\frac{1}{159W}$
6	Hydraulic unit	/	/	/	/

6.2.4. Consistency Indices of Machine Tool Components

The CI study is performed for the same MT components and states as in the EI study. The certification institute Eurovent [147] published an efficiency labelling standard for heat exchanger based on DIN EN 14511 [148], which outlines normative requirements. The highest efficiency class defines the BAT and leads to an reference efficiency of water cooled heat exchanger units of

$$\lambda_{CI,1,proc} = 5.05 \tag{6.33}$$

The ideal model of a spindle is a speed-controlled electric motor. Therefore, the consistency is obtained from standard DIN IEC/TS 60034-30-2 [139] for speed controlled electric drives. The

nominal power $P_{nom,2,EM,ref} = 7000W$ and nominal rotational speed $n_{nom,2,EM,ref} = 3880\dfrac{1}{min}$ of a speed controlled electric drive with efficiency class IE4 is derived by

$$
\begin{aligned}
\eta_{2,proc,ref} &= \frac{1}{100}\left(A\left[\log\left(\frac{P_{nom,2,EM,ref}}{1000W}\right)\right]^3 + B\left[\log\left(\frac{P_{nom,2,EM,ref}}{1000W}\right)\right]^2 + C\left[\log\left(\frac{P_{nom,2,EM,ref}}{1000W}\right)\right] + D \right) \\
&= \frac{1}{100}\left(\begin{array}{l} 0.3569\left[\log\left(\dfrac{7000W}{1000W}\right)\right]^3 - 3.3076\left[\log\left(\dfrac{7000W}{1000W}\right)\right]^2 \\[3mm] +11.6108\left[\log\left(\dfrac{7000W}{1000W}\right)\right] + 82.2503 \end{array} \right) \\
&\approx 0.90
\end{aligned}
\tag{6.34}
$$

with the interpolation coefficients A, B, C, and D. Since the efficiency of the actual system exceeds the one of the reference system and is therefore consider to be BAT, the actual system is assigned to the highest efficiency class leading to

$$
\eta_{EI/CI,2,proc} \qquad = \frac{\lambda_{EI,2,proc}}{\lambda_{CI,2,proc}} \triangleq 1 \Leftrightarrow \lambda_{CI,2,proc} = \lambda_{EI,2,proc}
\tag{6.35}
$$

The reference system efficiency of the cooling pump is derived from Commission Regulation (EU) No 547/2012 [149] implementing Directive 2009/125/EC [10]. The pump fulfills the requirement of a minimal efficiency index (MEI) of greater than 0.7, which is the highest efficiency class [150]. It is therefore considered to be BAT, which leads to

$$
\eta_{EI/CI,3,proc} \qquad = \frac{\lambda_{EI,3,proc}}{\lambda_{CI,3,proc}} \triangleq 1 \Leftrightarrow \lambda_{CI,3,proc} = \lambda_{EI,3,proc}
\tag{6.36}
$$

EN 13779 [151] classifies EA units according to their SFP. The reference efficiency of the EA unit is derived from the SFP of highest fan efficiency class and the SFP for a filter unit by

$$
\frac{1}{\zeta_{CI,4,proc,ref}} = \frac{1}{\zeta_{CI,4,fan,proc,ref} + \zeta_{CI,4\,filter,proc,ref}} \geq \frac{1}{(500+300)\dfrac{J}{m^3}} = 1.25\cdot 10^{-3}\,\frac{m^3}{J}
\tag{6.37}
$$

Since the efficiency of the actual system exceeds the one of the reference system, the actual system is assigned to the highest efficiency class leading to

$$\eta_{EI/CI,4,proc} \qquad = \frac{\lambda_{EI,4,proc}}{\lambda_{CI,4,proc}} \triangleq 1 \Leftrightarrow \lambda_{CI,4,proc} = \lambda_{EI,4,proc} \qquad (6.38)$$

The BAT in controls strongly depends on the computer architecture, software, and operations. The MT operates with the latest version of controls by the respective manufacturer.

$$\lambda_{CI,5,stby} \triangleq \lambda_{EI,5,stby} = \frac{1}{151W} \qquad (6.39)$$

$$\lambda_{CI,5,idle} \triangleq \lambda_{EI,5,idle} = \frac{1}{158W} \qquad (6.40)$$

$$\lambda_{CI,5,proc} \triangleq \lambda_{EI,5,proc} = \frac{1}{159W} \qquad (6.41)$$

The MT component CIs by machine state are summarized in Table 14.

Table 14: CIs of components by machine state.

i	$\lambda_{CI,i,s}$	Off	Standby	Idle	Processing
1	Heat exchanger unit	/	/	/	5.05
2	Spindle unit	/	/	/	0.96
3	Coolant unit	/	/	/	$5.67 \cdot 10^{-7} \frac{m^3}{J}$
4	EA unit	/	/	/	$1.31 \cdot 10^{-3} \frac{m^3}{J}$
5	Control unit	/	$\frac{1}{151W}$	$\frac{1}{158W}$	$\frac{1}{159W}$
6	Hydraulic unit	/	/	/	/

6.2.5. Total Energy Efficiency Indices of the Machine Tool Components and the Machine Tool

The TEEIs of MT components by machine state are derived based on the values in Table 12, Table 13, and Table 14. The results are listed in Table 15, which leads to the insight that the heat exchanger unit, the coolant unit, the EA unit, and the hydraulic unit underperform in their TEEI during idle state. Moreover, during processing the coolant unit and the hydraulic unit show a low performance.

Table 15: TEEIs of components by machine state.

i	$\eta_{TEEI,i,s}, \eta_{TEEI,MT,s}$	Off	Standby	Idle	Processing
1	Heat exchanger unit	/	/	0%	79%
2	Spindle unit	/	/	/	100%
3	Coolant unit	/	/	0%	24%
4	EA unit	/	/	0%	100%
5	Control unit	/	100%	100%	100%
6	Hydraulic unit	/	/	0%	0%
	MT	/	100%	8%	44%

6.3. Analysis of the Technical Building Service

6.3.1. Determining the Interfaces between Machine Tool and Technical Building Service

The electric power demand of the MT is metered align with the requirements stated in ISO 14955-1 [34] by using the multi-channel power metering system. The temperature measurements are carried for each operational state of the MT using the temperature measurement device NI 9214 by National Instruments with type K thermocouple sensors. For each operational state, the water volume flow is metered using the flow measurement device Cerabar S PMP75 by Endress Hauser. For a negligible low impact of the CA decompression on the heat balance the heat flow to the AC/EA system can be approximated by

$$\Delta \dot{Q}_{AC/EA-MT,s,act} \simeq P_{EC-MT,s,act} - \Delta \dot{Q}_{WC-MT,s,act} \tag{6.42}$$

with the electric power demand of the MT $P_{EC-MT,s,act}$ and the heat flow due to WC $\Delta \dot{Q}_{WC-MT,s,act}$. The volume flow of the norm compressed air flow is determined according to ISO 8778 [136] using the compressed air measurement device BS48 by Postberg+Co. Table 16 lists the power relevant values of the MT and the TBS.

Table 16: Power relevant values of the MT and the TBS.

Variable	Off	Standby	Idle	Processing
$P_{EC-MT,s,act}$	$0W$	$151W$	$2408W$	$4014W$
$\dot{V}_{WC-MT,s,act}$	$1.48\frac{m^3}{h}$	$1.48\frac{m^3}{h}$	$1.52\frac{m^3}{h}$	$1.59\frac{m^3}{h}$
$\vartheta_{WC-MT,s,act}$	$0K$	$0K$	$0K$	$1.24K$
$\Delta \dot{Q}_{WC-MT,s,act}$	$0W$	$0W$	$0W$	$2263W$
$\Delta \dot{Q}_{AC/EA-MT,s,act}$	$0W$	$151W$	$2408W$	$1751W$
$\dot{V}_{n,CA-MT,s,act}$	$0\frac{m^3}{h}$	$0\frac{m^3}{h}$	$5.23\frac{m^3}{h}$	$5.23\frac{m^3}{h}$

6.3.2. Sufficiency Indices of Technical Building Service Components

The TBS systems CA, WC, and AC/EA system are themselves controlled. Hence, the supplying services CA system, WC system, and EA system are directly linked to the utilization by the respective MT. The $\alpha_{SI,CA-MT,s}$, $\alpha_{SI,WC-MT,s}$, and $\alpha_{SI,AC/EA-MT,s}$ need to be determined dependent on the utilization by the MT.

CA is mainly used for sealing air in order to prevent the entry of dust, oil, and particles into the spindle unit, and in order to keep glass scales clean. During off and standby, the CA supply is completely shut off. Apart of during processing (and for short time periods after the grinding operation), sealing air can be abandoned leading to

$$\alpha_{SI,CA-MT,idle} = 0 \tag{6.43}$$

The CA supply is controlled both state dependent and in its volume flow leading to

$$\alpha_{SI,CA-MT,proc} = 1 \tag{6.44}$$

The WC system and the AC/EA system are controlled systems that remove the heat dissipated by the MT, which results in

$$\alpha_{SI,WC-MT,proc} = 1 \tag{6.45}$$

$$\alpha_{SI,AC/EA-MT,stby} = \alpha_{SI,AC/EA-MT,idle} = \alpha_{SI,AC/EA-MT,proc} = 1 \tag{6.46}$$

The SIs of TBS components by machine state are summarized in Table 17.

Table 17: SIs of TBS components by machine state.

TBS component name	Symbol	Off	Standby	Idle	Processing
CA system	$\alpha_{SI,CA-MT,s}$	/	/	0	1
WC system	$\alpha_{SI,WC-MT,s}$	/	/	/	1
AC/EA system	$\alpha_{SI,AC/EA-MT,s}$	/	1	1	1

6.3.3. Efficiency Indices of Technical Building Service Components

The data for calculating the electrical energy equivalents of the TBS components are derived from the TBS monitoring system Siloveda [152] at ETH Zurich and TBS data sheets, listed in Table 18. All delivered outputs (volume flows and heat flows) of the TBS are considered to be the same for both the actual MT and the reference MT. The assumption implies that the single MT has a negligible impact on the operational point of the TBS.

Table 18: Input and output values of the TBS derived from the TBS monitoring system Siloveda at ETH Zurich.

Variable name	Value
$P_{EC-CA-TBS,act}$	$261297 \dfrac{kWh}{a}$
$\dot{V}_{n,CA-TBS,act} = \dot{V}_{n,CA-TBS,ref}$	$2547325 \dfrac{m^3}{a}$
$P_{EC-WC-TBS,act}$	$1123435 \dfrac{kWh}{a}$
$\Delta \dot{Q}_{WC-TBS,act} = \Delta \dot{Q}_{WC-TBS,ref}$	$3141800 \dfrac{kWh}{a}$
$P_{EC-AC/EA-TBS,act}$	$384189 \dfrac{kWh}{a}$
$\Delta \dot{Q}_{AC/EA-TBS,act} = \Delta \dot{Q}_{AC/EA-TBS,ref}$	$621960 \dfrac{kWh}{a}$
$\dot{V}_{AC/EA-TBS,act} = \dot{V}_{AC/EA-TBS,ref}$	$142166040 \dfrac{m^3}{a}$

The electrical energy equivalent of the CA system including all compressors and auxiliary aggregates based on measurements is derived by

$$\kappa_{CA-TBS,act} = \frac{P_{EC-CA-TBS,act}}{\dot{V}_{n,CA-TBS,act}} = \frac{261297 \; kWh/a}{2547325 \; m^3/a} \approx 0.103 \frac{kWh}{m^3} \tag{6.47}$$

leading to the EI of the CA system

$$\lambda_{EI,CA-TBS} = \frac{1}{\kappa_{CA-TBS,act}} = \frac{1}{0.103\frac{kWh}{m^3}} \approx 9.75\frac{m^3}{kWh} \qquad (6.48)$$

The EI of the WC system equals its EER and is derived by

$$\lambda_{EI,WC-TBS} = \varepsilon_{WC-TBS,act} = \frac{\Delta\dot{Q}_{WC-TBS,act}}{P_{EC-WC-TBS,act}} = \frac{3141800\,kWh/a}{1123435\,kWh/a} \approx 2.80 \qquad (6.49)$$

The AC/EA system is responsible for conditioning the incoming air to a defined temperature of $20°C$ and supplying it to the facilities, which is both comprised by the power demand $P_{EC-AC/EA-TBS,act}$. The performance of the combined AC/EA system (comprising air cooling and ventilation) is described by

$$\lambda_{EI,AC/EA-TBS} = \varepsilon_{AC/EA-TBS,act} = \frac{\Delta\dot{Q}_{AC/EA-TBS,act}}{P_{EC-AC/EA-TBS,act}} = \frac{621960\frac{kWh}{a}}{384189\frac{kWh}{a}} \approx 1.62 \qquad (6.50)$$

The EIs of the TBS systems are summarized in Table 19.

Table 19: EIs of TBS components.

TBS component name	EIs of TBS components
CA system	$\lambda_{EI,CA-TBS} = 9.75\frac{m^3}{kWh}$
WC system	$\lambda_{EI,WC-TBS} = 2.80$
AC/EA system	$\lambda_{EI,AC/EA-TBS} = 1.62$

6.3.4. Consistency Indices of Technical Building Service Components

The EER benchmark value for CA generation can be derived from Figure 44 developed by Fraunhofer-Institut Systemtechnik und Innovationsforschung (ISI) [153], which states the SECs of CA systems dependent on their relative pressure and their technological standard.
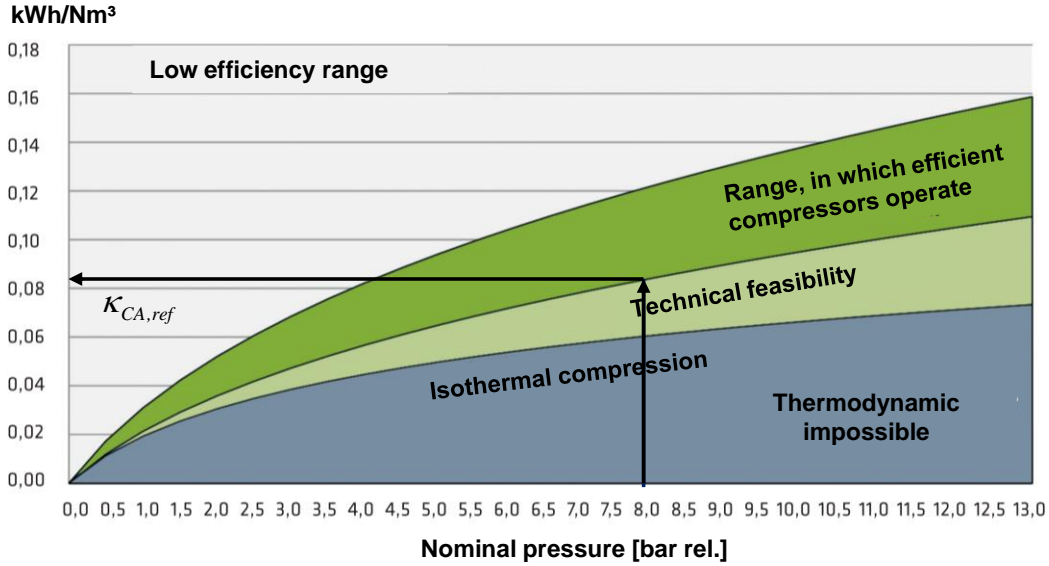
Figure 44: Efficiency of CA system (adapted from Fraunhofer [153]).

For a CA system with $8bar$ relative pressure (as supplied by the TBS) and for compressors with highest available efficiency, a EER of $\kappa_{CA,ref} = 0.085 \dfrac{kWh}{m^3}$ can be derived, leading to

$$\lambda_{CI,CA-TBS} = \frac{1}{\kappa_{CA-TBS,ref}} = \frac{1}{0.085 \dfrac{kWh}{m^3}} \approx 11.76 \frac{m^3}{kWh} \tag{6.51}$$

The SIA 382/1 [154] lists an energy efficiency classification of WC systems for industrial purpose with the highest efficiency class from $\varepsilon_{WC-TBS,ref} = 8.00$, leading to

$$\lambda_{CI,WC-TBS} = \varepsilon_{WC-TBS,ref} = 8.00 \tag{6.52}$$

The combined AC/EA systems reference efficiency composed of the ventilation systems efficiency and the cooling systems efficiency. The EER of the AC/EA system is derived from EC [155] for the case of the highest efficiency of air conditioners to be placed on the market from

2017 by $\varepsilon_{AC/EA-TBS,ref} = 6.10$. The SFP of the AC/EA system can be derived from the standard EN 13799 [151], which categorizes the ventilation for non-residential buildings. The BAT is derived for SFP1 and additional power demand for filtering by $\zeta_{AC/EA-TBS,ref} = 800 \dfrac{Ws}{m^3}$. The AC/EA systems reference efficiency is derived by

$$
\begin{aligned}
\lambda_{CI,AC/EA-TBS} \quad &= \frac{\Delta \dot{Q}_{AC/EA-TBS,ref}}{P_{EC-AC/EA-TBS,ref}} = \frac{\Delta \dot{Q}_{AC/EA-TBS,ref}}{P_{EC-AC/EA-TBS,fan,ref} + P_{EC-AC/EA-TBS,cool,ref}} \\
&= \frac{\Delta \dot{Q}_{AC/EA-TBS,ref}}{\zeta_{AC/EA-TBS,ref} \cdot \dot{V}_{AC/EA-TBS,ref} + \dfrac{\Delta \dot{Q}_{AC/EA-TBS,ref}}{\varepsilon_{AC/EA-TBS,ref}}} \\
&= \frac{621960 \dfrac{kWh}{a}}{800 \dfrac{Ws}{m^3} \cdot 142166040 \dfrac{m^3}{a} + \dfrac{621960 \dfrac{kWh}{a}}{6.10}} \approx 4.66
\end{aligned}
\tag{6.53}
$$

The CIs of the TBS systems are summarized in Table 20.

<p align="center">Table 20: CIs of TBS systems.</p>

TBS component name	EIs of TBS components
CA system	$\lambda_{CI,CA-TBS} = 11.76 \dfrac{m^3}{kWh}$
WC system	$\lambda_{CI,WC-TBS} = 8.00$
AC/EA system	$\lambda_{CI,AC/EA-TBS} = 4.66$

6.3.5. Total Energy Efficiency Indices of the Technical Building Service Components

The TEEIs of the TBS components supplying the MT are aggregated indices from the previously derived sustainability indices. The TEEIs of the CA system are derived by

$$\eta_{TEEI,CA-MT,idle} = \alpha_{SI,CA-MT,idle} \cdot \frac{\lambda_{EI,CA-TBS}}{\lambda_{CI,CA-TBS}} = 0 \cdot \frac{9.75 \frac{m^3}{kWh}}{11.76 \frac{m^3}{kWh}} = 0\% \tag{6.54}$$

$$\eta_{TEEI,CA-MT,proc} = \alpha_{SI,CA-MT,proc} \cdot \frac{\lambda_{EI,CA-TBS}}{\lambda_{CI,CA-TBS}} = 1 \cdot \frac{9.75 \frac{m^3}{kWh}}{11.76 \frac{m^3}{kWh}} \approx 83\% \tag{6.55}$$

The TEEI of the WC system for the processing state is derived by

$$\eta_{TEEI,WC-MT,proc} = \alpha_{SI,WC-MT,proc} \cdot \frac{\lambda_{EI,WC-TBS}}{\lambda_{CI,WC-TBS}} = 1 \cdot \frac{2.80}{8.00} \approx 35\% \tag{6.56}$$

The TEEIs of the AC/EA system dependent on the MT state are derived by

$$\eta_{TEEI,AC/EA-MT,stby} = \eta_{TEEI,AC/EA-MT,idle} = \eta_{TEEI,AC/EA-MT,proc}$$
$$= \alpha_{SI,AC/EA-MT,proc} \cdot \frac{\lambda_{EI,AC/EA-TBS}}{\lambda_{CI,AC/EA-TBS}} = 1 \cdot \frac{1.62}{4.66} \approx 35\% \tag{6.57}$$

The TEEIs of TBS components by machine state are summarized in Table 21.

Table 21: TEEIs of TBS components by machine state.

TBS system name	Symbol	Off	Standby	Idle	Processing
CA system	$\eta_{TEEI,CA-MT,s}$	/	/	0%	83%
WC system	$\eta_{TEEI,WC-MT,s}$	/	/	/	35%
AC/EA system	$\eta_{TEEI,AC/EA-MT,s}$	/	35%	35%	35%

6.4. The Total Energy Efficiency Index of the Integrated Machine Tool

The TEEI of the IMT is derived according to equation (5.50) by

$$\eta_{TEEI,IMT,s} = \frac{P_{EC-IMT,s,ref}}{P_{EC-IMT,s,act}} = \frac{1}{P_{EC-IMT,s,act}} \left(\begin{array}{cc} P_{EC-MT,s,act} & \eta_{TEEI,MT,s} & +P_{EC-CA-MT,s,act} & \eta_{TEEI,CA-MT,s} \\ + P_{EC-WC-MT,s,act}\eta_{TEEI,WC-MT,s} & + P_{EC-AC/EA-MT,s,act}\eta_{TEEI,AC-MT,s} \end{array} \right) \quad (6.58)$$

which includes the assumption that the MT TEEI derived from the composition of selected components equals the one of the entire MT. Table 22 lists the composition of the power demand and TEEIs of the IMT by machine state.

Table 22: Composition of the power demand and TEEIs of the IMT by machine state.

Name	Symbol	Off	Standby	Idle	Processing
MT	$P_{EC-MT,s,act}$	0W	151W	2408W	4014W
CA system	$P_{EC-CA-MT,s,act}$	0W	0W	536W	536W
WC system	$P_{EC-WC-MT,s,act}$	0W	0W	0W	809W
AC/EA system	$P_{EC-AC/EA-MT,s,act}$	0W	93W	1485W	1080W
IMT	$P_{EC-IMT,s,act}$	0W	244W	4429W	6439W
	$\eta_{TEEI,IMT,s}$	/	75%	16%	45%

The average TEEI of the IMT weighted by the power demand in each state is determined using equation (5.51) and the values in Table 10. The average TEEI along the energy conversion chain is calculated using equation (5.66). The results are listed in Table 23.

Table 23: Average IMT TEEI and average total IMT TEEI by type of production.

Symbol	Small series	Medium series	Large series
$\bar{\eta}_{TEEI,IMT}$	38%	41%	41%
$\bar{\eta}_{TEEI,IMT,tot}$	15%	16%	16%

6.5. Calculation of the Optimization Potential and Analysis

The EA unit has been classified as under dimensioned in processing state and needs to be maintained or replaced by a more powerful one. Apart of this, applying equations (5.58) to (5.63) leads to the optimization potential of MT components, the MT, and the TBS systems. The results are listed in Table 24, with the hotspots highlighted in bolt font. The table allows a ranking of energetic hotspot MT and TBS components within each state. In standby and idle state, the AC/EA system offers some potential. In idle and processing state, the MT components' optimization potential outweighs the one of the TBS components. More specifically, both the coolant unit and the heat exchanger offer the greatest improvement potential in idle state. In processing state the coolant unit has the main lever arm towards the power demand reduction. All in all, following hotspots can be derived:
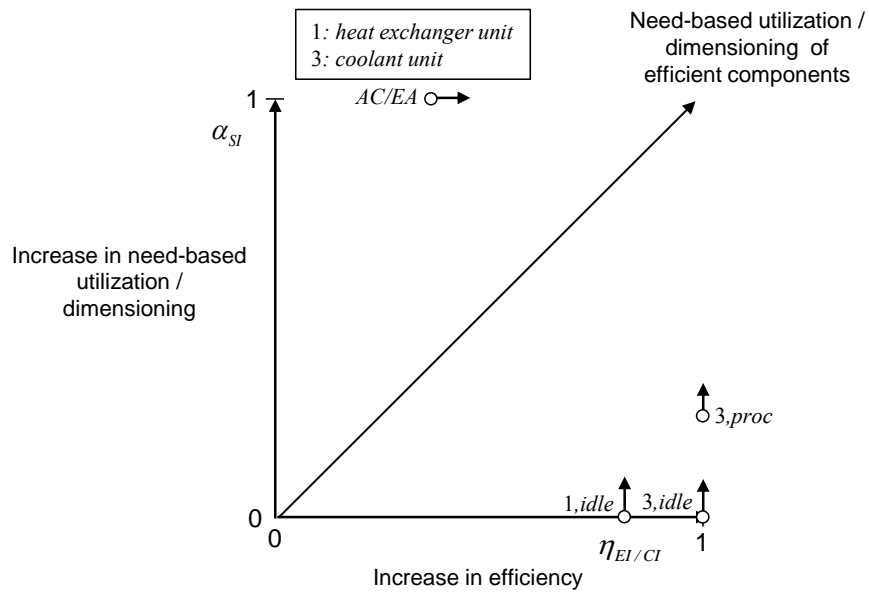
1. Heat exchanger unit in idle state
2. Coolant unit in processing state
3. Coolant unit in idle state
4. AC/EA system in standby state
5. AC/EA system in idle state

Table 24: Total energy efficiency optimization potential of MT and TBS systems by machine state.

Component name	Symbol	Off	Standby	Idle	Processing
Heat exchanger unit	$\eta_{TEEI,opt,MT,1,s}$	/	/	20%	3%
Spindle unit	$\eta_{TEEI,opt,MT,2,s}$	/	/	/	0%
Coolant unit	$\eta_{TEEI,opt,MT,3,s}$	/	/	37%	38%
EA unit	$\eta_{TEEI,opt,MT,4,s}$	/	/	4%	0%
Control unit	$\eta_{TEEI,opt,MT,5,s}$	/	0%	0%	0%
Hydraulic unit	$\eta_{TEEI,opt,MT,6,s}$	/	/	7%	4%
CA system	$\eta_{TEEI,opt,CA-MT,s}$	/	/	12%	1%
WC system	$\eta_{TEEI,opt,WC-MT,s}$	/	/	/	8%
AC/EA system	$\eta_{TEEI,opt,AC/EA-MT,s}$	/	25%	22%	11%

The identified hotspots are analyzed in more detail in order to deduce individual improvement measures by means of graphical representation. Figure 45 depicts $\eta_{EI/CI}$ against the α_{SI} for the before identified hotspots and serves as tool for deducing improvement measures for the MT and TBS design. The arrows indicate the direction of improvement of the respective component. None of the hotspot system has a balanced score. Hence, a single root cause can directly be defined. The AC/EA system (AC/EA) lacks in its relative conversion efficiency, which indicates that the current systems performance is significantly lower than the one of the BAT and rebuilding or replacing is required. Moreover, it can directly be deduced that the efficiency of the heat exchanger unit in idle state ($1, idle$) is less of an issue than the systems need-based utilization. The system could entirely be switched off in idle state. The same is true for the coolant unit during idle ($3, idle$), which is classified as BAT. The coolant unit in processing state ($3, proc$) lacks in its need-based utilization, respectively is over dimensioned. The issue can be addressed by re-dimensioning or by controlling the volume flow of the pump unit.

Figure 45: Mapping of hotspots according to sufficiency and relative conversion efficiency indicating a lack in efficiency of the AC/EA system as well as a lack in sufficiency of the heat exchanger in idle state (1) and the coolant unit in idle and processing state (3).

7. Discussion, Conclusion, and Outlook

Using the four assessment criteria derived in Chapter 3 leads to a characterization of the present work, which is listed in Table 25. In Chapter 4, the research gap is defined and used to derive the thesis objectives. Moreover, a metric to analyze and evaluate components, the MT and the IMT has been developed and applied in practice (Chapter 5 and 6). The application has been performed for all main operating states on an already produced MT. The test method applied is classified as component performance method.

Table 25: Characterization of the thesis.

Source	Completeness criteria							Characterization criteria						
	Level of evaluation			Operating states				Life cycle perspective			Test method			
● fulfilled ○ not fulfilled	Component	MT	IMT	Off	Standby	Idle	Processing	Design	Configuration	Use	Reference Part	Reference Process	SEC	Component Performance
	●	●	●	●	●	●	●	○	○	●	○	○	○	●

The metric bases on three sub-indices that are combined to the TEEI, which can be aggregated from lower to higher level. The evaluation of the SI, EI, CI, and TEEI is listed in Table 26. It can clearly be deduced that each of the sub-indices directly addresses one of the beforehand described sustainability strategies. The aggregated TEEI combines all these properties. The applicability of the metric has been proven in practice.

Table 26: Evaluation of the SI, EI, CI, and TEEI.

Symbol	Efficiency	Consistency	Sufficiency
α_{SI}	○	○	●
λ_{EI}	●	○	○
λ_{CI}	○	●	○
η_{TEEI}	●	●	●

The domains of efficiency, consistency, and sufficiency are integrated into the energy efficiency evaluation (**O1**). The developed metric is applicable to the MT and TBS components (**O2**) and can be aggregated to MT and IMT level (**O3**). Additionally, the potential of a MT or TBS component to improve the energy efficiency of the superordinate system can be calculated (**O4**). Altogether, the derived research gap has been bridged by fulfillment of all objectives **O1** to **O4** (compare Chapter 4). However, three points of concern shall be highlighted.

1. Even though the model for determining the power demand of the IMT is suitable for standardization, the TEEI metric application in the presented form exceeds the effort and complexity acceptable for successful implementation into the ISO 14955 series.

2. Whereby the metering and monitoring equipment is crucial for the calculation of the EIs of the MT, the CI calculations are mainly determined by the data availability of benchmark values form literature. Lacking data availability increases the calculation effort of the entire TEEI study significantly and impacts the quality of the calculation results negatively. The same is true for the calculation of the SI, which is additionally impacted by subjectivity and lacking guidance to determine each components SI.

3. The metric has been applied for four main operational states, whereas only one operational point of the processing state has been considered due to the requirement that each operational state has to be able to be hold until thermal equilibrium is achieved. With equipment to apply a constant torque to the MT spindle, the quasi-static assessment of the processing state can be carried out for more reference points. Using interpolation methods a TEEI map can be created in order to determine the TEEI of the IMT and each of the MT components at every operational point of the spindle. Together with production data (intensity, time shares in each operational state) the average TEEI of the IMT in industrial application can be determined.

Even though great progress in the field of total energy efficiency of IMTs could be made, research can be continued in various ways, in particular:

1. Simplification of the TEEI metric in order to increase the feasibility of integration in international standards.

2. Compilation of a list with efficiency benchmarks in order to simply the calculation of the CI and guidance to calculate the SI for main MT components.

3. Creating a TEEI map for variable components in order to be able to determine the TEEI of the MT at every operational point.

This thesis can be continued at these points in order to meet present and future objectives in energy efficiency in industries.

8. Bibliography

1. Meadows, D.H., D.L. Meadows, J. Randers, W.W. Behrens, *The limits to growth – A report for the Club of Rome's Project on the Predicament of Mankind*. 1972, New York, USA: Universe Books.

2. United Nations (UN). *Report of the World Commission on Environment and Development: Our Common Future*. 1987 [cited 2016 05.04.2016]; Available from: http://www.un-documents.net/our-common-future.pdf.

3. United Nations (UN). *2005 World Summit Outcome. Resolution A/60/1 adopted by the General Assembly*. 2005 [cited 2016 05.04.2016]; Available from: http://data.unaids.org/Topics/UniversalAccess/worldsummitoutcome_resolution_24oct2005_en.pdf.

4. Schaltegger, S., R.L. Burritt, H. Petersen, *An Introduction to Corporate Environmental Management: Striving for Sustainability*. 2003: Greenleaf Publishing Limited.

5. Meadows, D.H., J. Randers, D.L. Meadows, *Limits to growth: The 30-year update*. 2004, White River Junction, USA: Chelsea Green Publishing.

6. European Union (EU). *Eurostat - Energy balance sheets - 2013 data*. 2015 [cited 2016 27.01.2016]; Available from: http://ec.europa.eu/eurostat/documents/3217494/6898731/KS-EN-15-001-EN-N.pdf/e5851c73-9259-462e-befc-6d037dc8216a.

7. Gutowski, T.G., J.M. Allwood, C. Herrmann, S. Sahni, *A Global Assessment of Manufacturing: Economic Development, Energy Use, Carbon Emissions, and the Potential for Energy Efficiency and Materials Recycling.* Annual Review of Environment and Resources, 2013. **38**(1): p. 81-106.

8. European Union (EU). *Eurostat - Energy balance sheets - 2014 data - 2016 edition*. 2016 [cited 2016 02.08.2016]; Available from: http://ec.europa.eu/eurostat/documents/3217494/7571929/KS-EN-16-001-EN-N.pdf/28165740-1051-49ea-83a3-a2a51c7ad304.

9. European Commission (EC). *Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council*. 2005 [cited 2016 05.04.2016]; Available from: http://enver.eie.gov.tr/DocObjects/Download/633/directive_2005_32.pdf.

10. European Commission (EC). *Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products*. 2009 [cited 2016 05.04.2016]; Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0125&from=EN.

11. European Union (EU). *Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC*. Official Journal of the European Union 2012 [cited 2016 05.04.2016]; Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:EN:PDF.

12. European Commission (EC). *Report from the Commission to the European Parliament and the Council - on the voluntary ecodesign scheme for imaging equipment* 2013 [cited 2016 05.04.2016]; Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52013DC0023&from=EN.

13. Schischke, K., E. Hohwieler, R. Feitscher, S. Kreuschner, P. Wilpert, N. Nissen. *Energy-Using Product Group Analysis - Lot 5 - Machine tools and related machinery - Task 1 Report - Definition*. 2012 [cited 2017 03.01.2017]; Available from: http://www.ecomachinetools.eu/typo/reports.html?file=tl_files/pdf/EuP_Lot5_Task1_August2012_Final.pdf.

14. Fraunhofer Gesellschaft. *Energy Efficiency in Production - Future Action Fields*. 2008 [cited 2016 05.04.2016]; Available from: http://www.iwu.fraunhofer.de/content/dam/iwu/en/documents/EffPro_en.pdf.

15. Müller, E., J. Engelmann, T. Löffler, S. Jörg, *Energieeffiziente Fabriken planen und betreiben*. 2012, Berlin Heidelberg: Springer.

16. U.S. Energy Information Administration. *International Energy Outlook 2010*. 2010 [cited 2016 05.04.2016]; Available from: http://large.stanford.edu/courses/2010/ph240/riley2/docs/EIA-0484-2010.pdf.

17. Ess, M., *Simulation and Compensation of Thermal Errors of Machine Tools*, in *Institute of Machine Tools and Manufacturing (IWF)*. 2012, Swiss Federal Institute of Technology (ETH) Zurich: Zurich.

18. International Organization for Standardization (ISO), *DIN EN ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework*. 2006.

19. International Organization for Standardization (ISO), *ISO 20140-1:2013 - Automation systems and integration - Evaluating energy efficiency and other factors of manufacturing systems that influence the environment - Part 1: Overview and general principles*. 2013.

20. Weber, M., R. Züst, *Schneller, Günstiger und Umweltgerechter, Energieeffizienz Produktionseffizienz Materialeffizienz*, in *UmweltPerspektiven*. 2013, Galledia Verlag AG. p. 8-10.

21. Züst, R., S. Züst, S. Studer. *Ecodesign-Potenzialanalyse in der Schweizer MEM-Industrie - eine explorative Studie* 2010 [cited 2016 05.04.2016]; Available from: http://www.zuestengineering.ch/downloads/Schlussbericht_Ecodesign-MEM_Kurzfassung.pdf.

22. Züst, S., R. Züst, T. Schudeleit, K. Wegener, *Development and Application of an Eco-design Tool for Machine Tools.* Procedia CIRP, 2016. **48**(1): p. 431-436.

23. Deutsches Institut für Normung (DIN), *DIN 8580-09:2003 - Manufacturing processes - Terms and definitions, division*. 2003.

24. Deutsches Institut für Normung (DIN), *DIN EN ISO 14020:2000 - Environmental labels and declarations - General principles*. 2000.

25. Deutsches Institut für Normung (DIN), *DIN EN ISO 14021:2012 - Environmental labels and declarations - Self-declared environmental claims* 2012.

26. Deutsches Institut für Normung (DIN), *DIN EN ISO 14024:2001 – Environmental labels*

and declarations – Type I environmental labelling – Principles and procedures. 2001.

27. Deutsches Institut für Normung (DIN), *DIN EN ISO 14025:2011 – Environmental labels and declarations – Type III environmental declarations – Principles and procedures*. 2011.

28. European Union (EU). *Directive 2010/30/EU of the European Parliament and of the Council of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products*. 2010 [cited 2016 05.04.2016]; Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0001:0012:en:PDF.

29. Herrmann, C., L. Bergmann, S. Thiede, A. Zein. *Energy labels for production machines– an approach to facilitate energy efficiency in production systems*. in *40th CIRP International Seminar on Manufacturing Systems Location*. 2007. Liverpool, England.

30. Schischke, K., E. Hohwieler, R. Feitscher, S. Kreuschner, P. Wilpert, N. Nissen. *Energy-Using Product Group Analysis - Lot 5 - Machine tools and related machinery - Task 6 Report - Improvement potential*. 2012 [cited 2016 05.04.2016]; Available from: http://www.eup-network.de/fileadmin/user_upload/Produktgruppen/Lots/Final_Documents/EuP_Lot5_Task3_March2012.pdf.

31. Mudgal, S., S. Pahal, B. Tinetti, H. Falkner, *Impact Assessment Study for Sustainable Product Measures for Product Group: Machine tools and related machinery, Final Report prepared for European Commission – DG Enterprise and Industry*, M. Bennett, Editor. 2015, BIO by Deloitte.

32. European Association of the Machine Tool Industries (CECIMO). *Concept Description for CECIMO's Self-Regulatory Initiative (SRI) for the Sector Specific Implementation of the Directive 2005/32/EC (EuP Directive)*. 2009 [cited 2016 05.04.2016]; Available from: http://www.eceee.org/ecodesign/products/machine_tools/draft_agreement_machine_tools.

33. European Association of the Machine Tool Industries (CECIMO). *Self-Regulation Measure for Metalworking Machine Tools*. 2014 [cited 2016 06.01.2016]; Available from: http://www.eceee.org/ecodesign/products/machine_tools/ANNEX%20D%20CECIMO%20SRM_methodology_draft%204_20140409.pdf.

34. International Organization for Standardization (ISO), *ISO 14955-1:2014 - Machine tools - Environmental evaluation of machine tools - Part 1: Design methodology for energy-efficient machine tools*. 2014.

35. Verband Deutscher Maschinen- und Anlagenbau (VDMA), *VDMA 34179-03:2015 - Measurement instruction to determine the energy- and resource demand of machine tools for mass production*. 2015.

36. International Organization for Standardization (ISO), *ISO/CD 14955-2:2014 - Machine tools - Environmental evaluation of machine tools - Part 2: Methods for measuring energy supplied to machine tools and machine tool components*. 2014.

37. Hesselbach, J., C. Herrmann, R. Detzer, L. Martin, S. Thiede, B. Ludemann. *Energy efficiency through optimised coordination of production and technical building services*. in *LCE 2008: 15th CIRP International Conference on Life Cycle Engineering: Conference*

Proceedings. 2008. CIRP.

38. Verein Deutscher Ingenieure (VDI), *VDI 4661:2014 - Energetic characteristics – Fundamentals – Methodology* 2014.

39. International Organization for Standardization (ISO), *ISO 9000:2005 - Quality management systems - Fundamentals and vocabulary.* 2005.

40. Deutsches Institut für Normung (DIN), *DIN EN ISO 50001:2011 - Energy management systems – Requirements with guidance for use*. 2011.

41. Li, W., A. Zein, S. Kara, C. Herrmann, *An Investigation into Fixed Energy Consumption of Machine Tools*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach,C. Herrmann, Editors. 2011, Springer: Berlin Heidelberg. p. 268-273.

42. Zein, A., W. Li, C. Herrmann, S. Kara, *Energy Efficiency Measures for the Design and Operation of Machine Tools: An Axiomatic Approach*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach,C. Herrmann, Editors. 2011, Springer: Berlin Heidelberg. p. 274-279.

43. General Electric (GE) Fanuc. *The Environmenttal and Economic Advantages of Energy-Efficient Motors*. 2008 [cited 2016 05.04.2016]; Available from: http://leadwise.mediadroit.com/files/2928energy%20saving_wp_gft688.pdf.

44. Pears, A. *Energy efficiency–its potential: some perspectives and experiences*. 2004 [cited 2016 05.04.2016]; Available from: http://www.naturaledgeproject.net/Documents/IEAENEFFICbackgroundpaperPearsFinal.pdf.

45. Zein, A., *Transition towards energy efficient machine tools*. Sustainable production, Life cycle engineering and management. 2012, Heidelberg New York: Springer.

46. Seefeldt, F., M. Wünsch, C. Michelsen, W. Baumgartner, O. Ebert-Bolla, U. Matthes, P. Leypoldt, T. Herz. *Potenziale für Energieeinsparung und Energieeffizienz im Lichte aktueller Preisentwicklungen.* 2007 [cited 2016 05.04.2016]; Available from: http://www.prognos.com/uploads/tx_atwpubdb/070831_Prognos_BMWI_Potenziale_fuer_Energieeinsparung.pdf.

47. Schudeleit, T., S. Züst, K. Wegener, *Energy Equivalents to Quantify the Total Electricity Consumption of Factory-integrated Machine Tools*, in *International Journal of Advanced Manufacturing Technology*. 2016, Springer: London. p. 1-9.

48. Schudeleit, T., S. Züst, L. Weiss, K. Wegener, *The Total Energy Efficiency Index for Machine Tools.* Energy, 2016. **102**(1): p. 682-693.

49. Preißler, P.R., *Betriebswirtschaftliche Kennzahlen: Formeln, Aussagekraft, Sollwerte, Ermittlungsintervalle*. 2008, München Wien: Oldenbourg.

50. Bunse, K., J. Sachs, M. Vodicka, *Evaluating energy efficiency improvements in manufacturing processes*, in *Advances in Production Management Systems. New Challenges, New Approaches - IFIP advances in information and communication technology*, B. Vallespir,T. Alix, Editors. 2010, Springer: Berlin Heidelberg. p. 19-26.

51. International Organization for Standardization (ISO), *ISO 50006:2014 - Energy management systems - Measuring energy performance using energy baselines (EnB)*

and energy performance indicators (EnPI) - General principles and guidance. 2014.

52. Global Reporting Initiative (GRI). *Sustainability Reporting Guidelines*. 2011 [cited 2016 05.04.2016]; Available from: https://www.globalreporting.org/resourcelibrary/g3.1-guidelines-incl-technical-protocol.pdf.

53. Kara, S., G. Bogdanski, W. Li, *Electricity Metering and Monitoring in Manufacturing Systems*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach,C. Herrmann, Editors. 2011, Springer: Berlin Heidelberg. p. 1-10.

54. Herrmann, C., A. Zein, M. Winter, S. Thiede, *Procedures and tools for metering energy consumption of machine tools.* Mechanical Engineering and Production Management 2011. **15**(1): p. 87-102.

55. Saidur, R., *A review on electrical motors energy use and energy savings.* Renewable and Sustainable Energy Reviews, 2010. **14**(3): p. 877-898.

56. Weiss, L., *Energieeffizienz von Werkzeugmaschinen – Der schwierige Weg zur Entwicklung der Normenreihe ISO 14955*, in *2. Wiener Produktionstechnik Kongress*, F. Bleicher, Editor. 2014, Klein Publishing: Vienna, Austria.

57. Wegener, K., L. Weiss, A. Gontarz. *Methods and Tools for Evaluation of Energy Efficiency in Production*. in *International Chemnitz Manufacturing Colloquium ICMC 2012, 2nd International Colloquium of the Cluster of Excellence eniPROD*. 2012. Auerbach: Verlag Wissenschaftliche Scripten.

58. Schudeleit, T., S. Züst, K. Wegener, *Methods for Evaluation of Energy Efficiency of Machine Tools.* Energy, 2015. **93**(2): p. 1964-1970.

59. Japanese Standards Association (JSA), *JIS TS B 0024-1:2010 - Machine Tools - Test Methods for Electric Power Consumption - Part 1: Machining centres*. 2010.

60. Japanese Standards Association (JSA), *JIS TS B 0024-2:2010 - Machine Tools - Test Methods for Electric Power Consumption - Part 2: Numerically controlled turning machines and turning centres*. 2010.

61. Japanese Standards Association (JSA), *JIS TS B 0024-3:2010 - Machine Tools - Test Methods for Electric Power Consumption - Part 3: Horizontal grinding wheel spindle and reciprocating table type surface grinding machines*. 2010.

62. Japanese Standards Association (JSA), *JIS TS B 0024-4:2010 - Machine Tools - Test Methods for Electric Power Consumption - Part 4: Cylindrical grinding machines*. 2010.

63. Thiede, S., *Energy efficiency in manufacturing systems*. Sustainable production, Life cycle engineering and management, ed. C. Herrmann,S. Kara. 2012, Berlin New York: Springer.

64. Kellens, K., *Energy and Resource Efficient Manufacturing - Unit process analysis and optimisation*, in *Department of Mechanical Engineering - Centre for Industrial Management, Traffic and Infrastructure*. 2013, KU Leuven.

65. Kaufeld, M., *Energieeffizienz-Eine Möglichkeit des Maschinenvergleichs.* Werkstatt und Betrieb, 2011. **144**(12): p. 60-64.

66. Erlach, K., E. Westkämper, *Energiewertstrom: Der Weg zur energieeffizienten Fabrik*. 2009, Stuttgart: Fraunhofer.

67. Kara, S., W. Li, *Unit process energy consumption models for material removal processes.* CIRP Annals-Manufacturing Technology, 2011. **60**(1): p. 37-40.

68. Gutowski, T.G., M.S. Branham, J.B. Dahmus, A.I. Jones, A. Thiriez, D.P. Sekulic, *Thermodynamic Analysis of Resources Used in Manufacturing Processes.* Environmental Science & Technology, 2009. **43**(5): p. 1584-1590.

69. Sealy, M.P., Z.Y. Liu, D. Zhang, Y.B. Guo, Z.Q. Liu, *Energy consumption and modeling in precision hard milling.* Journal of Cleaner Production, 2016. **135**(1): p. 1591-1601.

70. Draganescu, F., M. Gheorghe, C.V. Doicin, *Models of machine tool efficiency and specific consumed energy.* Materials Processing Technology, 2003. **141**(1): p. 9-15.

71. Abele, E., P. Schraml, C. Eisele, *Abschätzung des Energieverbrauchs durch Kennfelder*, in *PRODUCTIVITY Management*. 2012, GITO Berlin. p. 26-28.

72. Verl, A., E. Abele, U. Heisel, A. Dietmair, P. Eberspächer, R. Rahäuser, S. Schrems, S. Braun, *Modular Modeling of Energy Consumption for Monitoring and Control*, in *Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd - 4th, 2011*, J. Hesselbach,C. Herrmann, Editors. 2011, Springer: Berlin Heidelberg. p. 341-346.

73. Abele, E., B. Kuhrke, S. Rothenbücher, *Energieeffizienz spanender Werkzeugmaschinen*, in *forschen - Wissenschaftsmagazin der TU Darmstadt*. 2011. p. 64-67.

74. Narita, H., H. Kawamura, T. Norihisa, L.-Y. Chen, H. Fujimoto, T. Hasebe, *Development of prediction system for environmental burden for machine tool operation.* JSME International Journal Series C, 2006. **49**(1): p. 1188-1195.

75. Patterson, M.G., *What is energy efficiency?: Concepts, indicators and methodological issues.* Energy policy, 1996. **24**(5): p. 377-390.

76. Bogdanski, G., T. Spiering, W. Li, C. Herrmann, S. Kara, *Energy Monitoring in Manufacturing Companies – Generating Energy Awareness through Feedback*, in *Leveraging Technology for a Sustainable World*, D.A. Dornfeld,B.S. Linke, Editors. 2012, Springer: Berlin Heidelberg. p. 539-544.

77. International Energy Agency (IEA). *Tracking Industrial Energy Efficiency and CO2 Emissions*. 2007 [cited 2016 05.04.2016]; Available from: https://www.iea.org/publications/freepublications/publication/tracking_emissions.pdf.

78. Verein Deutscher Ingenieure (VDI), *VDI 4070:2006 - Part 1 - Sustainable management in small and medium-sized enterprises*. 2006.

79. Deutsches Institut für Normung (DIN), *DIN EN ISO 14031:2013 - Environmental management - Environmental performance evaluation - Guidelines*. 2013.

80. Zhou, L., J. Li, F. Li, Q. Meng, J. Li, X. Xu, *Energy consumption model and energy efficiency of machine tools: a comprehensive literature review.* Journal of Cleaner Production, 2016. **112, Part 5**(1): p. 3721-3734.

81. Kuhrke, B., *Methode zur Energie- und Medienbedarfsbewertung spanender Werkzeugmaschinen*. Schriftreihe des PTW: "Innovative Fertigungstechnik", ed. E.

Abele. 2011, Darmstadt.

82. Mori, M., M. Fujishima, Y. Inamasu, Y. Oda, *A study on energy efficiency improvement for machine tools.* CIRP Annals - Manufacturing Technology, 2011. **60**(1): p. 145-148.

83. Duflou, J.R., K. Kellens, Renaldi, Y. Guo, W. Dewulf, *Critical comparison of methods to determine the energy input for discrete manufacturing processes.* CIRP Annals - Manufacturing Technology, 2012. **61**(1): p. 63-66.

84. Guo, Y.S., J. Loenders, J. Duflou, B. Lauwers, *Optimization of energy consumption and surface quality in finish turning*, in *5th CIRP Conference on High Performance Cutting 2012*. 2012. p. 512-517.

85. Branham, M., T.G. Gutowski, A. Jones, D.P. Sekulic, *A thermodynamic framework for analyzing and improving manufacturing processes*, in *2008 IEEE International Symposium on Electronics and the Environment, May 19-22*. 2008, IEEE: San Francisco, USA. p. 349-354.

86. Gutowski, T., J. Dahmus, A. Thiriez, M. Branham, A. Jones, *A thermodynamic characterization of manufacturing processes*, in *2007 IEEE International Symposium on Electronics & the Environment, May 7-10*. 2007, IEEE: Orlando, Forida, USA. p. 137-142.

87. Szargut, J., D.R. Morris, F.R. Steward, *Exergy analysis of thermal, chemical, and metallurgical processes.* 1988, New York Washington Philadelphia London: Hemisphere.

88. Renaldi, K. Kellens, W. Dewulf, J. Duflou, *Exergy Efficiency Definitions for Manufacturing Processes*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach,C. Herrmann, Editors. 2011, Springer: Berlin Heidelberg. p. 329-334.

89. Renaldi, K. Kellens, W. Dewulf, J.R. Duflou, *On the Implementation of Exergy Efficiency Metrics in Discrete Manufacturing System: The Dissipative Nature of Production Processes*, in *Leveraging Technology for a Sustainable World*, D.A. Dornfeld,B.S. Linke, Editors. 2012, Springer: Berlin Heidelberg. p. 545-550.

90. ElMaraghy, H.A., A.M.A. Youssef, A.M. Marzouk, W.H. ElMaraghy, *Energy use analysis and local benchmarking of manufacturing lines.* Journal of Cleaner Production, 2016(in press).

91. Stark, M., C. Dorn, F. Bleicher, *Energetic Comparison of Machine Tools*, in *Junior Scientist Conference 2010*, H.K. Kaiser,R. Kirner, Editors. 2010, Vienna University of Technology: Vienna, Austria. p. 363-364.

92. Giacone, E., S. Mancò, *Energy efficiency measurement in industrial processes.* Energy, 2012. **38**(1): p. 331-345.

93. Schlosser, R., F. Klocke, B. Döbbeler, B. Riemer, K. Hameyer, T. Herold, W. Zimmermann, O. Nuding, B.A. Schindler, M. Niemczyk, *Assessment of Energy and Resource Consumption of Processes and Process Chains within the Automotive Sector*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach,C. Herrmann, Editors. 2011, Springer: Berlin Heidelberg. p. 45-50.

94. Rajemi, M., P. Mativenga, A. Aramcharoen, *Sustainable machining: selection of optimum turning conditions based on minimum energy considerations.* Journal of Cleaner Production, 2010. **18**(10): p. 1059-1065.

95.   Narita, H., L.Y. Chen, H. Fujimoto, *Cost prediction system using activity-based model for machine tool operation*, in *Knowledge Sharing in the Integrated Enterprise: Interoperability Strategies for the Enterprise Architect*, P. Bernus, M. Fox, Editors. 2005, Springer: US. p. 399-407.

96.   Desmira, N., H. Narita, H. Fujimoto, *A Minimization of Environmental Burden of High-Speed Milling*, in *Service Robotics and Mechatronics*, K. Shirase, S. Aoyagi, Editors. 2010, Springer: London Dordrecht Heidelberg New York. p. 367-372.

97.   Cao, H., H. Li, H. Cheng, Y. Luo, R. Yin, Y. Chen, *A carbon efficiency approach for life-cycle carbon emission characteristics of machine tools.* Cleaner Production, 2012. **37**(1): p. 19-28.

98.   Gontarz, A.M., F. Hanni, L.B. Weiss, K. Wegener, *Machine tool optimization strategies for ecologic and economic efficiency.* Engineering Manufacture, 2013. **227**(1): p. 54-61.

99.   Kuznetsov, A.P., P. Blau, H.J. Koriath, M. Richter, *Criteria for Energy-efficiency of Technological Processes, Technological Machines and Production Engineering.* Procedia CIRP, 2016. **46**: p. 340-343.

100.   International Organization for Standardization (ISO), *ISO/TR 14062:2002 - Environmental management - Integrating environmental aspects into product design and development*. 2002.

101.   Mittal, S., F. Frayman. *Towards a Generic Model of Configuraton Tasks*. in *International Joint Conferences on Artificial Intelligence*. 1989. Detroit, Michigan, USA.

102.   Pine, J.B., *Mass Customization: The New Frontier in Business Competition*. 1993, Cambridge, MA, USA: Harvard Business School Press.

103.   Salvador, F., P.M. De Holan, F. Piller, *Cracking the Code of Mass Customization.* MIT Sloan Management Review, 2009. **50**(3): p. 71-78.

104.   Ehrlenspiel, K., A. Kiewert, U. Lindemann, M.S. Hundal, *Cost-efficient design*. 2007, Berlin Heidelberg: Springer.

105.   Diaz, N., S. Choi, M. Helu, Y. Chen, S. Jayanathan, Y. Yasui, D. Kong, S. Pavanaskar, D. Dornfeld, *Machine tool design and operation strategies for green manufacturing*, in *4th CIRP International Conference on High Performance Cutting, 2010*. 2010, UC Berkley, Laboratory for Manufacturing and Sustainability. p. 271–276.

106.   Seow, Y., S. Rahimifard, *Improving Product Design based on Energy Considerations*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach, C. Herrmann, Editors. 2011, Springer: Berlin Heidelberg. p. 154-159.

107.   International Organization for Standardization (ISO), *ISO 14044:2006 - Environmental management – Life cycle assessment – Requirements and Guidelines*. 2006.

108.   Chen, J.L., W.-L. Su, H.-C. Huang, *Method and Calculation Tool for Carbon Footprint Assessment of Machine Tool*, in *Re-engineering Manufacturing for Sustainability: Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore 17-19 April, 2013*, A.Y.C. Nee, B. Song, S.-K. Ong, Editors. 2013, Springer: Singapore. p. 215-220.

109.   Diaz, N., M. Helu, S. Jayanathan, C. Yifen, A. Horvath, D. Dornfeld, *Environmental*

analysis of milling machine tool use in various manufacturing environments, in *IEEE International Symposium on Sustainable Systems and Technology (ISSST)*. 2010. p. 1-6.

110. Kellens, K., W. Dewulf, M. Overcash, M.Z. Hauschild, J.R. Duflou, *Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)-CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description.* Life Cycle Assessment, 2012. **17**(1): p. 69-78.

111. Kellens, K., W. Dewulf, M. Overcash, M.Z. Hauschild, J.R. Duflou, *Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 2: case studies.* Life Cycle Assessment, 2012. **17**(2): p. 242-251.

112. Schmitt, R., J. Bittencourt, R. Bonefeld, *Modelling Machine Tools for Self-Optimisation of Energy Consumption*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach,C. Herrmann, Editors. 2011, Springer: Berlin Heidelberg. p. 253-257.

113. Brecher, C., S. Bäumler, J. Triebs, *Virtual Production Systems: Simulating the Energy Consumption of Machine Tools*, in *Future Trends in Production Engineering*, G. Schuh, R. Neugebauer,E. Uhlmann, Editors. 2013, Springer: Berlin Heidelberg. p. 379-387.

114. Brecher, C., W. Herfs, C. Heyers, W. Klein, J. Triebs, E. Beck, T. Dorn, *Ressourceneffizienz von Werkzeugmaschinen im Fokus der Forschung*, in *Werkstattstechnik*. 2010, Springer-VDI: Düsseldorf. p. 559-564.

115. Schäfer, R., *Ganzheitliche Analyse ermöglicht Auswahl des wirtschaftlichen Antriebs*, in *MaschinenMarkt*. 2008, Vogel: Würzburg. p. 42-43.

116. Abele, E., T. Sielaff, M. Beck, *Konfiguration energieeffizienter Werkzeugmaschinen*, in *Werkstattstechnik*. 2012, Springer-VDI: Düsseldorf. p. 292-298.

117. Harris, P., G.E. O'Donnell, T. Whelan, *Energy Efficiency in Pneumatic Production Systems: State of the Art and Future Directions*, in *Leveraging Technology for a Sustainable World*, D.A. Dornfeld,B.S. Linke, Editors. 2012, Springer: Berlin Heidelberg. p. 363-368.

118. Riemer, B., T. Herold, K. Hameyer, *Impact Assessment of Machine Tool Auxiliary Drives Oversizing to Energy Efficiency Aspects*, in *Sustainable Manufacturing*, G. Seliger, Editor. 2012, Springer: Berlin Heidelberg. p. 77-81.

119. Salgado, D.R., F.J. Alonso, *Optimal machine tool spindle drive gearbox design.* Advanced Manufacturing Technology, 2008. **37**(9/10): p. 851-860.

120. Gontarz, A., T. Schudeleit, K. Wegener, *Framework of a Machine Tool Configurator for Energy Efficiency*, in *12th Global Conference on Sustainable Manufacturing GCSM 2014 – Emerging Potentials*. 2015: Johor Bahru, Malaysia. p. 706-711.

121. Gutowski, T., J. Dahmus, A. Thiriez, *Electrical energy requirements for manufacturing processes*, in *13th CIRP International Conference on Life Cycle Engineering*. 2006: Leuven, Netherlands.

122. Gontarz, A., L. Weiss, K. Wegener, *Energy consumption measurement with a multichannel measurement system on a machine tool*, in *International Conference on Innovative Technologies IN-TECH 2010*. 2010: Prague, Czech Republic. p. 499-502.

123. Liu, Y., H. Dong, N. Lohse, S. Petrovic, N. Gindy, *An investigation into minimising total energy consumption and total weighted tardiness in job shops.* Cleaner Production, 2014. **65**(1): p. 87-96.

124. Schlechtendahl, J., P. Eberspächer, P. Schraml, A. Verl, E. Abele, *Multi-level Energy Demand Optimizer System for Machine Tool Controls.* Procedia CIRP, 2016. **41**(1): p. 783-788.

125. Mousavi, S., S. Kara, B. Kornfeld, *A hierarchical framework for concurrent assessment of energy and water efficiency in manufacturing systems.* Journal of Cleaner Production, 2016. **133**(1): p. 88-98.

126. Yan, J., L. Li, F. Zhao, F. Zhang, Q. Zhao, *A multi-level optimization approach for energy-efficient flexible flow shop scheduling.* Journal of Cleaner Production, 2016. **137**(1): p. 1543-1552.

127. Beck, M., M. Helfert, M. Burkhardt, E. Abele, *Rapid Assessment: Method to Configure Energy Performant Machine Tools in Linked Energy Systems.* Procedia CIRP, 2016. **48**(1): p. 514-519.

128. Abele, E., B. Kuhrke, S. Rothenbücher, *Maximierung der Energieeffizienz von Werkzeugmaschinen*, in *Maschinen Markt*. 2010, Vogel Würzburg. p. 26-29.

129. Herrmann, C., *Ganzheitliches Life Cycle Management: Nachhaltigkeit und Lebenszyklusorientierung in Unternehmen*. 2010, Berlin Heidelberg: Springer.

130. Diaz, N., E. Redelsheimer, D. Dornfeld, *Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach,C. Herrmann, Editors. 2011, Springer: Berlin Heidelberg. p. 263-267.

131. Züst, R., L. Weiss, A. Gontarz, J. Hauenstein. *Eco-effiziente Produktionsmaschinen in moderner Haustechnik bei Mettler Toledo - Hohe Energieeffizienz durch Optimierung des Gesamtsystems*. 2013 [cited 2016 19.01.2016]; Available from: http://www.zuestengineering.ch/downloads/Fallbeispiel_Mettler-Toldeo_Ecodesign-Werkzeugmaschine.pdf.

132. National Research Council, *Visionary manufacturing challenges for 2020*, ed. Committee on Visionary Manufacturing Challenges, Commission on Engineering and Technical Systems, Board on Manufacturing and Engineering Design, Division on Engineering and Physical Sciences,National Research Council. 1998, Washington, USA: National Academy Press.

133. Gontarz, A., S. Züst, L. Weiss, K. Wegener, *Energetic machine tool modeling approach for energy consumption prediction*, in *10th Global Conference on Sustainable Manufacturing GCSM 2012*. 2012: Istanbul, Turkey.

134. Schudeleit, T., S. Züst, L. Weiss, K. Wegener, *Machine Tool Energy Efficiency – A Component Mapping-Based Approach.* International Journal of Automation Technology, 2016. **10**(5): p. 717-726.

135. Bogdanski, G., M. Schönemann, S. Thiede, S. Andrew, C. Herrmann, *An Extended Energy Value Stream Approach Applied on the Electronics Industry*, in *Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services*, C. Emmanouilidis, M. Taisch,D. Kiritsis, Editors. 2013, Springer Berlin

Heidelberg. p. 65-72.

136. International Organization for Standardization (ISO), *ISO 8778:2003 - Pneumatic fluid power - Standard reference atmosphere*. 2003.

137. Deutsches Institut für Normung (DIN), *DIN EN 15603:2008 - Energy performance of buildings - Overall energy use and definition of energy ratings*. 2008.

138. International Electrotechnical Commission (IEC), *IEC 60034-1:2010 - Rotating electrical machines - Part 1: Rating and performance*. 2010.

139. Deutsches Institut für Normung (DIN), *DIN IEC/TS 60034-30-2:2014 (VDE V 0530-30-2) - Rotating electrical machines - Part 30-2: Efficiency classes of variable speed AC motors (IE-code) (IEC 2/1741/CD:2014)*. 2014.

140. Meister, M., *Vademecum des Schleifens*. 2011, München: Hanser.

141. Tönz, P., *Specific Heat Capactity of Blasogrind HC 5*. 2015.

142. Verein Deutscher Ingenieure (VDI), *VDI 3802-2:2012 - Air Conditioning Systems For Factories - Capture Of Air Pollutants At Machine Tools Removing Material*. 2012.

143. Züst, S., F. Pavlicek, L. Fischer, L. Weiss, K. Wegener, *Thermo-Energetic Modelling of Machine Tool Spindles with Active Cooling based on Macro Models.* Mechatronics and Manufacturing Systems, 2016. **[in press]**.

144. Krause, P.C., O. Wasynczuk, S.D. Sudhoff, *Analysis of electric machinery and drive systems*. 2 ed. IEEE Press series on power engineering. 2002, New York: Wiley-Interscience.

145. van der Broeck, H.W., H.C. Skudelny, G.V. Stanke, *Analytical Analysis of the Harmonic Effects of a PWM AC Drive.* IEEE Transactions on Industry Applications and Science in Soft Computing, 1988. **3**(2): p. 216-223.

146. van der Broeck, H.W., H.C. Skudelny, G.V. Stanke, *Analysis and Realization of a Pulsewidth Modulator Based on Voltage Space Vectors.* IEEE Transactions on Industry Applications, 1988. **24**(1): p. 142-150.

147. Eurovent. *RS 6/C/003-2016 - Rating Standard for the Certification of Liquid Chilling Packages*. 2016 [cited 2016 05.04.2016]; Available from: http://www.eurovent-certification.com/fic_bdd/fr/1454511712_2015-12_RS_6C003-2016_LCP.pdf.

148. Deutsches Institut für Normung (DIN), *DIN EN 14511-1:2013 - Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling - Part 1: Terms, definitions and classification*. 2013.

149. European Commission (EC), *Commission regulation (EU) No 547/2012 of 25 June 2012 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for water pumps.* Journal of the European Union, 2012. **L 165/28**.

150. Stoffel, B. *Ecopump work by europump - How the concepts of "House of Efficiency" and "Extended Product Approach" were developed and what they meant for Ecodesign developments*. 2013 [cited 2016 30.08.2016]; Available from: http://europump.net/uploads/presentation_workshop_Prof%20Stoffelb.pdf.

151. European Committee for Standardization (CEN), *EN 13779:2007 - Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems*. 2007.

152. Siloveda. *ETH Zurich - SILOVEDA WEB*. 2017 [cited 2017 03.01.2017]; Available from: https://emms-www.ethz.ch/.

153. Fraunhofer ISI. *Druckluft effizient: Fakten Thermodynamik*. 2003 [cited 2016 05.04.2016]; Available from: http://www.druckluft-effizient.de/downloads/fakten/02-thermodynamik.pdf.

154. Schweizerischer Ingenieur- und Architektenverein (SIA), *SIA 382/1:2014 - Lüftungs- und Klimaanlagen - Allgemeine Grundlagen und Anforderungen*. 2014.

155. European Commission (EC). *Commission Delegated Regulation (EU) No 626/2011 of 4 May 2011 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of air conditioners*. 2011 [cited 2016 05.04.2016]; Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011R0626&from=EN.

9. List of Publications

Conferences

- Züst, S., R. Züst, T. Schudeleit, K. Wegener, Development and Application of an Eco-design Tool for Machine Tools. Procedia CIRP, 2016. 48(1): p. 431-436.

- Gontarz, A., T. Schudeleit, K. Wegener, Framework of a Machine Tool Configurator for Energy Efficiency, in 12th Global Conference on Sustainable Manufacturing GCSM 2014 – Emerging Potentials. 2015: Johor Bahru, Malaysia. p. 706-711.

- Chen, D.F., T. Schudeleit, G. Posselt, S. Thiede, A state-of-the-art review and evaluation of tools for factory sustainability assessment. 2nd CIRP Global Web Conference - Beyond Modern Manufacturing: Technology for the Factories of the Future, 2013. 9(1): p. 85-90.

Journals

- Schudeleit, T., S. Züst, K. Wegener, Energy Equivalents to Quantify the Total Electricity Consumption of Factory-integrated Machine Tools, in International Journal of Advanced Manufacturing Technology. 2016, Springer: London. p. 1-9.

- Schudeleit, T., S. Züst, L. Weiss, K. Wegener, Machine Tool Energy Efficiency – A Component Mapping-Based Approach. International Journal of Automation Technology, 2016. **10**(5): p. 717-726.

- Schudeleit, T., S. Züst, L. Weiss, K. Wegener, The Total Energy Efficiency Index for Machine Tools. Energy, 2016. **102**(1): p. 682-693.

- Schudeleit, T., S. Züst, K. Wegener, Methods for Evaluation of Energy Efficiency of Machine Tools. Energy, 2015. **93**(2): p. 1964-1970.

- Chen, D., S. Thiede, T. Schudeleit, C. Herrmann, A holistic and rapid sustainability assessment tool for manufacturing SMEs. CIRP Annals - Manufacturing Technology, 2014. 63(1): p. 437-440.

Talks

- T. Schudeleit, Handlungsfelder bei der Normarbeit an der ISO 14955 Serie, Arbeitsgruppe Energieeffizienz von Werkzeugmaschinen des Swissmem, 2015, Zurich, Switzerland

- T. Schudeleit, Aktuelle Forschung an Energieeffizienz von Werkzeugmaschinen an der ETH / inspire AG, Arbeitsgruppe Energieeffizienz von Werkzeugmaschinen des Swissmem, 2015, Zurich, Switzerland

10. Curriculum Vitae

Personal Details

Name: Timo Steffen Schudeleit

Birth date, place: 23.04.1988, Goslar, Germany

Nationality: German

Education

10/2008 – 10/2013   Technical University Braunschweig, Germany

10/2011 – 01/2012   Linköping University, Sweden

10/2012 – 03/2013   Royal Institute of Technology (KTH) Stockholm, Sweden

04/2013 – 10/2013   University of New South Wales, Sydney, Australia

01/2014 – 12/2016   Swiss Federal Institute of Technology (ETH) Zurich, Switzerland

02/2016 – 05/2016   Massachusetts Institute of Technology, Cambridge, USA

Employment

01/2014 – 12/2015   Research Assistant at inspire AG for Mechatronic Production Systems and Manufacturing Technology, Switzerland

01/2016 – 12/2016   Research Assistant at the Institute of Machine Tools and Manufacturing (IWF), ETH Zurich, Switzerland

Others

01/2016   Years best high school degree, Christian-von-Dohm Gymnasium, Goslar, Germany

04/2012   Years best bachelor's degree, Technical University Braunschweig, Germany

04/2014   Years best master's degree, Technical University Braunschweig, Germany

04/2014   Winner of the VDI University Award, Braunschweig, Germany