Diss. ETH Nr.: 22889

Energy Assessment of Machine Tools within Manufacturing Environments

A thesis submitted to attain the degree of

DOCTOR OF SCIENCE of ETH ZURICH

(Dr. sc. ETH Zurich)

presented by

Adam Martin Gontarz

Dipl.-Ing., University of Stuttgart

Born on January 11th, 1982

Citizen of Germany

accepted on the recommendation of

Prof. Dr. Konrad Wegener, examinor

Prof. Dr. Paul Schönsleben, co-examinor

2015

To my family.

knowledgment

My development, professional career and this thesis would not be possible without the generous support of a lot of people, who shaped and helped me invaluably throughout my personal and vocational training. Without these people this thesis would not have been the same.

At first I would like to thank my supervisor Prof. Konrad Wegener giving me the opportunity to do a doctorate at the renowned *Institute of Machine Tools and Manufacturing IWF*, a detailed and intensified view and knowledge of engineering, manufacturing and the preparation for my startup in this field. I would like to thank him for his deep knowledge, support, trust, patience and all the inspiring discussions.

I would like to thank my co-supervisor Prof. Paul Schönsleben, head of the department of Management, Technology, and Economics, BWI Center for Industrial Management at ETH Zürich, for the common projects and revealing interest in my PhD thesis, his reviews, his support and helpful suggestions.

Very special thanks go to the former research assistant, todays' business partner and friend David Hampl for all his support during my time at the Institute and in our daily professional life, which lead to a promising common project resulting from this PhD.

Special thanks go to the head of my working-group Lukas Weiss for all his support since the very first start at the institute 9 years ago, during my semester thesis, my employment and my work as a PhD student. He supported me in my technical education and with his patient explanations as well as cheerful and also difficult discussions. I also like to thank Dr. Rainer Züst for his inspiring ideas and great network and supportive advice in the common past and future projects.

I am very thankful for the inspiring and supportive works of my students, who allowed me to supervise their semester thesis, bachelor, and master thesis. Without their work lot of great idea and developments would never come true: Simon Züst, Florian Hänni, Pascal Bosshard, Christian Elbe, Kai Neugebauer, Lukas Geissmann, Andreas Krättli, Michael Lang, Philip Roh, Hummam Haider, Thomas Bormuth, David Michel, Andre Ulbers, and Moritz Töpfer. In the same manner special thanks go to the supportive research assistants Conni Dietschwieler, Jason Avramiotis, Vasileios Saplamidis, Simon Holtz and Manuel Wälchli.

The professional and comfortable working atmosphere and my work at the institute would not be the same without the help and support of my former colleges, Dr. Eduardo Weingärtner, Dr. Carl Wyen, Dr. Jens Barthelt, Dr. Daniel Politze, Mansur Akbari, Noelle Jufer, Dr. Robert Transchel, Sebastian Kollert, Simon Züst, Nikolas Schaal, Dr. Johannes Plehn, Dr. Alexander Sproedt, Dr. Eduardo Weingärtner, Andreas Leuenberger, Jens Boos, Albert Weber, and Sandro Wigger. I would like to thank them for their comprehensive technical and organizational support and related machining test, measurement support and prototype build-up. The work as it is done is strongly motivated and inspired by the industrial needs and the trust and motivation of related persons such as Wolfgang Labus, Antonio Bottazzo and Roberto Perez – thank you for trust and support.

I dedicate this work to my mum and my family, who always supported me and thought me how to achieve goals in life and their support in good and in bad times.

Adam Gontarz
May 2015

Contents

knowledgment iv
List of Symbols ix
List of Abbreviations xii
Abstract xv
Kurzfassung xvii
1 Introduction 1
2 State of the Art 4
2.1 Sustainability evaluation approaches in manufacturing 4
2.1.1 Definition of Sustainability 4
2.1.2 Sustainability Evaluation Methods 5
2.1.3 Top down approaches for sustainable evaluation 7
2.1.4 Bottom up approaches for sustainable evaluation 9
2.2 Machine tool measurement 12
2.3 Analysis and findings 21
2.4 Simulation approaches for energy evaluation 24
2.5 Research gaps and need for action 28
3 Machine Tool energy measurement 31
3.1 Introduction 31
3.2 Energy forms and dependencies 31
3.3 System boundaries 32
3.4 Electrical power measurement 34
3.5 Sampling rate and resolution 36
3.6 Multichannel measurement 39
3.7 Synchronization 44
3.8 Sensor comparison and selection 46
3.9 Compressed Air Measurement 51
3.9.1 Introduction 51
3.9.2 Conversion factor 51
3.9.3 Measurement equipment 55

3.9.4 Sensor comparison 57
3.10 Measurement methodology 60
3.10.1 Measurement preparation 61
3.10.2 Machine tool preparation 62
3.10.3 Machining processes 62
3.11 Measurements and resulting findings 64
4 Simulation 68
4.1 Introduction 68
4.2 Energetic modeling approaches 68
4.3 Requirements 69
4.4 Electrical component modeling 70
4.5 EMod 71
4.6 Teach-in 83
4.6.1 Machine tool component selection and measurement 84
4.6.2 *Teach-in* example 86
4.7 Comparison and conclusion 89
4.8 Compressed air simulation 92
4.8.1 Distribution system 94
4.8.2 Modeling of Leakage 97
4.9 Conclusion 102
5 Analysis and Optimization 103
5.1 Introduction 103
5.2 Analysis of Measurement Findings 104
5.3 Requirements for data analysis 112
5.4 Analysis tools 113
5.4.1 Functional Component classification 113
5.4.2 Retrofit Indication 122
5.5 Economic Analysis 131
5.6 Conclusion 138
6 Monitoring 140
6.1 Introduction 140
6.2 Requirements 142

6.3 Implementation methodology 143
Machine tool selection 143
1. Component classification 145
6.4 Conclusion 155
6.5 Case study 156
7 Conclusion and Outlook 159
A Appendix 162
A.1 Overview of standards and technical guidelines 162
A.2 Pipe equivalents 163
A.3 Overview of power sensors 164
A.4 Example Raw data of the multichannel measurement 165
A.5 Gini Measurement point classification 166
Bibliography 167
List of Publications 179
List of Supervised Theses 183

List of Symbols

Symbol	Unit	Description
A_1	m^2	Cylinder cross section
A	$m\,s^{-1}$	Speed of sound
B	mm	Cutting depth
c_p	$J\,kg^{-1}\,K^{-1}$	Heat capacity
E	J	Energy
F	Hz	Frequency
F_C	N	Cutting force
F_f	N	Feed force
F_p	N	Passive force
h^{1-z_c}	mm	Equivalent chipping thickness
I	A	Current
J	$kg\,m^2$	Torque of intertia
k	-	Sensor geometrical constant
$k_{c1.1}$	N/mm^2	Specific cutting force coefficient
L	m	Length of tube
M	Nm	Torque
$\dot{m}$	$kg\,s^{-1}$	Massflow
Ma	-	Mach number
N	min^{-1}	Rotational speed
P	W	Power
P	Nm^{-2}	Pressure
Q	VAR	Reactive power
$\dot{Q}$	W	Heat flux
R	$J\,kg^{-1}\,K^{-1}$	Gas constant
Re	-	Reynolds number
S	VA	Apparent power
T	s	Period
U	V	Voltage
U	-	Operational level or input signal
V	m^3	Volume
$\dot{V}$	$m^3\,s^{-1}$	Flow rate
v_c	$m\,s^{-1}$	Cutting speed or feed rate
Y	-	Output signal

Greek Symbol	Unit	Description
α	rad	Tilt angle of retrofit regression line
γ	-	Adiabatic coefficient
Δ	-	Differential between values
σ	-	Component state
ε	-	Compression ratio
ζ	-	Carnot coefficient
η	-	Efficiency
θ	-	Description of function
ϑ	K	Temperature
κ	-	Isotropic exponent
κ_a	$Nm\,A^{-1}$	Tilt angle of settings
κ_i	$Vs\,rad^{-1}$	Speed constant
λ	-	Friction coefficient
λ_i	$W\,mK^{-1}$	Thermal conductivity
ν_z	$mm\,s^{-1}$	Speed in z-direction
ν_x	$mm\,s^{-1}$	Speed in x-direction
ν_i	$kg\,sm^{-1}$	Kinetic viscosity
π	-	Phi value
ρ	$kg\,m^{-3}$	Density
Σ	-	Sum
φ	rad	Phase angle
Ψ	-	Discharge function
ω_C	$rad\,s^{-1}$	Rotational speed
ω	$rad\,s^{-1}$	Fluid velocity

Subscript	Description
A	Acceleration
Amb	Ambient
Aux	Auxiliary
B	B axis
Cc	Chip conveyor
Cf	Cooling fluid
Cmp	Component
Comp	Compressor
const.	Constant
Ctrl	Control
Crit	Critical
Dmd	Demand
Eff	Effective
El	Electric
Init	Initial
L	Load
Leak	Leakage
Ln	Phase n
Max	Maximum
Mch	Machine
M	Component number
Mot	Motor
N	Time steps
Nom	Nominal
P	Peak
PR	Process
R	Rated
Rdy	Ready
Sc	Spindle cooling
Sec	Second
SP	Spindle
Stby	Standby
Sys	System
T	Tank
Th	Thermal
Tot	Total
V	Loss
X	X axis
X	Y axis
Z	Z axis

List of Abbreviations

Abbreviation	Description
A/D	Analog / Digital
ABE	Activity-based energy calculating methodology
AC	Alternating current
ANR	Atmosphere Normale de Reference
ANSI	American National Standards Institute
APP	Application software
BFE	Swiss Federal Offices of Energy
BUIS	Operating Environment Information System
CAPP	Computer Aided Process Planning
CECIMO	European Association of the Machine Tools Industries
CIP	Continuous Improvement Process
CLT	Measurement device from Christ Electronic
CNC	Computerized Numerical Control
CORBA	Common Object Request Broker Architecture
CSR	Corporte Social Responsibility
CT	Current transformer
DC	Direct current
DDE	Dynamic Data Exchange
DFMA	Design for Manufacture and Assembly
DI	Deionized
DIN	Deutsches Institut für Normung
DMS	Strain gauge (dt. Dehnungsmessstreifen)
DNC	Heidenhain Direct Numeric Control
EDM	Electro Discharge Machining
EMC	Electromagnetic Compatibility
EMF	Electromotive force
EMod	Energy Modelling framework
EMS	Energy Measurement System
EnMS	Energy Management System
EnPI	Energy Performance Indicator
ERP	Enterprise Resource Planning
ErP	Energy related products

ESG	Environmental Social Governance
EU	European Union
EuP	Energy using products
EVSM	Environmental Values Stream Map
FOCAS2	Fanuc Open CNC API Specification Version 2
GRI	Global Reporting Initiative
HF	High Frequency
HMI	Human-Machine Interface
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communication Technology
IEA	International Energy Agency
IEC	International electro-technical Commission
IO	Input-Output
IPO	Input-Processing-Output
IRR	Internal rate of return
ISO	International Organization for Standardization
JSA	Japanese Standards Association
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCM	Life Cycle Management
MES	Manufacturing Execution System
MQL	Minimal quantity lubricant
MTM	Methods-Time-Measurement
NC	Numerical control
NGO	Non-Governmental Organization
NPV	Net present value
OECD	Organization for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OPC	OLE for Process Control
OPC DA	OLE for Process Control Data Access
PC	Personal Computer
PLC	Programmable Logic Control
PM	Performance Measure
PMC	Programmable Motion Control
PPC	Production Planning and Control
QSS	Quasi -static simulation
REFA	Association for Work Design, Industrial Organization and Corporate Development

ROI	Return on investment
RSM	Response Surface Methodology
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SME	Small and Medium Sized Enterprises
SRI	Self-Regulatory Initiative
SRM	Self-Regulatory Measure
TBL	Triple Bottom Line
TCM	Tool Condition Monitoring
TCO	Total cost of ownership
TCP/IP	Transmission Control Protocol / Internet Protocol
TPC	Tool Center Point
TPS	Toyota Production System
UPLCI	Unit Process Life Cycle Inventory
USB	Universal Serial Bus
UTC	Coordinated Universal Time
VDI	German Engineer Association
VDW	German Machine Tool Association
VR	Virtual Reality
VSM	Value Stream Map
ZVEI	German Electrical and Electronic Manufacturers Association

Abstract

Energy efficiency in manufacturing is gaining importance due to legislative pressure and as a potential economic factor. It is addressed by multiple approaches in research and industry, resulting in a wide field of different approaches for measurement, analysis, and optimization. In research, two principal approaches for the energy evaluation can be distinguished – bottom up and top down. Only a few research results are implemented in todays' industrial environment, whereas other application fields, e.g. building technologies, are more advance in respect of energy efficiency. The application of energy efficiency improvement developments from research into the industrial environment requires comprehensive and methodological evaluation approaches, e.g. elaborate and standardized measurement on the machine tool level or multilevel LCAs, and an economic incentive. A further reason for the limited application of energy efficiency solutions in industrial environments is, that rule-based optimization strategies show low effectiveness due to and depending on the variability of machine tools, their configuration, individual utilization, and specific machining processes. Lack of simple and effective evaluation approaches, in combination with the low cost share for energy in manufacturing and an ex-ante unknown optimization potential, lead to a gap between research results and industrial requirements.

Investigations for the comprehensive machine tool evaluation, based on detailed measurement within industrial settings, have been made. The research shows, that standardized and methodological approaches on the machine tool and component level are missing but required, as they represent a key element for an effective optimization of the machine tool energy efficiency.

This thesis deals with the characterization, the measurement and evaluation of the energy consumption of machine tools and its components. The focus is given on a methodological approach and related measurement equipment for selective measurements and monitoring applications, that meets the industrial requirements.

In order to achieve a fundamental understanding of the machine tool evaluation requirements, a series of measurements on machine tools with multiple configurations and various machining processes were performed in industry. The measurements revealed the energetic relevant machine tool states, relevant components, their individual energetic machine tool behavior, and potential optimization measures. These findings show that synchronized multichannel measurements on machine tools are required but not present in research and industry of today.

Generally, the machine tool is seen as an assembly of components, e.g. motors, spindles and fans with different control settings and resulting energetic behavior. This behavior can be classified in three categories - constant, controlled-constant, and variable, whereas constant represents a stationary energetic behavior. Based on this classification, further analysis algorithms and a machine tool monitoring

strategy were developed. The analysis algorithms allow to indicate the individual energy efficiency of components within a machine tool system. This evaluation leads further to the indication of specific on and offline optimization measures.

In order to establish a technically and economically reasonable measurement and monitoring strategy, a methodological implementation approach was developed. The combination of data generated by measurements, through internal and external sensors in combination with simulation, represents a sensible tradeoff between costs and accuracy as well as application and simplicity of the system according to industrial requirements.

The developed findings were implemented in the ISO14955 standard as well as the SRM legislation process on the European legislation level, and serve as a basis for the ETH startup SIGMAtools LLC.

Kurzfassung

Energieeffizienz innerhalb der industriellen Fertigung erfährt durch die aufkommenden gesetzgebenden Ansätze, als auch als potentieller wirtschaftlicher Faktor, zunehmend an Relevanz. Energieeffizienz an Werkzeugmaschinen wird heute durch verschiedene Ansätze zur Messung, Analyse und Optimierung in Industrie und Forschung adressiert. Im Bereich der Forschung zeigt sich, dass die heute verfügbaren Optimierungsansätze grundsätzlich in zwei Kategorien unterteilt werden können – einem Bottom-up- und einem Top-down-Ansatz. Nur wenige Ansätze werden auch industrieseitig implementiert, wohingegen in anderen Industriezweigen, z.B. der Gebäudetechnik, Ansätze zur Energieeffizienz bereits erfolgreich umgesetzt werden. Die Anwendung von Lösungen aus dem Forschungsbereich in der Industrie, erfordert einen umfassenden und methodischen Bewertungsansatz, z.B. ein standardisiertes Messverfahren oder mehrstufige LCAs auf der Werkzeugmaschinen- und Komponentenebene, als auch einem wirtschaftlichen Anreiz. Ein weiterer Grund für den geringen Einsatz von Bewertungs- und Optimierungsverfahren in der Industrie ist dadurch gezeigt, dass regelbasierte Optimierungsansätze nur eine geringe Effektivität aufgrund und in Abhängigkeit der Variabilität von Werkzeugmaschinen, ihrer Konfiguration, dem individuellen Gebrauch sowie dem spezifischem Maschinenprozess, zeigen. Der Mangel an einfachen, universellen und effektiven Bewertungsansätzen, in Zusammenhang mit einem geringen Gesamtenergiekostenanteil und unbekanntem Optimierungspotential, führt zu einer Diskrepanz zwischen dem Forschungsresultaten und den industriellen Erfordernissen.

In der vorliegenden Arbeit wurden Untersuchungen zur umfassenden Werkzeugmaschinenbewertung auf Basis detaillierter Energie- und Ressourcenverbrauchsmessungen in der Industrie durchgeführt. Die Forschungsarbeit zeigt, dass standardisierte, methodische Ansätze auf der Werkzeugmaschinen- und Komponentenstufe heute nicht vorhanden sind. Diese gelten allerdings als Kernelement für eine effektive Optimierung der Energieeffizienz an Werkzeugmaschinen.

Die vorliegende Arbeit behandelt die Messung sowie Beurteilung des Energieverbrauchs von Werkzeugmaschinen und deren Komponenten. Fokussiert wird dabei auf methodische Ansätze auf Basis selektiver Messungen durch Mehrkanalmesstechnik, sowie dem Einsatz von Überwachungssystemen, die den industriellen Anforderungen entsprechen.

Für das grundlegende Verständnis der industriellen Anforderungen, wurden mehrere Mehrkanalmessungen auf verschiedenen Werkzeugmaschinen mit unterschiedlichen Konfigurationen und Maschinenprozessen durchgeführt. Die Ergebnisse der Untersuchungen zeigen, dass synchronisierte Mehrkanalmessungen an Werkzeugmaschinen notwendig sind. Diese sind heute, weder in der Forschung, noch in der Industrie vorhanden.

Grundsätzlich kann die Werkzeugmaschine als Verbund unterschiedlicher Komponenten, z.B. Motoren, Spindeln und Lüftern, mit unterschiedlicher Regelung und hieraus resultierenden energetischen Verhalten, verstanden werden. Dieses energetische Verhalten kann prinzipiell in drei Kategorien unterteilt werden – konstante, konstant-geregelte sowie variable Verbraucher. Auf Basis dieser Komponenteneinteilung, konnten weiterführende Analyseverfahren zur Energieeffizienzoptimierung entwickelt werden. Die Analysealgorithmen erlauben die Bewertung der individuellen Komponenteneffizienz innerhalb des Maschinenverbunds. Sie erlauben auch eine zielgerichtete Indikation auf spezifische Online- und Offlineoptimierungsmassnahmen.

Zur Entwicklung einer technisch und wirtschaftlich angemessenen Mess- und Überwachungsstrategie, wurde ein methodischer Implementierungsansatz entwickelt. Die Kombination aus Messdaten, durch interne und externe Sensoren in Kombination mit Simulationen, löst den sensitiven Zielkonflikt zwischen Investitionskosten und Messgenauigkeit, unter der Berücksichtigung einer einfachen Anwendbarkeit des Systems in der Industrie.

Die Forschungsresultate wurden in die Norm ISO 14955 sowie in das Selbstregulierungskonzept SRM auf Europäischer Gesetzebene aufgenommen und dienen als Basis für das ETH Startup-Unternehmen SIGMAtools GmbH.

.

1 Introduction

“Measurement is the first step that leads to control and eventually to improvement. If you can’t measure something, you can’t understand it. If you can’t understand it, you can’t control it. If you can’t control it, you can’t improve it.” — H. James Harrington.

The evaluation of energy and resource consumption in manufacturing is gaining increasing importance and is equally represented in research, legislation, and industry. Thus the motivation for suitable methods for the measurement, analysis, and optimization of energy efficiency affects economic considerations, legislation, and standardization and leads to further technical application requirements.

Today, more than 200’000 machine tools are installed in the Swiss metalworking industry [1]. It is further assumed that more than 3.8 million machine tools are currently installed worldwide. The industry sector, including manufacturing, is one of the biggest consumers of energy [2]. It represents with 34% of the entire energy share, one of the major consumers of energy and emitters of CO_2, according to the International Energy Agency IEA [3]. In addition, the Swiss Federal Offices of Energy (BFE) determined an overall energy demand raise of +11,5% [4] since 2001. Energy has become a major cost driver [5], whilst the relative cost for electricity, in Switzerland, remained on the same level or has even fallen [6, 7]. Nevertheless, the electric energy demand in the industrial sector raised by +22.1% between 2000 and 2011 [7]. According to Klocke et al. [8], the metal-working manufacturing accounts for 68% of the total industrial energy consumption. In response, the IEA [9] as well as the European Commission [10] and the German Electrical and Electronic Manufacturers Association ZVEI [11] estimate an energy saving and energy efficiency potential in the manufacturing sector between 13% and 29%.

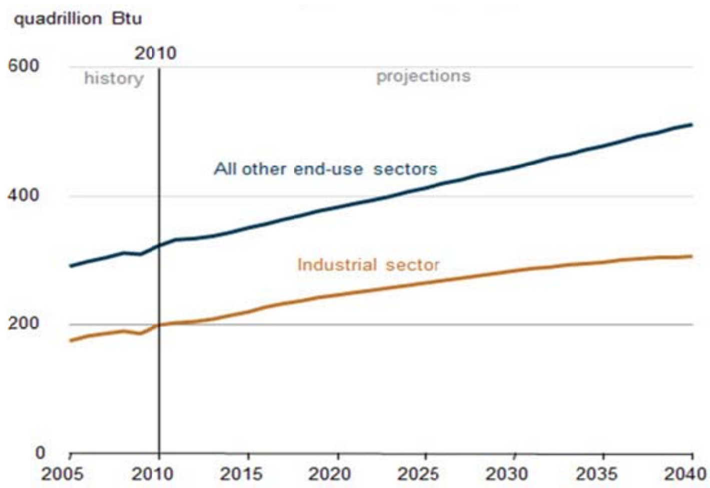


Figure 1.1: World industrial sector and all other delivered end-use energy consumption, 2005-2040 [12].

The economic importance of the manufacturing sector in relation to energy efficiency measures is also accentuated by Swiss industry turnover of 100 billion Swiss francs with an export rate of more than 85% [1]. This leads to an in-depth impact and competitive advantages on and towards the global manufacturing sector. Energy efficiency implies not only environmental and economic benefits, but is also relevant for statutory auditing. Despite the importance of energy consumption traditional goals in manufacturing such as costs, quality, time, flexibility and reliability are still dominant. A systematic approach for the quantification, effective analyses and optimization approaches of this potential on machine tools are still missing according to Schleich [13] and Dietmair et al.. Schichke et al. [14] and Zein [15] point out, that a structured consideration, assessment, analysis and implementation of energy-related improvements is not yet given. Besides the relatively small share of energy prices in comparison to other production cost, the unknown and individual energy improvement potential, and its dependency on assumptions, energy efficiency requires a higher effort than benefit. Still, it is generally recognized that the energy consumption of machine tools is gaining economic relevance according to Kuhrke [16], Denkena [17] und Abele [18]. An early relation and general insight for the relation between energy consumption and economic importance is introduced by Meadows [19], who conducted the energy dependency for economic benefit. Pilogea et al. [20], Berndt [21] confirm that the economic growth and industrial productivity is directly connected to the energy consumption and its improvement.

The European Union (EU) introduced a regulatory framework which targets at 20% emission reduction by 2020 compared to 1990 [22]. Machine tool and production systems are in the review process for the extension of the Eco-design Directive and related assessment as they are also considered as energy related products (ErP) [23]. A current alternative approach, based on the Eco-Design Directive and towards potential legislative initiatives, is currently launched by the European Association of the Machine Tools Industries (CECIMO) with the Self-Regulatory Initiative (SRI) / Self-Regulatory measure (SRM) [24]. According to the CECIMO study [25] only a minority of interviewed companies are able to quantify their energy consumption while more than 60% see this as essential. The legislative approach is accompanied with related standardization efforts (Appendix A.1). These approaches indicate potential fields of interest in upcoming legislative initiatives. The ISO14000 [26] series, in particular the ISO14001, address aspects for companies and organizations to identify and to control their environmental aspects. This also includes the assessment of energy and resource consumption. On basis of the ISO14001 standard, the ISO50001 [27], describing energy management systems and required data acquisition, is currently of particular interest for organizations and companies in Germany, as its certification can lead to tax reduction. Muller et al. [28] conduct that measurement equipment for various energy forms exist, whilst a poor linkage between Energy Measurement Systems (EMS) and Manufacturing Execution Systems (MES) is given in order to satisfy the requirements the current standard ISO EN ISO 50001 [27]. MES represent production management systems and is used for the scheduling and planning of the production. Based on the machine tool level and in line with the SRI/SRM approach, the currently established standard ISO14955 [29], deals with the evaluation of energy and resources on the shop floor level.

From a technological point-of-view upcoming solutions are related to the analysis and improvement of energy efficiency in manufacturing. The continuous monitoring of the machining process, especially in the aerospace and automotive industry is required. The automotive industry further requires detailed information on the actual cost incurred during machine tool life and the machining process for TCO and LCC calculations. To consider energy and resource efficiency on installed machine tools and production systems an increased demand on retrofit and service and maintenance solutions can be observed.

In this regard, comprehensives measurement or monitoring equipment for machine tools that foster different energy forms with additional real-time analysis tools are currently not existent in industry. Measurement and analysis on more specific levels, e.g. process unit and component level, are required in order to understand the full energy consumer behavior and to enable remaining unnoticed optimization potentials. The major challenges for the evaluation and analysis of manufacturing systems in order to model, improve and forecast energy and resource consumption are primarily given by the variety of machine production systems and processes, the selection of adequate system boundaries, multidisciplinary energy conversion factors and environmental evaluation metric, as well as the economic amortization of eco-friendly solutions. Furthermore, possible upcoming statutory requirements from the EU [23], the resulting Self- Regulatory Initiatives [25], and the fact that there are no related standards on this topic are challenging for machine tool builders as well as users for the application of adequate machine tool measurement and monitoring approaches.

2 State of the Art

2.1 Sustainability evaluation approaches in manufacturing

The following chapter describes the current state of the art for evaluation methods for energy efficiency and related sustainability. In this context the common definitions of sustainability, efficiency, and effectiveness are assessed. Furthermore, current measurement and monitoring approaches are evaluated towards their technical and economic benefit, as well as resulting challenges and requirements. This also includes the evaluation of potential sources for information, e.g. measurement or simulation approaches, and solutions for the evaluation of the machine tool system and resulting findings. The structure of this chapter is given as follows:

- Definition of Sustainability,
- Sustainable Evaluation Methods,
- Machine Tool Measurement,
- Analysis and findings and
- Simulation Approaches.

2.1.1 Definition of Sustainability

The most widely used definition for the sustainable development is provided by the United Nations' Brundtland Commission [30]: "*Sustainable development seeks to meet the needs and aspiration of the present without compromising the ability of future generations to meet their own needs*". The evaluation of Ferstel et al. [31] on the given definitions of sustainability revealed a strong dependency on the inspected matter. Teichert [32] confirms the difficulty for a proper definition and that a common definition is not given. Huber et al. [33] separates sustainability in three strategies such as efficiency, sufficiency, and consistency. Whereas sufficiency represent the amount of resources based on the abdication of goods and can therefore lead economic and social constriction and stagnation. Efficiency strategy aims to increase the resource productivity in order to perform tasks with a minimum use of resources. Consistency, on the other hand is environmental based and represents a strategy that shields against environmental effects or aims to be fully compatible with it. Based on the Agenda 21 [34] of the UN Department of Economic and Social Affairs, and the basic principles of a sustainable development, environmental, economic and social goals were combined. This model, called Triple Bottom Line (TBL), represents a triangle in which the single goals influence each other, as shown by Elkington [35].

As stated by Jayal et al. [36] research activities reveal a resource efficient and effective manufacturing and its evaluation. Duflou et al. [37] distinguish between efficiency and effectiveness where efficiency refers to the amount of resources required to produce an defined output, and effectiveness is focused on making wise choices with respect to how resources are used. ISO 9000 [38] confirms the efficiency definition as the relation between results achieved (outputs) and resources used (inputs). Efficiency can be enhanced by achieving better results with less resources or same results with less resources, which is in line to the economical principle of the maximum and minimum principle according to Pehnt [39].

The given literature research shows that a clear definition of sustainability is missing and dependent on the intended goal. The given definitions have in common that sustainability in general contains actions and measures to reduce resource use and to increase efficiency. Sustainability is therefore understood in line to the efficiency strategy definition by Huber et al. [33] and follows the ecological and economic branches of the TBL.

2.1.2 Sustainability Evaluation Methods

For the effective evaluation of sustainability various aspects and application levels can be considered including the product, the manufacturing process, the product supply chain, and the manufacturing system across multiple life-cycles, as indicated by Jayal et al. [36]. Jayal et al. further show that todays' sustainability evaluation methods can be applied on the product, process, and system level. Resources in general represent all inputs, e.g. energy or materials, to fulfill a designated manufacturing process as defined by Newman et al. [40]. As indicated by Ostrom et al. [41] the resource utilization is directly associated with the sustainability performance. According to Beltratti [42] and based on the manufacturing sector, resources can be divided in technical-economic resources, such as labor, maintenance, capital, knowledge, and natural resources. The approaches have in common that energy must be considered on all relevant application levels. For the evaluation of used or needed resources and depending on the individual assessment goal, Vijayaraghavan and Dornfeld [43] and Neugebauer et al. [44] introduced different application level. Brecher et al. [45] define resources on the machine tool level as electrical energy, compressed air, cooling media (water, recirculated air) and process gases. According to Neugebauer et al. [44] the energy relevant hierarchy in production technology consists of:

- Product definition
- Manufacturing Process
- Machine tool
- Production System
- Factory

In relation to sustainable production, Zein [46], Bellgram et al. [47], and Schieferdecker [48] define the interrelation between the elements of a production system as shown in Figure 2.1. Zein [15] further states that manufacturing systems contain the elements process, operand, and operator. Schieferdecker [48] further diversified the process system in unit process, supplementary, and auxiliary system. The unit process defines the entity where the designated value creation occurs. This statement is in line with the definition of the reference process according to the functional evaluation given by ISO14955 [29].

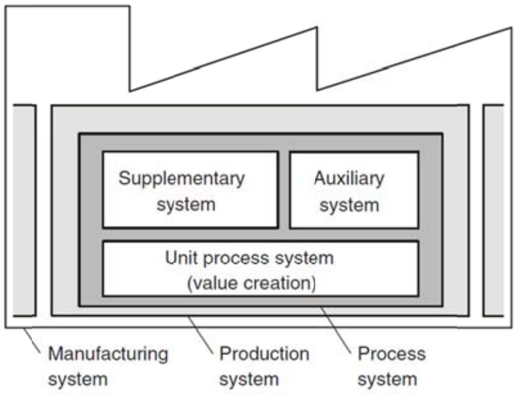


Figure 2.1: Elements for energy analysis in manufacturing, adapted from Zein [15] , Bellgran et al. [47], Schieferdecker [48].

Traditionally, levels of information density and range of decision making within an organization are classified on the strategic, tactical and operational level. Based on the operational level Duflou et al. [49], classify manufacturing activities into global supply chain, multi-factory system, facility, multi-machine system and unit process system. This classification is also adapted by the authors of Figure 2.1. According to Thiede et al. [50], environmental performance assessment in manufacturing demands for a comprehensive and system oriented approach to avoid focusing on aspects of little relevance. In order to improve the overall eco-efficiency, this requirement is extended to economic performance dimensions such as costs and productivity.

In principle, the evaluation of sustainability can be addressed by two general approaches, by a comprehensive top-down approach with an estimative, indicative and quantifying character, and an application-specific bottom-up approach as shown in Figure 2.2. Top-down approaches are mainly addressing aggregated system levels which cannot be split further into particular information, whereas bottom-up approaches address detailed assessment levels which are based on information for further aggregation, e.g. resources and energy assessment on subcomponent and process level. In the following different sustainability methods from both approaches are reviewed.

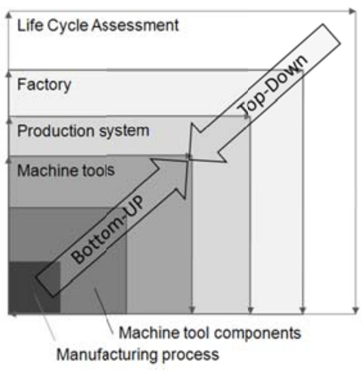


Figure 2.2: Evaluation approaches on dependent and independent application level and related system boundaries based on own classification.

2.1.3 Top down approaches for sustainable evaluation

In reference to comprehensive top-down approaches for the assessment of resources in production, Westkämper et al. [51] and Hauschild et al. [52] introduce and apply the Life Cycle Management (LCM) and Life Cycle Assessment (LCA). LCAs represent a methodology for assessing the environmental impact and resource consumption for products throughout their entire life cycle. Whereas products are defined as "*any goods or services*" by ISO 14040 and can therefore contain logistics, maintenance or any other supporting service as well. Thus, LCA encompasses all processes and environmental releases across the entire product life cycle, as confirmed by Xirouchakis [53].

Jayal et al. [54] depicts that LCAs attempt to quantify the overall environmental and economic impact, considering all resources such as materials and energy along the entire life-cycle. The authors further state that a practical application is cumbersome. Despite several attempts to simplify LCA as shown by Kaebemick et al. [55], the practical application remains difficult, is not possible due to the level of detail, or cannot replace a full LCA. Reap et al. [56] further state that even though this is the most common method for evaluating the environmental footprint, it is not suitable for economic or social aspects as it reflects a static behavior.

In line with the definition of sustainability towards efficiency, the evaluation of resource use in manufacturing is essential to determine the input-output ratio of resources as described by Hendrickson et al. [57]. It is further seen by Zein [15] as a basis in order to improve the energy and resource efficiency which is deemed as a highly cost-effective and immediate measure. Gutowski et al. [58] as well as Thiede et al. [59] introduce an output-input model for the resource assessment in manufacturing along with the quantification of material and energy flows. In industry, and in line with strategic and legal requirements, a comprehensive and general approach to assess the sustainable performance is given by sustainability reports on the enterprise or company level. Those annual reports describe the strategic orientation towards given or individual sustainability goals and the current and historical sustainability performance as shown by Kolk [60]. Chen et al. [61] evaluated different sustainability assessment tools on the factory level. Chen et al. concluded that the vast majority of given indicators can only be used for product or branch specific assessment tools. Bunse et al. [62] examined the requirements of the manufacturing industry towards sustainability and compared them to the scientific literature on the integration of energy efficiency performance in production management. Bunse et al. [62] concluded that various energy efficiency performance measures on an aggregated level are available, e.g. on the enterprise or country level to analyze the success or failure of policy initiatives, but unfortunately these performance measures are not necessarily suitable to assess the energy efficiency performance of single manufacturing processes. In addition, Bunse et al. showed that the manufacturing industry is lacking of appropriate energy efficiency metrics on the machine tool, manufacturing process and plant level.

Top-down approaches primarily depend on the variety of machine production systems and processes, the selection of adequate system boundaries, reasonable energy equivalents and environmental evaluation metrics, as well as the economic amortization of eco-friendly solutions. This variety and complexity therefore endorse the missing development and application of standards.

As mentioned by Adams et al. [63], the resulting holistic understanding of the overall system is crucial when considering multi-criteria eco-efficiency improvements. Value stream mapping (VSM), originating from the Toyota Production System (TPS), represents an approach to combine system analysis and system description in order to increase productivity in manufacturing. Erlach and Westkämper [64] introduced an adaption of VSM, incorporating energy streams. Sproedt and Plehn [65] proposed a conceptual model for discrete-event simulation also including environmentally relevant material, water, waste and emission flows. According to Sarkis [66] and Schönsleben [67] energy efficiency performance has to be considered simultaneously with other organizational performance measures such as cost, quality, time and flexibility. The resulting Energy Management System (EnMS) supports decision makers in assessing the impact and effects of energy efficiency measures. Generally EnMS are defined as a framework for managing and continually improving energy-related policies, processes and procedures of an organization [27]. Figure 2.3 shows the concept of EnMS in production as proposed by Bunse et al. [62].

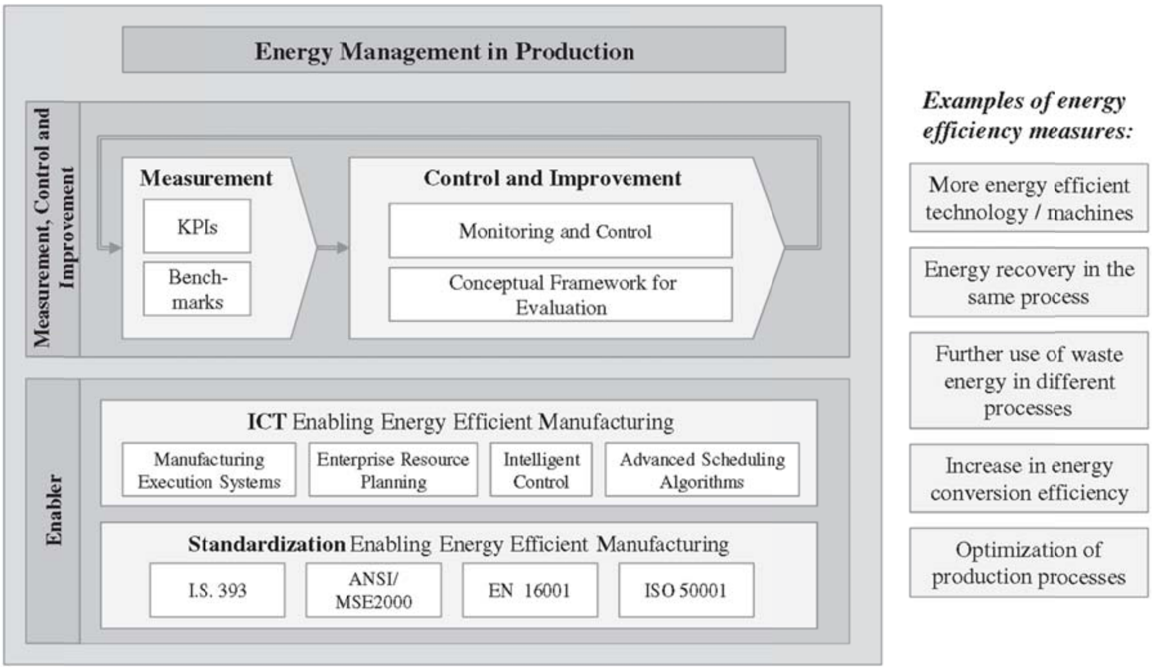


Figure 2.3: Concept of an Energy Management System (EnMS) in Production [62].

Figure 2.3 shows the relation for the energy management in manufacturing based on the measurement of Performance Measures, KPIs and Benchmarks, and supported by adequate Information and

Communication Technology Tools (ICT). This approach does not consider the data and information sources and the aggregation of the collected information.

The Global Reporting Initiative (GRI) represents one of the world's most prevalent standards for sustainability reporting based on predefined indicators. It is related to the Ecological Footprint Reporting, Environmental Social Governance (ESG) reporting, Triple Bottom Line (TBL) as well as the Corporate Social Responsibility (CSR) reporting, and extended by additional KPIs. Organizations publicly communicate their economic, environmental, and social performance based on accredited evaluation schemes. Kolk [60] showed that sustainability reports often fail to follow a certain standard. GRI seeks to make sustainability reporting comparable to the financial reporting. Hussey et al. [68] indicate in their study and comparison on different GRI reports from industry that this approach is promising even though its completeness is often not given and its structure is still undefined. Still, more than 1,500 corporate businesses, public agencies, smaller enterprises, and NGOs from more than 60 countries use GRI. Another evaluation approach on the wider organization and country level is given by the OECD indicators. The Organization for Economic Co-operation and Development (OECD) addresses with more than 46 indicators a broad spectrum of sustainable development concerns across its program of work [69].

The evaluation of sustainability in manufacturing is also addressed by standardization. ISO14040:2006b and ISO14040 [70] represents a standard procedure for the application of the LCA [71] as introduced by Finkbeiner et al. [72] and Reap et al. [56]. ISO14031:2013 [73] gives guidance on the design and use of the environmental performance evaluation. It further guides on the proper identification and selection of environmental performance indicators to be used by all organizations regardless of their type, size, location or complexity. ISO 50001 [27] provides a systematic approach to implement an EnMS for continuous improvement independent from the energy form. Assistance on how the needed information has to be procured is not given.

2.1.4 Bottom up approaches for sustainable evaluation

Bottom up approaches are used on specific applications with defined system boundaries and based on information from measurements or simulation. They are applied on the manufacturing process-, system-, and component level, and represent a specific or process-related assessment.

Brinksmeier [2], Schulz [74], Kuhrke [75], and Augenstein et al. [76] have introduced bottom up approaches in which direct process parameters, e.g. cutting force or cutting depth, are used for calculation of the related energy consumption. Schulz [74] points out that there are three major initial energy consumption fields such as chip removal, machine internal process, and machine external peripheral. Newman et al. [77] describe the Computer Aided Process Planning (CAPP) and how it helps to release energy efficient processes. Newman et al. further recommend the electrical consumption measurement of a machine tool as a low cost, highly reliable, flexible, and quick method for tool condition monitoring. Based on their findings they suggest a number of general approaches to increase the efficiency of metal cutting processes, e.g. redesigning machines and controllers, redesigning controller software and adding external devices to regulate energy use. Dahmus et al. [78] introduced a system-level environmental analysis of machining. In this work they describe an analysis together with a breakdown of energy usage for different machine tool types. An event stream processing-based framework has been introduced by Vijayaraghaven [43]. This framework identifies five different levels of manufacturing analysis scales. Each level represents its own temporal decision scale, energy consumption characteristics, and affecting parameters for further evaluation. Behrendt et al. [79] provide a test procedure to evaluate the energy consumption of production systems. The methodology is based on the JSA standard to define different sized workpieces which are relevant for the reference process. The goal of this approach is a lookup table which indicates the relation of the energy consumption of the machine tool towards the given machining parameters. Behrendt et al. [79] also emphasize that a general methodology to determine the environmental impact of machine tools is not present in research or industry. Diaz-Elsayed et al. [80] confirm this statement by their analysis of available environmental assessment tools in industry.

Lv et al. [81] developed an activity-based energy calculating methodology (ABE) which can calculate the required energy demand of a machine tool based on the given machining processes. The ABE methodology distinguishes between the energy consumption of the machine components into fixed energy and variable energy. This methodology uses the NC machining process file as the input source. The authors claim that there is no need to measure all components to evaluate the energetic machine tool behavior. The methodology neglects the dynamic machine tool behavior, e.g. spindle starts or tool changes. Hu et al. [82] developed an energy evaluation tool based on estimations and single point measurement to indicate the energy efficiency of a machine tool. The estimations are based on the combination of component measurement and information of the machine tools operating state. In this approach energy efficiency is understood as the ratio of the total input energy and the required energy for cutting. Hu et al. [82] state that measurement equipment is essential and further indicates the need of an economical use of measurement systems within industrial environments. A sensor-free energy evaluation method is presented by He et al. [83]. In their research the authors suggest a practical estimation method for evaluating the energy consumption of machine tools based on the correlation between NC codes and the energy-consuming components of machine tools. This correlation characterizes the energy consumption of components and results in the estimation of the total machine tool energy consumption. This method is independent from measurements but limited in its accuracy. Steinhilper et al. [84] developed a procedure which allows the identification of inefficient machine tools within a factory. The methodology strongly bases on expert judgment and a questionnaire applied on each machine tool. Steinhilper et al. [84] suggest a longstanding experience in the machine tool industry as fundamental for a successful application of this method.

Conclusion

Approaches for the evaluation of sustainability, and more specific the resource and energy consumption, are present in research, industry, and legislation. Furthermore, approaches can be distinguished by the intended goal, related system boundary as well as accuracy in top down and bottom up approaches. Today, the required information is based on general and aggregated data, on assumptions or is revealed by complex task specific measurements based on defined machining parameters. Relevant parameters are further dependent on the specific definition of sustainability.

Benchmarks or standardized approaches for the assessment of energy efficiency of machine tools are missing. Available performance measurement approaches as well as other evaluation approaches consider the sustainability performance on general application level in order to access the effectiveness and strategic orientation towards sustainability goals, but do not adequately assess the resource consumption of machine tools or production process in order to define individual optimization measures. Some approaches are inconsistent due to the lack of appropriate and required data. Up to now, only a few key statements and findings are consistent in cross-comparison. This is mainly the result of the degree of individuality and the fully arbitrary systems- and system-boundary definitions. The evaluation shows that top-down approaches are based on aggregated data which strongly depend on the selected evaluation method and intended goals. On the other hand bottom-up approaches represent a strong connection to the machining process, specific analysis and optimization goals. Both approaches rely on detailed information either from measurements, simulations or trusted assumptions.

The research shows that relations to the energy consumption and resulting system efficiency is not determined or standardized yet and that these further dependent on the analyzed machine system, system boundaries, machine configuration, and the operating mode. A generalized methodology for the evaluation of the environmental impact of production systems is not yet established. From industrial areas that are more advanced in energy assessment, such as building technology, it is known that knowledge of the behavior of the consumer is the key point in efficient energy management. Even though the influence of a machine tool user is limited and requires more system-dependent interventions in comparison to building technologies. Energy audits are seen as one example of a systematic and analytic approach, to monitor industrial energy consumption and to identify sources of wastage. The developed and applied analytical methods for machine tool energy consumption analysis differ in their results, are not comparable among each other and not universally applicable.

In conclusion and apart diverging approaches, detailed data is needed to conduct performance evaluation and optimization indication on machine tools and production systems. Reliable data is also required on the factory and enterprise level. For this reason further research focus is given on todays’ measurement equipment.

2.2 Machine tool measurement

As stated by Duflou et al. [85], manufacturing activities dominate the industrial energy consumption. A major focus must be therefore given on energy measurement and monitoring strategies during the use phase of production systems. Measurement represents a selective data acquisition for the description of a certain system state or temporary behavior, whereas monitoring is considered as continuous measurement. Thus, measurement is seen as an essential element of a monitoring application. The following chapter introduces various approaches for energy measurements and monitoring on production systems.

Referring to the lack of appropriate energy efficiency metrics on machine tools as indicated by Bunse et al. [62], emerging new sensor technologies and smart embedded devices, in the field of energy monitoring, enable operation-based process measurements. Furthermore this technology can provide accurate information for the production performance monitoring as stated by Karnouskos et al. [86]. Dietmair and Verl [87] indicate that a clear picture of the energy consumption of machines and production systems does not exists. Furthermore, the saving potentials are unknown or based on assumptions. Dörr et al. [88] indicate that the consumption of energy of processes is rarely known because of an insufficient existing infrastructure and missing measuring devices. The evaluation of the energy consumption and associated adequate optimization measures requires comprehensive information about the actual energy demand on the machine tool as indicated by Jaffe and Stavins [89] and Larek et al. [90]. Koopman et al. [91], as well as Schleicher [92] confirm the statement of Dietmair and Verl [87] of missing or imperfect information on the energy consumption of machine tools. Zein [15] states that the missing or deficient information is not only given by the lack of the energy or power measurements, but also by poor operating performance monitoring and missing information of actual machine tool use. Zein [15], Brecher et al. [93], and Kellens et al. [94] confirm that effective power profiles of machining processes represent an essential element in order to indicate the share of productive and non-productive times of machine tool operations. Wanke and Trenz [95] indicated that the reason for missing information is the complexity, individual design, and diverse use of machine tools, as well as the general unwillingness of machine tool builders as well as users to perform measurements. This is mainly caused by the fear of expensive and/or time-consuming measurements as stated by Stasinopoulos [96]. Schleich [92] further depicts that as long as the optimization potential and actual saving are unknown, manufacturer nor users are willing to perform measurements or implementations. As shown by Abele et al. [97], the average industrial energy cost represent 2.2% of the gross production value in the German metal processing sector. From the economic perspective the costs and effort of energy measurements with available measurement equipment of today in order to improve energy efficiency on given machine tools is not justified. Therefore, evaluation must be performed cost-effectively or combined with other benefits, e.g. macro or micro optimization or purchasing, and need to consider energy-efficiency related parameters, e.g. machine tool usage.

Brecher et al. [45] confirm that in most cases machine tools are over-dimensioned as there is commonly no information on the actual energetic needs or control-dependency of auxiliaries in relation to the actual machining process. The maximum connected load of the machine tool is known and taken as a reference for the sub-component selection, while not even the actual average consumption is not known, as depicted by Lindemann [98]. In most cases the actual power consumption of machine tools is significantly lower than the connected load as shown by Abele and Kuhrke [99, 100]. Dietmair et al. [101] confirm that the connected load does not imply the actual power consumption of the machine tool auxiliary. In accordance to the sub-component selection without energy measurements Schäfer [102] estimates a general safety margin for machine tool auxiliaries of 1.2 to 2 to ensure all possible load conditions and to guarantee the machine tool and process reliability. A general estimation proposed by Abele et al. [99] identified a square proportion of the weight of horizontal lathe to its connected load due to dynamic forces and additional cooling auxiliaries. Therefore, it can be confirmed that over-dimensioning and inefficient construction of machine tools is caused by reliability reasons and results from missing information on the actual energetic need.

The relevance to delve into the data acquisition, analysis and optimization actions is not only given by the technical efficiency but can also reveal economic benefits, as mentioned by Kuhrke [16]. According to Brecher et al. [45], only one third of manufacturers in industry disposes measures, methods, and guidelines on the strategic management level to push energy efficiency and resource saving. In most of those cases amortization periods of investments are unclear or considered as uneconomical. Therefore, it is essential that measurement and monitoring equipment justify the effort in comparison to the potential improvement. Neugebauer et al. [103] estimate the total saving potential in manufacturing up to 30%. Schischke et al. [104] and Hegener [105] assorts an indicative ranking of energy efficiency measures revealing an estimated relative improvement potential of up to 40%. Thus, different studies underline the significant potential for improving the energy and resource potential. 10% to 40% of efficiency improvement can be achieved with available technology of today if the required measure is known, as stated by Thiede et al. [106].

Before any machine tool data can be analyzed, data and related information have to be collected by measurements, simulations or assumptions. Schischke et al. [107] derive a definition of machine tools, based on engineering considerations, economic classifications, standards and legal framework in the following way:

'A machine tool is a stationary or transportable [. . .] assembly, dependent on energy input [. . .] when in operation, consisting of linked parts or components, [. . .] which are joined together for a specific application, which is the geometric shaping of workpieces made of arbitrary materials using appropriate tools and forming, cutting, physical-chemical processing or joining technologies, resulting in a product.

In line with this definition, Tönshoff [108] mentions that machine tools consist of joined parts and moving components enabling the entire system to perform a complex and useful functions. These functions are represented by geometric forming, shaping or joining workpieces with appropriate, complex and individual tools and technologies in the requested quality and quantity. Tönshoff [108] further depicts that machine tools consist generally of a machine frame, guides, drives and control unit. As confirmed and extended by Weck et al. [109] a machine tool can be considered as an assembly of electrical components, such as drives, pumps, fans, signal elements, actuators, wiring and measurement systems. The energetic behavior of the machine tool is thereby characterized by the connected components and interaction between them, the temporal accumulation, and individual power consumption for each component as stated by Zein [15].

Based on this definition it is obvious that a machine tool consumes energy, which is considered as the energy input, resulting in a product and waste energy, which is considered as the output. According to the above mentioned machine tool description an adequate system boundary has to be defined. ISO 14955-1 [29] (Figure 2.4) defines a system boundary around the entire machine tool and all required auxiliaries or share of auxiliaries to ensure a machining process and to provide an essential and immediate contribution to perform the value creation as confirmed by Zein [46]. Duflou et al. [85], Kellens et al. [110], and Kara et al. [5] introduce the Process Unit, which defines the machine tool and its subcomponent which requires all relevant resources to perform a machining process.

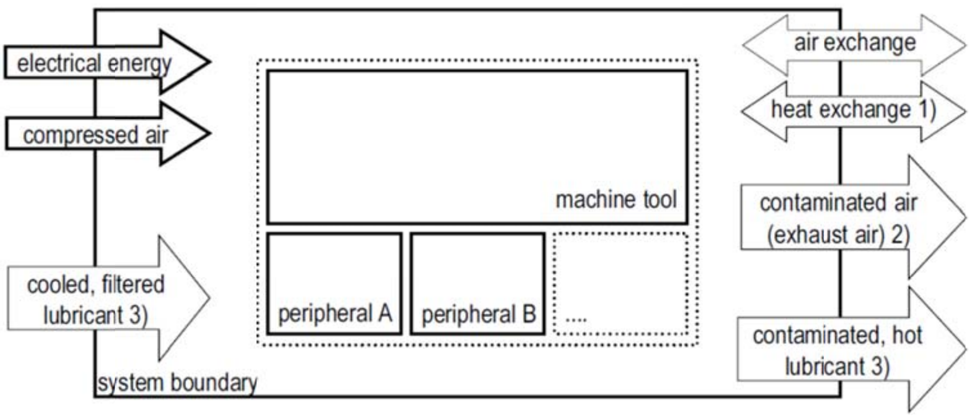


Figure 2.4: Machine tool system boundary according to ISO14955-1 representing the process unit.

Zein [46] follows a similar approach by defining the system boundary containing different entities as shown in Figure 2.5, e.g. control unit, drives, actuators and others. This approach is in line with the ISO14955 standard. The process and related machine tool states are defined independently from the system boundary.

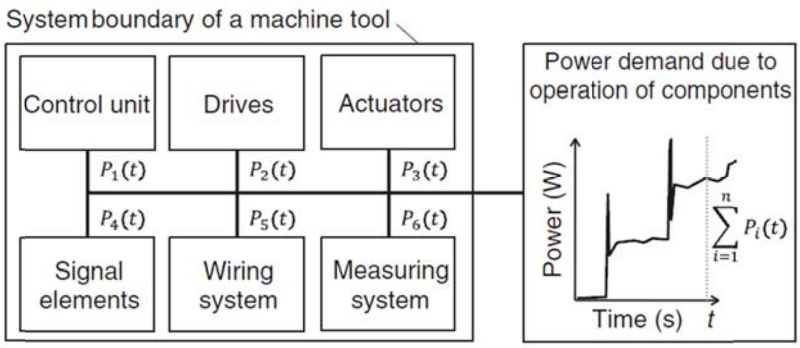


Figure 2.5: System boundary of a machine tool according to Zein et al.[15].

The applied measurement equipment and related measurement methodology have a key significance for the assessment of the environmental performance of a machine tool and are required to adopt energy improvement potential as stated by Kara et al. [5]. Measuring strategies and required level of detail depend on the actual application, relevant system boundaries, and individual goal of the assessment. The application and level-dependent measurement strategy as well as the level of detail is exemplarily shown by Vijayaraghavan et al. [43]. Kara et al. [5] defines three levels of application for measurements; factory level, department level (process division), and unit process level (machine tool and component level). Each application level comprises its own technical requirement towards metering and monitoring methodology and equipment.

In the following, a closer look is given on the manufacturing equipment, sub-components and the production system level. This level is commonly characterized by Kara et al. [5], Kellens et al. [110] and Hermann et al. [111] as the Process Unit Level. In reference to the performed LCA on machine tools, the use phase is considered as the relevant product life phases for a machine tool as indicated by Dahmus and Kellens et al. [110, 112]. LCAs depend on data input on used resources. For the chemical production several database set for the LCA input are available. The Ecoinvent Database by the Ecoinvent Centre [113] represents the most common database. However, data about the environmental impact of discrete part manufacturing processes, such as turning, grinding, or electrical discharge machining, are very rare or do not meet the required level of detail and accuracy in order to indicate optimization measures. Hence, Kellens et al. [110] developed a methodology for a systematic analysis and improvement of manufacturing Unit Process Life Cycle Inventory (UPLCI) based on the CO2PE! initiative. In this approach multiple machine tool measurements were performed, including relevant environmental conditions and a clearly defined system boundary.

Apart from the measurement point allocation and the system boundary definition, it is essential to define what needs to be measured and which energy forms are relevant. Zein [15] describes energy as a scalar quantity that exists in different forms, e.g. chemical, electrical, magnetic, mechanical or thermal energy.

For the application on machine tools and production systems, measurements should consider the final energy as defined by Pehnt [39], which is revealed through transformation processes from secondary energy and is further transformed to so-called useful energy, e.g. heat, light or mechanical energy. On the machine tool and production system level, forms of useful energy, in accordance with the guideline on energy systems VDI 4608 [114], are primarily represented by electricity and compressed air. Other media and energy forms, e.g. steam and cooling water, must be considered if they are relevant as stated in the ISO 50001 [115] and ISO 14955 [29]. The measurement of final energy is done indirectly through the measurement of the effective power. As indicated in the EuP-Report by Fraunhofer IZM [116], electrical energy has the highest relevance of environmental parameters in comparison to other energy forms. According to the sustainability report of Daimler AG [117] the electrical energy is the dominating form of energy with a share of 43% of the total energy demand. A review of three Volkswagen automotive manufacturing factories [118] revealed a share of 48% to 65% electrical energy. Those figures reflect a generic magnitude based on the total energy demand.

Further dominating energy forms within a manufacturing system are compressed air, process gases or steam as confirmed by Thiede et al. [119, 120] and Gutowski et al. [58]. While these energy forms represent the input streams, Thiede et al. [119] further identified and defined three different output or waste streams, such as waste energy, e.g. heat, gas emissions, e.g. SOx, NOx, CO_2 and material waste, e.g. chips, rejected products. Due to the heat transfer and large share of waste heat, a measurement strategy for the energy output streams is not applicable or does not justify the needed effort. Furthermore, the entire input energy is considered as consumed. Duflou et al. [85] and Kara et al. [5] confirm that electrical energy represent the most important resource in industry and manufacturing as it can be easily converted into many lower energy forms such as heat, light, compressed air, and mechanical torque. Szargut et al. and Gutowski et al. [121, 122] point out the high exergy value in electrical energy if the generation and transmission is neglected.

Kara et al. [5] states that the consumption of electrical energy can be easily measured with high precision in comparison to other energy forms, e.g. compressed air or cooling media flow. This also reflects the fact, that today’s commercially available measurement equipment is focusing on the quantification of effective power and electrical energy, and enables fast and clear measurement in research and industry. The power and resulting energy consumption of machine tools and components are predominantly measured by direct or clamp-on multimeters as described by Kordonowy [123]. O’Driscoll and O’Donnell [124] state that industrial power meters typically consist of the three elements; a voltage sensor, a current sensor and a microprocessor. Furthermore, different sensor settings and architectures are possible and dependent on the intended application and measurement goal.

Multimeters are often used in industrial settings for selective measurements. Effective power measurement equipment is well developed but implicates considerable instrumentation effort for multichannel measurements for 3-phases alternating current (AC). Due to the used power generator voltage and current can deviate significantly from a sinusoidal shape, for instance though harmonics and distortions. Therefore, the relevant measuring output is not necessary limited to instant or average real power but may include information about the phase angle, e.g. $cos\,\varphi$ or the waveform. Clamp-on multimeter require tapping of voltage for each phase separately. Especially if multiple machine tool components are measured the procedure can be complex as confirmed by Brecher et al. [125]. A wattmeter simplifies the measurement process by calculating the effective power in one step. For this reason mainly wattmeters and power analyzers are used in industry and research.

Brecher et al. [93] combined power analyzers to cover power measurements of various machine tool components in parallel. Up to 6 channels can be measured in parallel as introduced by Brecher et al. [45]. Furthermore, the authors combined different flow and pressure sensors to analyze the subcomponents of the system. This approach is based on a research project and leads to an expensive, complex and machine-dependent measurement architecture layout for research purposes. A significant cost driver are the appropriate sensors for various energy forms. O'Driscoll and O'Donnell [124] point out that the most important criteria for the proper measurement sensor evaluation are: Sampling rate, accuracy, and resolution. Especially the output resolution is a dominant cost driver as indicated by Kara et al. [5]. To enable and assist an industrial application, O'Driscoll and O'Donnell [124] further segregate power meter in the following clusters: The level of application, sampling rate and accuracy, communication methods and regulatory compliance. Energy related information can also be obtained from a machine tool control, e.g. via control-internal parameter readout, or Programmable Logic Control (PLC) as shown by Siemens [126]. Brecher et al. [45] use internal measurement systems for data acquisition in order to measure the machine tool efficiency. However, it is not specified which information and information interfaces are used and limited to specific machine tool components. Moreover internal sensor and control information, e.g. the spindle torque or direct effective power measurement, indicates and provides data on the energy consumption of a machine tool or production system. Still this information is hardly used in todays' industrial environment. Today, the functionality of internal sensor readout is predominately used for machine tool monitoring for compensation or accuracy analysis within research as shown by Byrne et al. [127].

Power and energy measurement equipment of today is capable to measure multiple different parameters, e.g. total (I_{tot}) and phase current ($I_{L1}, I_{L2,} I_{L3}$), effective power (P_{eff}), idle power (P_{stby}) among others. Most measurements in manufacturing are focused on measuring effective power (P_{eff}). An overview of different measurement techniques is given by Weiss [128]. O'Driscoll et al. [129] assessed and classified different metering systems for the effective power measurement. Their proposed system architecture is designed for monitoring purposes of electrical consumers within a manufacturing environment. Other energy flows, e.g. compressed air or process gases, are not considered. Behrendt et al. [130] and Avram et al. [131] use conventional single channel 3-phase metering systems in their electric measurement activities. Beside the measurement equipment and measurement architecture the sampling rate leads to a trade-off between needed accuracy and sensor costs. Behrendt et al. [130] has performed measurements with an output frequency f of $1\ Hz$ with and a pre-sampling of $12.5\ kHz$. According to Kuhrke [132] this sampling rate is not sufficient to assess fast dynamics, e.g. spindle startups or fast axis movement, on a machine tool. This statement is confirmed by Avram [133] in order to perform analysis of the tool condition and energy consumption. Vijayaraghavana and Dornfeld [134] showed a range of needed resolution and temporal decision scale between milliseconds and days, depending on the application level and related optimal resolution rate.

The majority of commercially available measurement equipment and services are tailored to buildings, facilities, and energy networks as indicated by Bornholdt et al. [135]. Consequently, the majority of the measuring systems are designed for this application and single point measurements. The core element of this measurement equipment is represented by the power sensors which are based on the hall-effect principle. Hall-effect sensors, can be used without the interruption of the circuit as pointed out by Avram [133]. Energy meters and analyzers for 1- and 3-phase for a single channel are available from various manufacturers, e.g. Fluke [136], Chauvin Arnoux [137] or Siemens [138]. The field of multichannel or synchronized sensor architecture is application-specific. Multichannel measurement systems for machine tools are commercially available from Bosch Rexroth [139], Komet Brinkhaus [140], and Siemens [141]. Those measurement applications are mostly related to building technologies or address research applications. They are partially used in the overall production system analysis or represent devices to enable synchronized analog data capturing.

Besides electrical energy also other resources and flows must be measured. Weiss [128] merges all energy forms besides electrical energy to "*non-electrical energy distribution*". The electricity used by air compression systems amounts to 7.5% of energy consumption in 2004 in the EU-15 states as indicated by Radgen and Blaustein [142]. Curtner et al. [143] estimate that 3% to 9% of total energy consumed is encountered for air compression in manufacturing. Compressed air is widely used for operations such as actuating, cleaning, cooling, drying parts, removing metal chips. As it is also mostly generated apart of the machine tool, its consumption is underestimated as indicated by Sweeney [144]. In most cases it is used as sealing air to prevent entering chips into the linear drive and guiding, as developed by Klabunde [145]. Compressed air is evaluated, measured, and optimized by compressed air audits as indicated by Yuan et al. [146] and Saidur et al. [147]. The energy efficiency on compressed air systems is also addressed by the improvement and measurement campaign "*Druckluft effizient*" as introduced by Radgen and Blaustein [142]. Those evaluation and optimization approaches are not intended to provide a direct comparison and calculation with electrical or other energy forms within a machine tool system boundary. Zein [15], Avram [133] and Brecher et al. [45] do not consider or cumulated compressed air with other energy forms, e.g. electrical power, in their machine tool evaluation as well, whereas Kellens et al. [148] consider compressed air. Still, Kellens et al. [148] consider compressed air as an own entity without a direct comparison or conversion with and into electrical power. Their consumable study is done in parallel with time and power study and considers materials, semi-products and operating supplies like compressed air or lubricants per operating state and unit process. Additionally, in the emission study, which takes place also in parallel, all relevant aerosol, particle, and gas emissions are examined. Hermann and Thiede [149] indicate the necessity for compressed air assessment but refer to technical documentations or rudimental measurements. It can be therefore seen, that resources on machine tools are evaluated by different approach, however, a combined evaluation of compressed air and electricity is not applied in research or industry. An overview on possible measurement principles and measurement equipment for compressed air can be taken from Radgen [150]. Saidur et al. [147] further point out 14 most important datasets for compressed air energy audits, including mass flow rate, temperature and pressure.

Besides selective measurements, energy monitoring applications are becoming increasingly important. Monitoring is commonly defined as continuous data acquisition for the purpose of supervising activities to ensure performance targets. Salonitis and Ball [151] point out that traditionally the performance of a production system is assessed by the monitoring of costs, time, quality, and throughput rate, without the consideration of energy consumption. In most cases monitoring systems on machine tools represent a sensor network and are mainly used for the surveillance of the machining process and tool condition monitoring, e.g. tool breakage, TCP position, vibration, and thermal state, as shown by Tönshoff et al. [152], Byrne et al. [127], Kim et al. [153] and Hu et al. [82] point out that TCM application can also be done by cost effective indirect methods, e.g. usage of power measurement systems. Vijayaraghavan and Dornfeld [43] introduced an energy machine tool monitoring approach based on event stream processing using the standard interface MTconnect. A similar approach is given by the Profienergy working group [154] with the limiting factor that only devices can be monitored and controlled that are equipped with a standard data bus, e.g. MTconnect, Profibus, Profinet, AutomationML or OPC. Behrendt et al. [155] introduced a monitoring approach based on a three-step methodology and aggregated system level. O´Driscoll et al. [156] introduced a metering approach on an aggregated level. This can be used to calculate values for the manufacturing performance and KPI evaluation. However information on component level cannot be revealed or require additional sensors.

Hu et al. [157] introduce an online monitoring approach that is based on an energy consumption model of the machine tool. The advantages of this approach, e.g. cost savings and low implementation effort, are accompanied by certain disadvantages, e.g. accuracy in the revealed consumption data and poor interoperability with other machine tool systems. Due to accuracy and reliability reasons, as well as reliable monitoring features, screened data cables within manufacturing environments are required. Electromagnetic Compatibility (EMC) interferences in the measurement can occur, particularly in industrial environments and larger sensor networks, as shown by Singh et al. and Timperley [158, 159]. The communication network has to be secured against noise, electromagnetic interferences, mechanical stress and chemical corrosion. Data security within the organization must also be insured. Today, commercially available machine tool manufacturer-dependent and independent sensor and communication elements for the machine tool monitoring are given. The user interface CELOS from DMG

Mori contains elements for the machine tool energy monitoring [160]. Energy information is represented on an aggregated level with electrical energy and compressed air with integrated analysis features. The manufacturer-independent solution smartPN-Units by Harting [161] represents a sensor network and analysis feature for production system energy monitoring. This system leaves it up to the user where sensors must be implemented and what has to be analyzed.

Conclusion

Different hard and software approaches for the energy measurement and monitoring are given in research and industry for various energy forms. While the main resources are seen in electrical energy and compressed air, available measurement approaches neglect a combined and time-synchronized assessment of various energy streams based on one energy equivalent. Furthermore, the application of selective measurements based on single energy flow is common. Although machine tools represent an assembly of different components, combined multichannel measurements are rarely applied, but are technically reasonable for a comprehensive machine tool analysis and improvement. The literature research further reveals a tradeoff between the needed accuracy and costs for hardware and implementation. This also results in the poor application of measurement and evaluation procedures.

A universally applicable method of capturing and interpreting the resource and energy consumption on various machine tools, machine tool configurations and manufacturing processes, is not yet available. Furthermore, the available evaluation approaches are based on complex and expensive measurement architectures. It is also seen that the diversity and complexity of machine tools make it difficult to propose a reasonable method. It can be revealed that multichannel measurements of electrical, pneumatic, and thermal energy, can indicate the energetic significance of each component and lead to the indication of optimization measures, for instance by retrofit solutions. An evaluation of the energy consumption and energy efficiency of different process technologies, machine tool configurations and given components can hardly be achieved by applying only a single point measurement. Commercially available interfaces and solutions for the energy monitoring are given. Still solutions from machine tool manufacturers only represent aggregated energy data, or solutions which leave it open to the users where and how these solutions are applied and further how the revealed data needs to be analyzed.

A defined and individual potential assessment can only base on adequate measurement equipment. It is obvious that detailed measurement information can be up scaled on high application level, e.g. production line, factory or KPI calculation, whereas aggregated information can be easily obtained, e.g. billing information from the energy provider, but cannot be assigned to the machine tool or subcomponent level. Up to now comprehensive measurement equipment is missing. For the visualization and analysis of fast dynamics on machine tool systems, e.g. spindle start up or tool change, no unified resolution or sampling rates are defined but represent a strong cost driver for sensor equipment. For this reason commercially available measurement equipment of today is only used for individual and non-standardized measurements and analysis in research and industry.

Apart from the application level, sensors choice, related physical principle, sensor accuracy and resolution, it is important to provide adequate solutions for the data acquisition and analysis, e.g. software. Chapter 2.3 reviews some approaches towards the analysis of revealed machine tool energy and resource consumption data.

2.3 Analysis and findings

This chapter addresses analysis and findings from machine tool evaluation and measurements from literature and shows findings on how data is used to indicate optimizations, help to evaluate the machine tool, or indicate a value add information.

Energy and power consumption data is commonly represented by time-based profiles (P-t-diagrams), tables or pie charts. Depending on the applied system level and used measurement equipment, different resolutions are possible as indicated by Vijayaraghavan and Dornfeld [43]. Which makes it possible to evaluate and analyze the energetic behavior of production systems and machine tools, e.g. with peak load, constant and variable load, and the alternation of component power depending on the component state. In combination with the P-t-diagram, Brecher and Weck [162] introduce a power log chart on the machine component level. This evaluation visualizes synchronously the energetic behavior and consumption of the machine tool components during machine operations. Brecher et al. [45] and Draganescu et al. [163] synchronize these diagrams with machining parameters.

Brecher et al. [125] confirm that the visualization of energy consumption leads to awareness and could also lead to energy saving and is therefore of particular importance. A common method for energy and resource visualization is the Sankey diagram as shown by Augste et al. [164]. Sankey diagrams allow the visualization and indication of energy flows in complex systems, e.g. machine tools or production systems. The actual energy need towards the resulting output is visualized. Neugebauer et al.[165] show that this method makes the visualization of connections between system components on various levels of detail possible. Moreover, other extensive properties like materials or costs can be illustrated by Sankey diagrams according to their amount and distribution within a system, as described by Neugebauer et al. [166], Hu et al. [82], and Dietmair and Verl [87]. Today, multiple software tools for the Sankey visualization are commercially available as presented by Wohlgemüth [167]. Neugebauer et al. [165] introduce the 3D-Sankey diagram for the examination of energy flows within a machine tool. The diagram is combined with the virtual reality (VR) sketch of the related machine tool, in which the diameter of branches flow represents the average energy and the color the currently active flow. Thereby the evaluation of time characteristics of the system and the representation of the location of the energy flow is possible. Hence, the proposed 3D-Sankey diagram represents additional and dynamic information in comparison to energy flows of conventional Sankey diagrams, which are introduced by Dietmair and Verl [87].

A visualization and analysis tool on the factory level is represented by the Environmental Value Stream Map (EVSM). EVSM, as proposed by Sproedt and Plehn [168] is an adaption of Value Stream Mapping for energy and resource-related data in combination with other production-related information, e.g. cycle times, setup times, scrap rates, and lot sizes. In contrast to traditional value stream mapping, EVSM is enhanced by environmentally relevant input and output flows such as energy, materials, water, waste, and emissions and can be used to evaluate the economic performance of a factory and related machining processes. An analysis approach on the machine tool and production line level is presented by Linnhoff and Hindmarsh [169] with the pinch design method which indicates the most efficient plant layout with the highest degree of energy recovery possible. This method is based on the analysis of the thermal input and output streams within the production site. It is designed for the optimal plant layout in the chemical industry.

Based on power over time studies Kordonowy [123] (Figure 2.6), Dahmus and Gutowski [78], Gutowski et al. [58, 170] and Li et al. [171] distinguish in their analysis of machine tool power consumption between constant and variable power consumers among machine tool components.

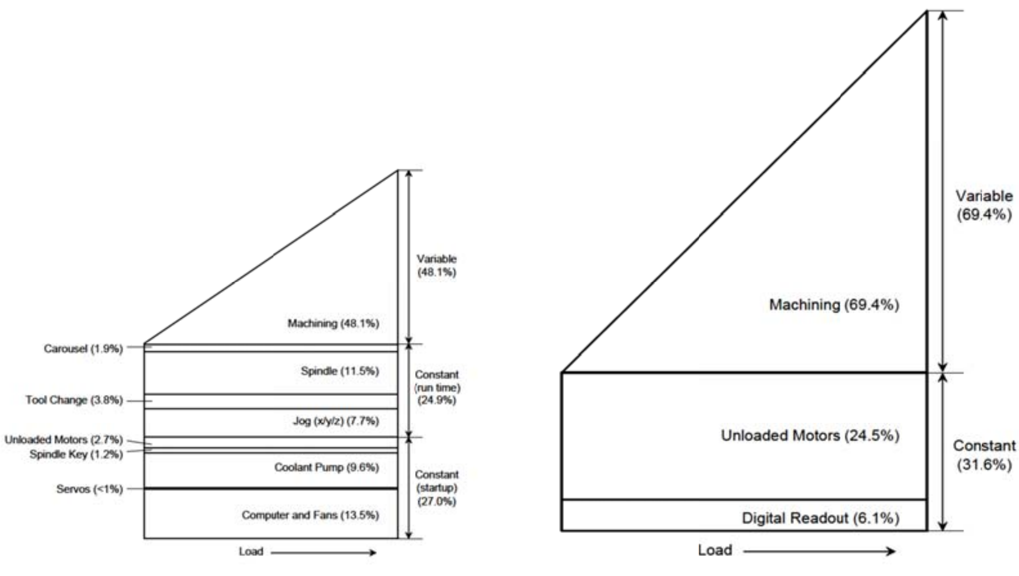


Figure 2.6: Typical constant and variable power consumption diagrams by Dahmus and Gutowski [78] and Kordonowy [123].

Gutowski et al. [58] demonstrated that the energy demand can vary significantly depending on the individual machining process. The consumption and emission profile of single machining processes and related components can be cumulated. Those load profiles are relevant to consider different analysis parameters, e.g. costs, peak surcharges, component dimensioning, and control of the auxiliary equipment.

Schulz [74] and Dietmair [87] found out that the major share of energy consumption of a machine tool is load-independent and used by peripheral equipment. This load is further frequently independent from the given machining process. These findings are also confirmed by Neugebauer [166] and Akbari et al. [172], who point out that up to 78% of the total energy consumption of a machine tool is a process-independent base load. Therefore, a classification into value-adding energy share, e.g. direct process-dependent spindle movement and non-direct-value-adding energy share, e.g. chip conveyor motor, appears to be reasonable. Furthermore, it shows that energy and power consumption-related control applications are generally not implemented. To these findings, contradictory statements are given by Rothenbücher [23] and Diaz [173] where the major energy share of the machine tool is represented either by the process cooling system or the drives. Dahmus and Gutowski [78] present an environmental analysis of machining processes by balancing the material removal process, material, and cutting fluid preparation. It shows that the required energy for the actual cutting can be small compared to the total energy required by the machine tool for material removal.

Besides this variety of different physical evaluation and optimization approaches within various system boundaries, several economic approaches can be pointed out to evaluate a production system in relation to the energy and resource consumption. An approach that refers to a simultaneous view of economic and ecologic objectives within a manufacturing system is represented by Franke [174] with the Operating Environment Information System (BUIS). In line with Franke [174], Bruns et al. [175], applies simulation of the energy- and resource consumption of a manufacturing system and computes the resulting energy costs. Reich-Weiser [176] established a metric that is based on economic and environmental basis for decision making for efficiency optimization measures. Nevertheless, this methodology neglects process-dependent metrics. Energy efficiency measures, e.g. retrofitting or procurement of new machine tools, cost related analyses such as TCO or LCC are becoming increasingly important as stated by Denkena et al. [177] and Harizopoulos et al. [178]. According to Kuhrke [16] and Kircher [179] the economic relevant phases are represented by the procurement phase, use phase, and post use or recycling phase of the machine tool. Most cost-related analysis approaches, such as TCO, LCC, and ROI are applied on the procurement and use phase. The authors confirm that despite the focus on the procurement and use phase, energy efficiency measures are hardly applied and rely on inconsistent information from the manufactures. This confirms therefore the requirement for reliable information and measurement data.

Conclusion

A method for the visualization and interpretation of the energy consumption of various machine tools is not yet available. The diversity and complexity of machine tools makes it difficult to propose a reasonable and universal method. Available methods are application-specific and not usable for comprehensive optimization comparison. Even though certain offline and online analysis and visualization tools are available, a direct indication for optimization still requires an expert or the combination of different information. Further analysis indication, e.g. Sankey diagrams, pie charts, EVSM and Pitch Analysis help to understand the energetic flows and can be used for further analysis. All available methods require reliable information on different energy forms. A structured energy data analysis and visualization method in combination with the indication on individual energy optimization, e.g. component over dimensioning, is not yet available. Today, a general and universal approach for data visualization and analysis is represented by time-based profiles, e.g. P-t-diagrams. This profiles leave it open to the user how to proceed further. The application of the mentioned methods requires a physical machine tool system. For this reason a research on given simulation approaches for the energy evaluation is introduced in the following section.

2.4 Simulation approaches for energy evaluation

The following chapter addresses simulation approaches for the energy evaluation of machine tools and its components. Furthermore, the current fulfillment of industrial requirements and practical application are considered. A major requirement for the energy evaluation and measurements is the accuracy of the results. This requirement is also valid for simulation approaches. Simulation in relation to energy efficiency is seen essential in order to indicate, optimize, or forecast the energetic behavior of machine tool without given sensors or physical machine tool systems, for instance in an early development stage. For this reason existing works on energy modeling are evaluated.

A model is a description of effects and dynamics, e.g. energetic behavior, without the need of physical entities. Based on this description and in relation to energy evaluation and optimization of machine tools, reasonably simplified simulation approaches are required to be used for monitoring and analysis. Due to the large variety of models it is advisable to classify model and simulation approaches. Domschke and Scholl [180] classify models in their intended application in descriptive, causal, forecast, optimization and simulative models. In relation to the given model input models can be further classified in black box, grey box or white box models as defined by Kroll [181]. Black box models represent a defined output based on defined inputs, whereas grey box and white box models combine the partial theoretical structure with data, e.g. additional measurements or signals. Models can be further classified in static or dynamic, deterministic or stochastic, continuous or discrete. Bi and Wang [182] classify methodologies of energy simulation into three types; energy modeling for material removal, energy modeling for machine tools, and integrated energy modeling for machining processes. In order to use simulations for the component behavior simulation and further analysis purpose, main focus is given on discrete-event simulations and the modeling of machine tools and machining process.

The application of models for the monitoring purpose strongly depends on accuracy requirements. Therefore, not only energy or power consumption measurements are used for data acquisition, as shown by Brecher et al. [93] and Nelles et al. [76] for various components of a machine tool, but also simulations, as shown by Dietmair and Verl [87] or Eisele et al. [183]. As confirmed by Thiede et al. [119], modelling of energy consumption of manufacturing processes can provide an indication for optimization and better understanding of where and how efficient energy is used within the system. As stated by Hermann et al. [184] energy consumption of machine tools is nontrivial to estimate or predict, because several dependencies on the system, e.g. thermal condition, and its environment, e.g. multiple energy supplies, need to be considered. The power demand of machine tools is commonly variant and dynamic due to specific operational modes, process settings, machine use, and the component configuration. This can impede the application of models as confirmed by Schultz [185] and Hermann et al. [186]. In line with the above mentioned system boundaries, Shao et al. [187] defines a system boundary based on the machining system as a whole, including activities such as tool preparation, material handling, material removal, tool changing, cooling, cleaning and the chip conveyor in his simulation approach.
Verl et al. [188] focus on direct machine tool control mechanisms through simulation of components. The authors introduce a generic component of a machine tool with defined inputs and outputs based on a modular approach. Due to the expected inaccuracy of the resulting data, this approach is considered as an estimation tool rather than a monitoring application. An approach of a process chain simulation that is supposed to enable production system design and control regarding economic and ecological variables is given by Herrmann and Thiede [149]. This approach does not aim to reflect the behavior of a single technical system by analyzing the physical detail, but considers the coherent manufacturing process on the factory level and results in aggregated in and output data. A model based energy monitoring approach on the machine tool level is introduced by Hu et al. [82]. This approach mainly focuses on cost saving through indirect data capturing methods without using external sensors and is based on empirical data and estimations. Furthermore, this approach is only covering the main drives and strongly depends on cutting parameters which have to be revealed through extensive cutting experiments. Commercially available manufacturing system simulation software such as Plant Simulation by Siemens [189] and Quest by Delmia [190] do not cover energy- and resource consumption so far but are currently developing related solutions. Shao et al. [187] confirm that up to now there is not much demand for simulation technology to deal with sustainability or energy consumption features, so that software vendors and analysts have not addressed these issues yet. Despite the missing need the given approaches only address the entire production layout and not machine tools or its components.

Götze [191] describes a general descriptive model for technical processes focusing on material and energy flows on the basis of an Input-Throughput-Output-Modeling. In his approach Götze [191] presents the combination of experimental and simulated data resulting in an energetically-environmental accounting model. In the context of Computer Aided Process Planning (CAPP), Newman [40] applies a mathematical model that takes into account materials, environmental data, and environmental impact of the materials based on existing commercial database tools to compute an environmental score for each tooling operation. Based on LCC, the International Electro-technical Commission (IEC) [192] developed an extensive LCC model that can be used for all electric and electronic products. Dietmair and Verl [87] point out the optimal combination of process parameters for doing a particular cutting job can be solved by a mathematical optimization formula. Their mathematical model for the machine tool's energy consumption as a function of its working parameters underlies this approach and essentially influences the machining results. Due to the process complexity and related parameterization the approach is limited to certain machining processes and not generally applicable.

Whereas most authors focus on the electrical energy, Santo et al. [193] focus on the modeling of the machining process including needed cutting fluids. Based on the machining process, a well-known process model for geometrically defined cutting edges is described by Kienzle and Victor [194]. This model describes the relation between the actual cutting, feed forces, and passive forces on the axes which are dependent on the cutting profile. The system boundary is defined as the immediate zone around the cutting tool. This approach allows the computation of the mechanical power which is required for the cutting process. By extending the system boundary by the main drive, the energy flow from electrical to mechanical power at the cutting edge can be revealed. Draganescu et al. [163] describe a statistical approach for the modelling of the process and the drive subsystem. The authors identified the coefficients of a second order approach for the description of the electrical to mechanical power transformation efficiency, depending on process parameters and based on the Response Surface Methodology (RSM) in combination with empirical data taken from experiments. This approach requires a physical machine tool and a large set of measurements, but it is capable to describe non-linear effects over a wide range of process parameters variance to calculate the electric energy consumption. This approach provides further an appropriate mathematical model of a machine tool based on few parameter sets.

The required energy for a machine tool consists of the energy for machining processes, e.g. forces at the TCP in milling processes, together with the required energy for the auxiliaries. Thus, considerations must include the overall energy which is required to fulfill a certain machining process with a defined quality, reproducibility and output quantity. Therefore, auxiliaries must be included in the overall evaluation as indicated by Avram et al. [195]. Li and Kara [196] introduced an empirical approach including the auxiliary devices by a simplified model to predict the total energy consumption of a lathe. A combination of statistical and physical modelling is shown by Avram [133]. This approach combines measured data with physical models in a modular machine tool model. The author provides a statistical measurement database for certain machining processes. Based on different weighting factors, the author provides a selection of the optimal machining process parameters with respect to economy, technology, and ecology.

A second database includes the components and the system topology. The two databases are combined with defined relations from the component model, its parameters and the related measurement database.

A similar approach is introduced by Eisele et al. [183] and is based on physical models of the components followed by measurements to identify the system parameters. The authors use this model for the system optimization in order to increase the energy efficiency of the machining process. By changing the component parameters and characteristic, based on the performed measurements and simulated interrelations, the overall efficiency can be optimized. This has been done on the example of a lubricant system containing a motor, a pump, valves and pipes in an early machine tool development phase as shown by Eisele et al. [183]. Nevertheless, both approaches require measurements from an existing machine tool or production system and are specifically designed of the given machine tool configuration and machining process, or limited to one consumer. Sheng et al. [197] introduce a methodology using an environmental-based process model for the calculation of energy use and wastes together with other process parameters. As an extension of previous methods based on the machine tool subsystems, Narita et al. [198] developed a simulation approach to find the environmentally optimized parameter sets for dry, minimal quantity lubricant (MQL) and wet machining processes, based on the electrical power consumption, cutting tool status, coolant quantity, lubricant oil, metal chips, and other factors. An energy model focusing on the machine tool and machining process optimization is represented by Bi et al. [199]. Roman and Bras [200] use an empirical database and modeling approach for the setup optimization. Rajemi et al. [201] focus with their optimization model on the tool life in relation to the energy consumption.

Conclusion

The literature review showed that models focusing on the energetic behavior on the machining process, the machine tool auxiliaries, and the entire production systems are represented by multiple concepts in research. It further reveals that models and simulations for energy efficiency are highly various and based on their intended goal and application. Furthermore, this review shows that modelling and simulations are used in the context of energy efficiency and are applied for evaluation, prediction and optimization. The available concepts and techniques differ in the applied system boundaries, their underlying calculation methods, accuracy, detail and their individual purpose. For evaluation and optimization on machine tools it is commonly accepted that the system boundary of machine tools is covering the subsystems including all auxiliaries needed to perform a manufacturing task. There exist various types of machine tool models. Physical, statistical and black-box models are used for process and machinery simulation. These models focus on the machining process and the machinery performing the corresponding axis movements. The review also reveals that modular approaches are useful and necessary.

As confirmed by Shao et al. [187] a defined industrial need for energy simulation cannot be recognized yet. Therefore, most modelling approaches are represented in research rather than in industry. The most relevant modeling purpose is the prediction of the environmental impact depending on different parameters. Due to their complexity, frequently cumbersome parametrization, and parameter-dependent accuracy, simulations are generally not used for the substitution of sensors in order to collect data. The revealed models are either specifically defined for a certain machine tool type or for ad hoc application. Process models, describing the needed energy for a certain machining process based on the relevant forces and velocities with the interconnection to higher evaluation approaches, e.g. LCA, always require a measurement database for its development and setup. Some approaches discuss possibilities to replace sensors entirely, as shown by Hu et al. [82]. Those approaches are designed to describe the machining process, but neglect the machine tool auxiliaries. Therefore, depending on the accuracy and robustness of the model, applications for sensor replacement have to be proven.

2.5 Research gaps and need for action

From the existing literature, it is obvious that a lot of research on the analysis, assessment, and optimization for energy and resource efficiency in manufacturing has been done. The indication of limited resources, related to the limited ability of the environment to absorb material streams without being harmed, was already mentioned in 1972 by Meadows [202]. Energy and resource efficiency in general is still up to date and is also important for the economic benefit in order to produce "*more with less*" and to ensure the productivity, efficiency and resulting competitiveness of European production sites. The literature review examined related procedures and methods, e.g. approaches for the evaluation, monitoring, measurement and optimization of energy efficiency; as well as simulation concepts to foster energy efficiency on machine tools and production systems.

The power consumption and energetic behavior of machine tools and production systems are known in principle. Still, optimization potentials are present and improvements can be made on the right selection and dimensioning of machine tool components, adjusting the machine tool configuration towards the actual need, minimize the power consumption of auxiliary in non-value adding machine tool modes and machining times. Due to unknown economic potentials and missing tools for improvement those improvements are hardly implemented in industry of today.

The review of the sustainability evaluation methods revealed that despite the fact that the given approaches proofed their feasibility and credibility, machine tool builders as well as users are still hesitating to apply those concepts in industry. Besides unclear economic relevance this is mainly caused by the current legislation which is not clearly derived. Furthermore, it is revealed that most concepts are not suitable, because of their individual system boundary determination, to be adapted due to the large variety of machine tools and production systems. This is especially the case for top down approaches. Available bottom up approaches however are process and application specific, neglect auxiliaries and are dependent on adequate measurement data. For this reason accurate data of the overall machine tool and production system, including all relevant components and energy forms, is required to consider comprehensive bottom up analysis approaches for enabling the given assessment and evaluation concepts.

The review of machine tool measurement and simulation shows that in general two possible ways of collecting information for data analysis can be distinguished. One can either measure quantities on physical systems or build a more or less complex model and use simulations to collect the required data. Depending on the use case, it might be also appropriate to combine both methods. With the review on the analysis and current findings it is shown that the combination of an appropriate measurement and monitoring application, with selective simulations including technical and economic analysis, is not given yet. This combination is required to close the gap between technical efficiency and appropriate investment. This is further required to achieve the goals of improved energy efficiency and related economic benefit.

The review of current analysis procedures shows that technical approaches for the modeling of resource consumption on different system levels with their limitations and specific focuses are already present in science. Nevertheless, a guideline for the evaluation, analysis, optimization, and reduction of the overall energy- and resource consumption cannot yet be derived from these approaches. Furthermore, and also as a result of missing standards and legislation, the manufacturing management of today relies on unclear databases or rudimental data information. Measurement and monitoring applications represent therefore essential industrial requirements to assess the entire power consumption of a machine tool or production system.

The review further reveals that there is a gap between the machine tool process and component level, e.g. process-dependent initial energy usage of a machine system component, and reasonable manufacturing performance indicators for the strategic management. This is needed to analyze, define, and optimize energy consumption and to foster energy consumption saving applications, e.g. through EnMS. In addition, these optimizations also refer to several unvalued technical process-independent factors, e.g. output rate or machining modes and usage. The strategic management, represented by operating data logging, production dashboards and other monitoring entities must therefore be extended by an expedient input for the initial energy and resource location. For this reason a comprehensive machine tool measurement and monitoring methodology has to be found to fulfill the information gaps in research and industry.

With all the needs shown above four main research objectives in this thesis can be summed up:

- Development of a suitable and industrial applicable measurement equipment and procedure to evaluate the energy consumption of machine tool and production systems for further analysis.
- Development of suitable analysis procedures based on the industrially applicable measurement methodology and equipment.
- Development of a suitable and industrially applicable monitoring procedure to monitor the energy and resource consumption including a suitable implementation methodology based on the developed measurement and analysis approach.
- Bridge the gap between technical development, legislative issues and industrial requirements to enable potential applications for the measurement, evaluation, analysis and optimization of machine tools and production systems with top-down and bottom-up evaluation methods.

Out of the scope of this thesis are

- Machine tool simulations and analysis without a physical machine tool system for the machine tool design and consumption prediction.
- Measurement and analysis of material and resources other than energy compressed air and fluidic media.
- Influences on energy efficiency and related parametrization of the machining processes and thermal behavior.

3 Machine Tool energy measurement

3.1 Introduction

Measuring represents a selective and punctual acquisition of defined information during a certain state and / or observation period, whereas monitoring approaches represent continuous measurements, in most cases, combined with an embedded metering system. The following chapter focuses on the selection and development of an appropriate measurement equipment with related methodology for the effective power and energy measurement of machine tools within industrial environments. Based on this development and resulting findings monitoring equipment and related implementation methods will be defined.

3.2 Energy forms and dependencies

The relevant energy forms for measurement and monitoring primarily depend on the manufacturing process and applied system boundary. Based on the ISO 8580 classification of manufacturing processes, Dornfeld [203] classified four groups of energetic flows related to the given machining processes.
Table 3.1 indicates that electrical energy and compressed air are relevant energy forms and present in most machining processes, whereas the utilization of other energy forms, e.g. process gases or fluids, depends on specific processes.

Table 3.1: Relation of DIN 8580 with relevant energy flows.

Coherence state	Machining processes	Relevant energy flows
Create	Creating material by casting, iron casting, and extrusion	Electrical energy, compressed air, thermal energy, chemical media, oils
Maintain	Arrangement of material by volumetric and geometric changes to the bonding structure, forming	Electrical energy, compressed air, water, oils, solid waste,
Reduce	Shearing, cutting, e.g. removal, grinding, milling, electro discharge machining (EDM), punching.	Electrical energy, water, oils, compressed, air, solid waste, liquid waste, cutting tools
Increase	Formation of material layer, joining, bonding and assembly.	Electrical energy, water (DI), solid waste, liquid waste, hazardous waste, chemicals (solidifying agents, adhesion

According to ISO14955 [29] and based on the machine tool system boundary, all energies that are supplied to the machine tool and that are necessary to perform a defined machining process must be considered. The amount of energy consumed of all the resources must be expressed in a common unit, in order to allow the consolidation and comparison of the different energy forms. This is necessary for the comparison of different energy carriers and components, in order to perform further analysis and optimization measures. Performed measurements on multiple machine tools and production systems revealed that in 92% of all cases, electrical energy and compressed air represent the only relevant energy form. Thus, measurements focus on these two energy forms with the optional consideration of other process-dependent energy forms.

3.3 System boundaries

As the measurement, monitoring and further analysis depends on the intended scope and reference object on the machine tool and production system, a valid and explicit definition of the applied system boundaries is required. In the following, the system boundary is applied on the unit process level as introduced by Kellens [204]. Based on this consideration level, the system boundary not only defined as a physical entity, but also in relation to the life cycle phase. In relation to performed LCA analysis of machine tools [112], the use phase is further considered in the given measurements as it represents the dominant phase for the energy and resource consumption as confirmed by Avram [133]. Zein [15] and Schischke [205] bring to attention that a definition of a unified system boundary as well as measuring routine is challenging due to the variety of machine tools and its applications. The system boundary must enclose all consumers and energy inputs to the machine tool system, which are required to perform the intended machining process. A measurement based on this system boundary definition must therefore include relevant machine tool components and auxiliaries in order to evaluate the energy efficiency and potential optimization. Thus, components of machine tools that are connected to an external or centralized auxiliary system, e.g. heat exchange, chip removal or exhausting system, must be adequately considered as well. For instance, external cooling water can either be counted as a heat sink $(-\dot{Q})$ within the system boundary or must be add as the energy supplied $(+E)$, according to the electrical energy equivalent of the cooling water, i.e. the energy needed for pumping and cooling the cooling water by the infrastructure outside the system boundary. The same applies for production systems in combination with tempered rooms. The ISO 14955 defines energy forms as relevant if the electrical energy equivalent exceeds $10\,\%$ of the total energy E_{tot} supplied to the system in all machine tool states. The relevance for the required consideration of a component is therefore dependent on the component power share during different machine tool states, e.g. off, standby, ready, and machining. Besides this general applicable definition, ISO14955-2 defines also variable system boundary definitions in order to cover the large variety of machine tools. Based on this request, a classification in 3 different system boundary applications as defined in Figure 3.1 - Figure 3.3 can be applied. Own measurements proofed that in 92% in all cases for measurements in industry, electricity and compressed air, are given and correspond therefore to the system boundary as shown in Figure 3.2. Figure 3.2 represents the most common case in the machine tool and production system power evaluation.

Machine tools with only external electricity supply (Figure 3.1): This system boundary covers only the external electricity supply and represents a basic system boundary without the need of energy conversion of other energy forms. All needed energy forms are generated by the supplied electrical energy, e.g. internal compressor for compressed air generation.

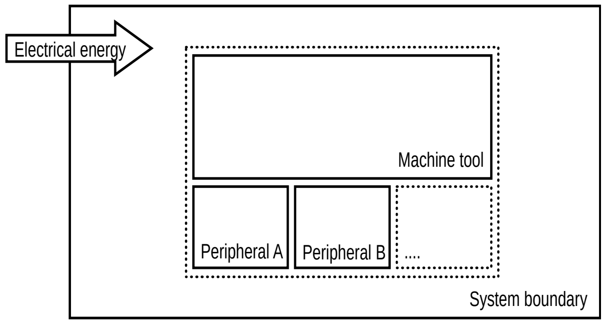


Figure 3.1: System boundary definition with only external electricity supply.

Machine tools with external electricity and compressed air supply (Figure 3.2)*:*
This category represents all machine tools with more than one energy form supply and the process is independent of ambient conditions. This system boundary represents the most typical energy supply of machine tools, in particular for milling and grinding operations. As compressed air is supplied externally a conversion factor has to be determined for the quantification of the energies within the system boundary.

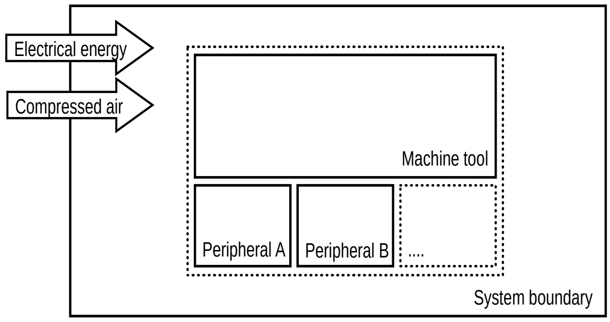


Figure 3.2: System boundary definition with electrical and compressed air supply.

Machine tools with complex energy infrastructure (Figure 3.3):
This category represents all machine tools and production systems with complex or individual energy supplies and multiple energy forms or energy is supplied decentralized.
It also includes systems where the infrastructure is process dependent. In this category the system boundary definition must be set individually.

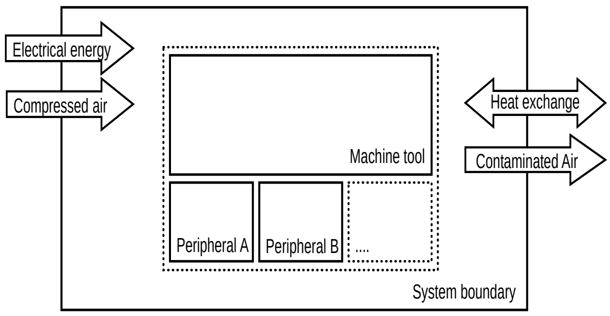


Figure 3.3: System boundary definition with individual energy supply.

3.4 Electrical power measurement

For the electrical power measurement on machine tools and production systems different measurement approaches in research and industry can be distinguished which depend on the connection type and given production infrastructure. For the physical fundamentals on power measurement further reference is given to [206-210].

The relevant parameter for the energy evaluation is the measurement of the effective power P_{eff} in relation to the observation period. In manufacturing and on machine tool components direct current (DC) and alternating current (AC) systems with a line frequency of $50\,Hz$ or $60\,Hz$ are usual. However, DC components are seldom applied on machine tools and can be typically found in robotics for drives or process control systems. DC current is further used in specific areas, e.g. in electrochemical processes and aluminum production, whereas AC current represent a worldwide commonly used power supply [184]. In direct current the product of current $I(t)$ and voltage $U(t)$ results in the power $P(t)$:

$$P(t) = U(t) \cdot I(t) \tag{3.1}$$

AC electrical power supply sources with 3 - phase systems, if a neutral conductor is applied, are most common in manufacturing. Thus, it is reasonable to consider apparent power $S[VA]$, reactive power $Q[var]$, as well as harmonics.

The effective power $P_{eff}(t)$ within an electrical AC power supply results in:

$$P_{eff} = U_{eff} \cdot I_{eff} \cdot \cos\varphi \tag{3.2}$$

with

$$P_{eff} = U_{eff,L1} \cdot I_{eff,L1} \cdot cos\varphi_1 + U_{eff,L2} \cdot I_{eff,L2} \cdot cos\varphi_2 + U_{eff,L3} \cdot I_{eff,L3} \cdot cos\varphi_3 \tag{3.3}$$

Where φ_n represents the phase angle between the current I_n and the voltage U_n for each phase. As a simple arithmetic mean value calculation of the alternating current and voltage results in zero, effective values for the current I_n and voltage U_n are calculated. Effective values are root mean square values and represent equivalent values for the current I_n and voltage $U_n$in AC systems. This results in:

$$U_{eff} = \sqrt{\frac{1}{T}\int_0^T (u(t))^2 dt} \tag{3.4}$$

Due to the power network quality with the resulting asynchrony of each phase, it is needed to measure voltage $U(t)$ and the current $I(t)$ of each phase separately. The share of inductivity and capacitance of each electric consumer leads to an asymmetric dispersion of the phase-specific sinus waves and high range of $cos\varphi$. Frequency converter can lead to a distortion of the current with harmonic waves. Harmonic waves have an influence on the power consumption and zero-crossing-detection within a measurement device and therefore on the identification of the periodic time T of the measured sinus waves as shown by Ellis and Eng in [211]. The main requirement for power measurements on machine tools is represented by a 3 - phase system for voltages of up to $U_{max} = 600\ V$ and currents up to $I_{max} = 100\ A$.

The measurement of the voltage must be performed by direct connecting to each phase L_n (Figure 3.4). A direct tapping of voltage in machine tools and production systems is not intended by manufacturers nor standardized. An individual tapping by following the installation safety according to DIN EN61010 [189] is therefore required. Wrong voltage tapping points, e.g. before or after the rectifier, has significant influence on the measurement results and data accuracy. Not employing the voltage tapping by assuming a constant power factor with a constant voltage lead to wrong effective power calculations resulting from asymmetric phase displacement of current I and voltage U, as confirmed by Paetzold [212] and own measurements.

The measurement of the current I is done indirectly based on the magnetic field around the conductor through hall-effect sensors and the usage of current transformers (CT). As commercially available sensors are mostly limited to $10\ kW$ to $12\ kW$ effective power (P_{eff}), additional CTs need to be used for power levels above $12\ kW$ as well. The selection of the appropriate CTs depends on the measurement range and need to be selected based on available data sheets and e-schemes of the target system. Table 3.2 shows the specification of one of the used sensors for effective power measurement.

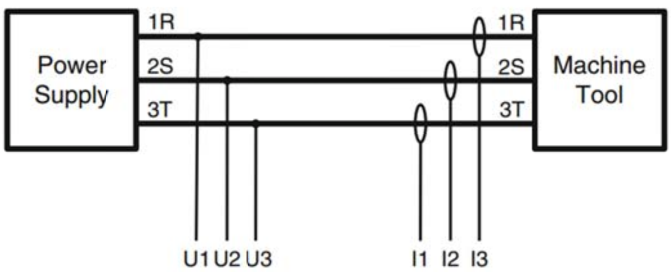


Figure 3.4: A schematic of a 3-phase, 3-load, and 3-wire measurement used to monitor input electrical energy consumption for a machine tool according to [203].

Table 3.2: Technical specification of a sample measuring device CLT.

Measuring principle	3-phase direct voltage measurement with hall effect current transformer
Sampling rate	4000 Hz
Output sampling rate	≤ 5 Hz
Measuring error	U,I ≤ ± 1,0 % of measuring range
Output signal	bidirectional serial interface RS232

The following test setup was chosen to perform measurements of the effective power and electrical energy. Figure 3.5 shows the setup for a 3-phase effective power measurement with and without CTs. The used sensor (CLT) is equipped with an internal A/D converter and transmits values to the external PC via RS232 and sensor-based protocol.

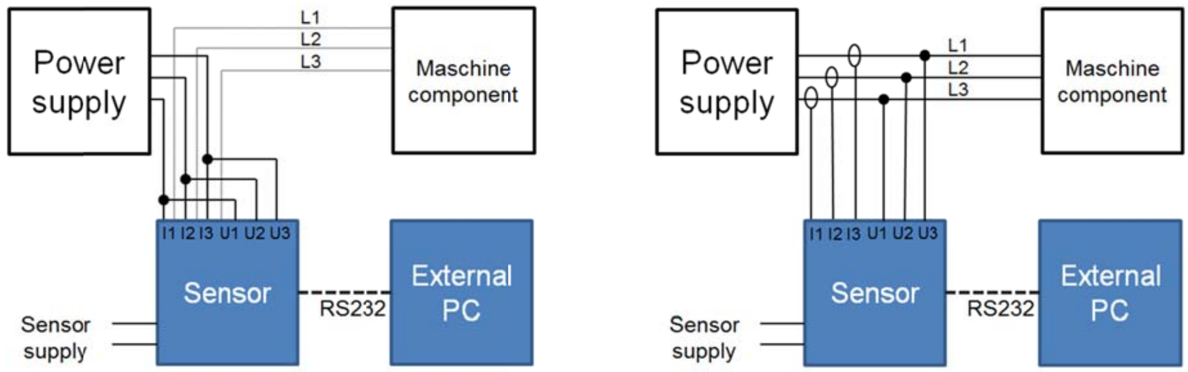


Figure 3.5: Measurement setup for effective power measurements for ≤ 12kW (left) and above >12 kW effective power (right).

3.5 Sampling rate and resolution

In order to evaluate machine tools and production systems it is important to record all possible and relevant machine states and dynamic operations and related power fluctuations, e.g. spindle startups. For this reason an adequate sampling and resolution must be guaranteed. For the data acquisition of dynamic components, e.g. spindles and motors, a refreshing rate of at least $5\ Hz$ of the computed apparent output value is required. A typical pre-sampling rate on commercially available sensors in order to avoid aliasing is given with $\geq 4000\ Hz$.

One of the main cost drivers for effective power measurement device is the sampling rate and resolution as confirmed by O'Driscoll and O'Donnell [213]. The measurement resolution implies the tradeoff between the full energetic picture and a cost effective measurement approach. According to Zein [15] measurements with an output resolution of $1\,Hz$ are obtained and suitable for most application on the process unit level. According to Kellens [204] and Herrmann et al. [111] this refreshing rate facilitates the indication of dynamics and the data handling in further analysis of the machine tool. Kara et al. [5] define a resolution range for the unit process level for highly and low dynamic, dependent of the analysis goal, in resolution from $10\,Hz$ to $0{,}003\,Hz$. High sampling rates can lead to a large amount of data. For instance, measurements with 16 three-phase channels with the additional measurement of compressed air create $17\,MB/h$ data with a output rate of $5\,Hz$. Large data packages hamper the calculation with analysis algorithms.

The requirement for the output sampling rate of the sensor is dependent on the intended measurement application, e.g. network quality analysis, peak loads from electrical components and compressed air. Peak analyses are performed to evaluate start and stop events on the component level and the dimensioning of the wiring and related fuses. For the quantification and measurement of the peak power two parameters need to be analyzed.

- Peak height $P_{P,max}$
- Peak duration t_P

Starting of three-phase standard motors leads to a start current I up to 6-8 fold motor rated current I_e and resulting motor torque M_y with a given load torque M_L as shown in equation (3.5). The motor torque M_y lasts until the motor rotation speed n is reached. The motor startup time t_A is dependent on the motor specific acceleration torque $M_B[Nm]$, the shaft moment of inertia $J'[kgm^2]$ and the motor rotational speed $n[min^{-1}]$:

$$t_A = \frac{J' \cdot n}{9.55 \cdot M_B} \tag{3.5}$$

Based on own measurement measurements cross peak load duration from $0{,}1s$ to several seconds were detected. Figure 3.6 shows a peak analysis with different output sampling rates based on a measurement of an exhausting system with a rated power $P_N = 1\ kW$.

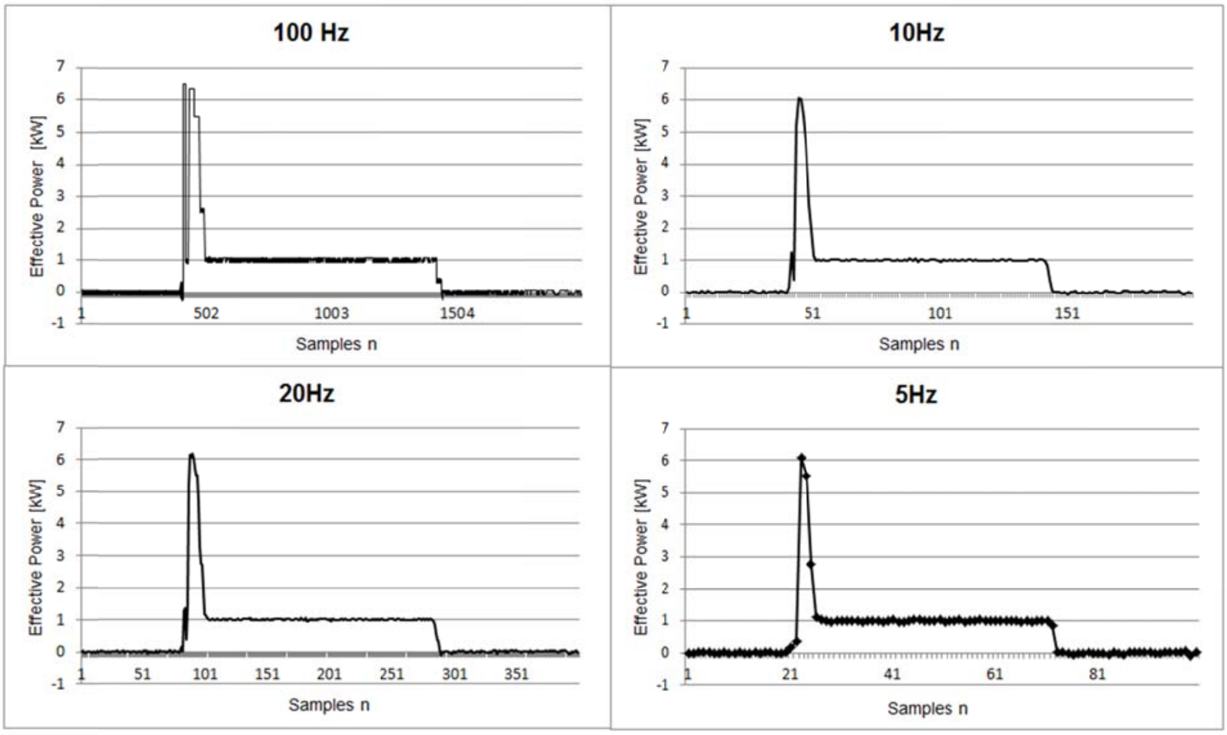


Figure 3.6: Effective power analysis with 100Hz, 20Hz, 10 Hz and 5 Hz sampling based on an exhausting system with a rated power of $\boldsymbol{P_N = 1\ kW}$.

The power measurement of the exhaust system startup was performed based on a $4000\ Hz$ pre-sampling and output rates of $100\ Hz, 20Hz, 10\ Hz$ and $5\ Hz$. The $5\ Hz$ sampling rate indicates the peak with 3 measurement points. A further downscale of the sampling rate towards $1\ Hz$ does not show and peak rated values. As confirmed by TDK-Lambda [214] an initial startup current only lasts for 200 milliseconds to a few seconds.

The measurement with the output sampling rate of $100\ Hz$ shows the power peak with a total duration $\Delta t_P = 0.185\ s$ starting at $t = 3.815s$. The maximal peak power $P_{p,max}$ is measured with $7.80\ kW$ and sampled by 22 sample points which results in peak core duration of $\Delta t_{P,core} = 0.22s$. Same picture results from the $20\ Hz$ sampling where the peak is sampled by at least 5 measurement points. The $10\ Hz$ sampling covers at least two peak sampling point whereas $5\ Hz$ guarantees at least one peak sampling point. Thus, for the peak power analysis an output sampling rate of at least $5\ Hz$ is required. Data acquisition with an n-fold sampling rate according to the signal of interest and the application of a Zero-Crossing-Detection filter can minimize the effects of harmonic waves.

In the practical implementation, the measurements within a $50\ Hz$ network show that low pass filtering of $2000\ Hz$ fulfill the requirements of harmonic waves influence identification. A low output sampling can lead to false signal interpretation due to the Shannon-Nyquist theorem:

$$f_{sample} \geq 2 \cdot f_{signal} \tag{3.6}$$

The applied analog low-pass filters cut off all signals above $2000\ Hz$ to avoid the interference with harmonic waves. To avoid aliasing, the filtered signals of $U(t)$ and $I(t)$ are sampled by a sampling rate of $4000\ Hz$ by the A/D converter.

3.6 Multichannel measurement

Machine tools consist of different interrelated or independent electromechanical subcomponents, e.g. fans, pumps, and motors. Furthermore, these components vary in their energetic behavior, depending on the given infrastructure, individual use, machining process and machine tool state. The vast variability of production systems with more than 400 different machine tool types in combination with various configurations and different energy supplies impedes a comprehensive approach based on commercially available measuring equipment. Todays' measurements and service approaches for detailed resource consumption evaluation on machine tools are laborious, expensive, time-consuming, and requests significant personnel resources. The costs for measurement equipment and its implementation complexity often exceeds the theoretical optimization potential of machine tools and production systems. This is particularly true for SMEs with limited personnel and the priority for productivity, product quality and costs.

The review revealed available systems that support the multichannel measurement [139, 140, 215]. However, these systems are limited to electrical components, analog signals, and require additional sensors with limited data analysis features. The available systems are mainly designed for network analysis with sampling rates $> 2000\ Hz$. A detailed measurement of a production system is principally possible but time-consumption, due to selective measurements and complex data synchronization. This results in poor inter-operational information on the component control dependency often based one energy form.

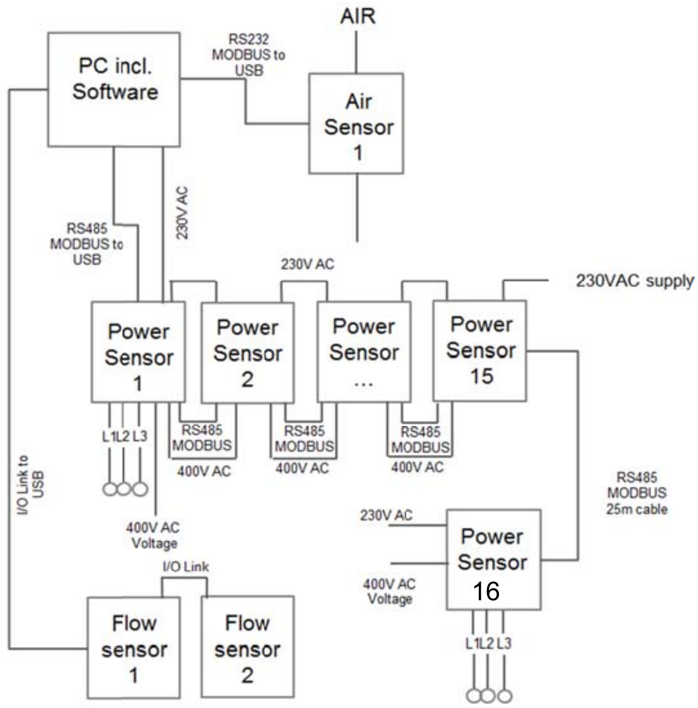


Figure 3.7: Multichannel sensor architecture with 15+1 channels and compressed air measurement.

Figure 3.7 shows an example of the modular multichannel measurement system based on 16 three-phase channels with an additional external power sensor and compressed air measurement. This system was party published in [216]. A modular and mobile multichannel and multi-energy measurement system for simultaneous data acquisition of all active machine tool components, electrical and compressed air, was developed. Based on industrial requirements and resulting feedback further development was undertaken and published in [217]. The development comprises the knowledge-based measurement equipment, methodology, and analysis variability. This system allows a standardized measurement within the machine tool system boundaries as introduced in chapter 3.3. The electrical consumers are measured by a 3-phase direct voltage measurement system with a hall-effect current transformer. The data is used to calculate the consumed power with a data refreshing rate of $0.2\ s$. Compressed air and other gases are measured by a calorimetric flow sensor and a pressure sensor as shown in chapter 3.9. The sensor data is transferred through a RS-232 bidirectional serial and RS-485 Modbus interface and stored on an external computer or the machine tool HMI for further evaluation.

The benefits of the multichannel measurement are shown on an example based on the measurement of a Chiron 12.3W 5-axis machine center. Figure 3.8 shows the total effective power measurement $P_{eff,tot}$ during machine tool startup. The machine tool was turned on after $t_1 = 20s$ and the drives were switched on after $t_2 = 160s$. An emergency stop was activated at $t_3 = 230s$. From the revealed data the total average effective power ∅ $P_{eff,t}$ and peak power $P_{eff,p}$ during startup and according to the actual machine tool state can be quantified.

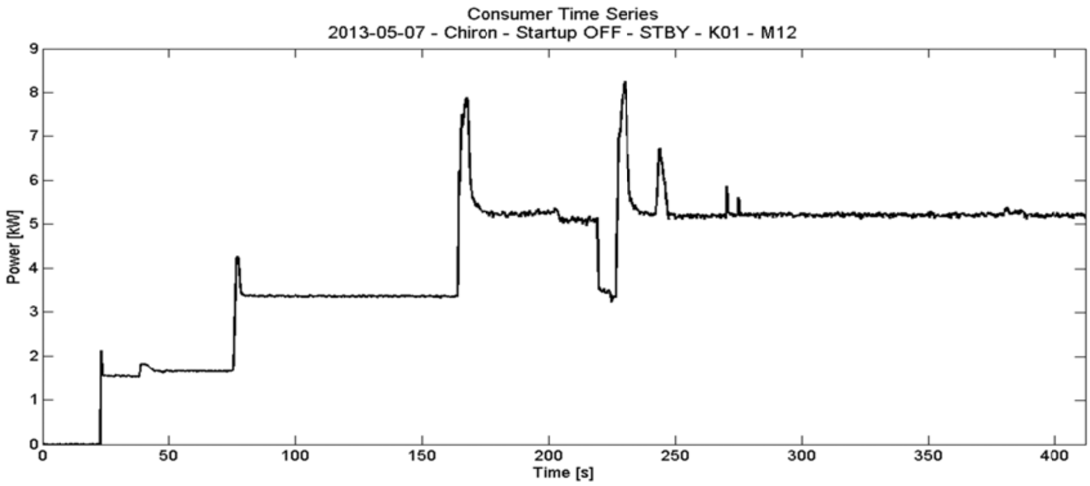


Figure 3.8: Effective power measurement $\boldsymbol{P_{eff,t}}$ on the main supply of the Chiron 12.3W during machine tool startup.

This measurement can be performed with conventional measurement equipment. The analysis and resulting findings for optimization are limited to macro optimization measures with operational changes, e.g. minimizing standby time or machine tool comparison. Information on the energetic behavior of machine tool components is not available from this measurement.

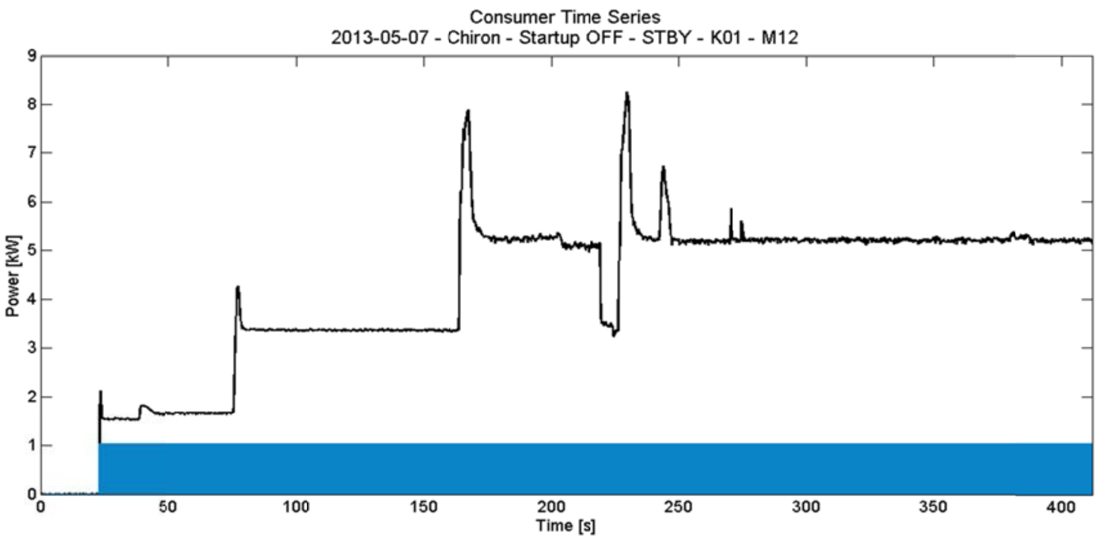


Figure 3.9: Effective power measurement $\boldsymbol{P_{eff,t}}$ on the main supply of the Chiron 12.3W during machine tool startup with additional measurement on the machine tool coolant pump.

The example in Figure 3.9 shows a synchronized two-channel measurement of the total effective power on the main supply and the coolant pump. This measurement can either be performed by a synchronized measurement with two measurement channels or a sequential measurement with one channel on two measurement points. It shows that the coolant pump is always on and fully independent of the machining process or machine tool startup. Additional sensors based on CNC kernel data can provide the effective power of each axis ($P_{eff,X}, P_{eff,Y}, P_{eff,Z}, P_{eff,B}$) as well the main spindle $P_{eff,sp}$. The power loss P_V of the CNC system is taken from the data sheet of the control manufacturer:

$$P_{eff,CNC} = P_{eff,X} + P_{eff,Y} + P_{eff,Z} + P_{eff,B} + P_{eff,sp} + P_v \quad (3.7)$$

which results as the delta between the CNC system supply and the sum of all axes ($P_v = P_{eff,CNC} - \sum P_{axes} + P_{eff,sp}$).

The synchronization of the NC information results in the power measurement in Figure 3.10 and shows the share of the variable effective power on the CNC system including the CNC kernel, amplifier and drives.

Figure 3.10: Effective power measurement $P_{eff,t}$ on the main supply of the Chiron 12.3W during machine tool startup in combination with the CNC system supply.

The synchronization of the measurements of the three machine tool components; main supply, coolant pump, and CNC system supply can either be done offline, based on a sequential measurement or by a multichannel measurement system. Due to the manual positioning and the sequence control of the NC, even the same NC program can lead to a different energetic behavior of the machine tool subsystem and is therefore not identical. For instance, due to the periodic thermal behavior of the machine tool auxiliary equipment, e.g. switch on and off of the cooling compressor, the energetic behavior of the machine tool can vary and lead to a ΔP in y-direction or x-direction. A precise synchronization of two sequential measurements is therefore cumbersome, not possible and impedes therefore the precise analysis of the control behavior and related control dependencies of the subcomponents.

Figure 3.11 shows a full synchronized multichannel measurement with an output sampling rate of $5Hz$ and based on all active machine tool components including the compressed air.

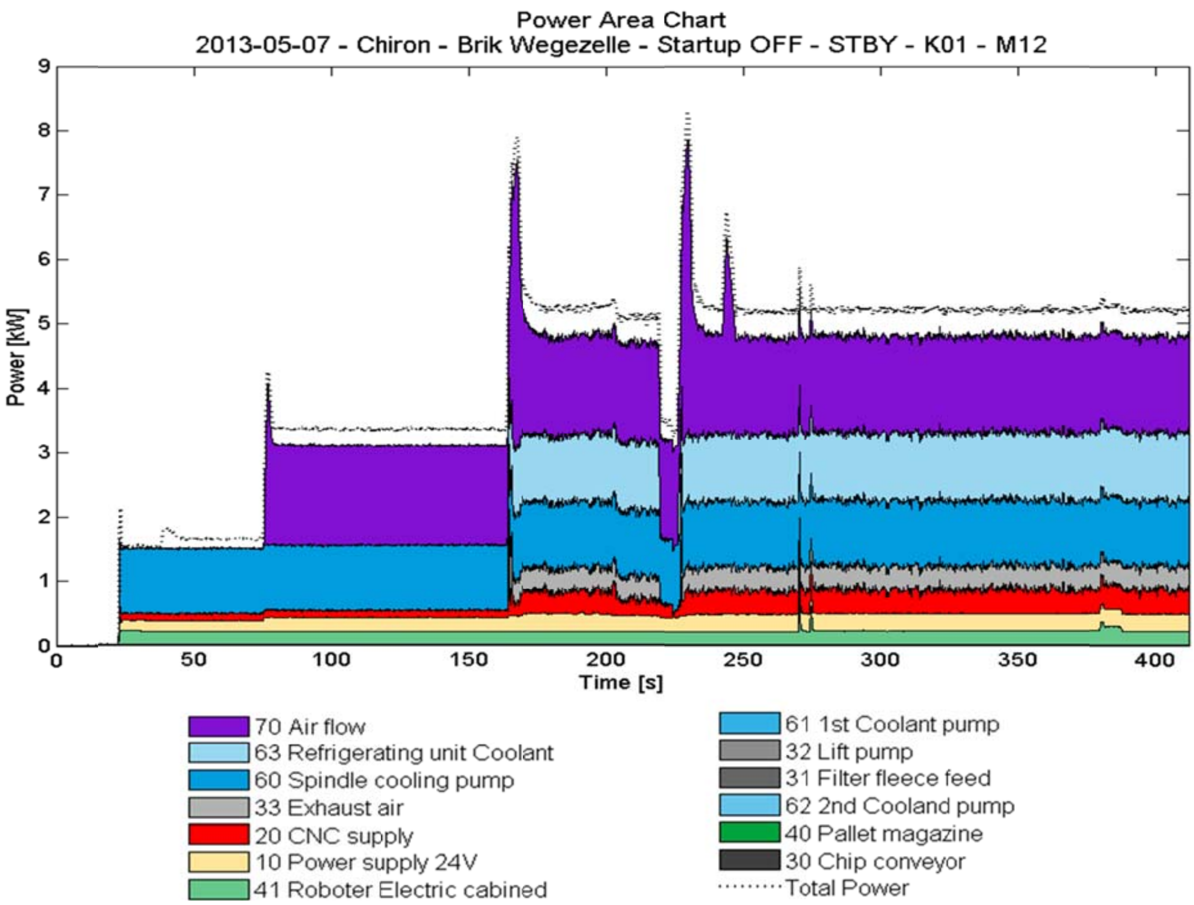


Figure 3.11: Effective power measurement $P_{eff,t}$ on the main supply of the Chiron 12.3W during machine tool startup in combination with the CNC supply.

Based on the multichannel measurement as shown in

Figure 3.11 and measurement equipment as shown in Figure 3.7 the following indication can be made:

1. Machine tool state: The measurement shows all active machine tool components and peak behavior. This analysis can indicate active components with and without direct value add or machine function and their actual power share within a specific machine tool mode.

2. Component behavior: A classification of the machine tool components in constant, controlled-constant and variable consumers can be made. The dynamic energetic behavior and control accuracy of the components can be seen. For instance it shows that the peak load is caused by the compressed air.

3. Share of compressed air: The combined plot shows the share of compressed air in comparison to the total effective power $P_{eff,t}$ and compared to the auxiliary components $P_{eff,n}$. Herewith two energy forms can be compared with each other.

4. Component dependencies: Based on the synchronized measurements the component and control dependencies can be revealed, e.g. the exhaust air system starts with the refrigerating coolant system.

5. Analyzed share: As defined in ISO 14955 the analysis needs to cover at least 80% of all active machine tool components. The example measurement shows the delta between the sum of all components $\sum P_{eff,n}$ and the total effective power $P_{eff,t}$. In the following example over 90% of all active components are covered.

6. Trend and thermal behavior: Based on the energetic behavior of the components, e.g. fluid pump, indication on the thermal behavior, viscosity or filter condition can be made. For instance, this can be seen by an increasing or decreasing effective power value on the pump system.

3.7 Synchronization

The start and the stop of measurement of all sensors are controlled by global software trigger. Still this does not guarantee a synchronized measurement as data read and write times are not synchronized. Thus, the synchronization of the raw data within the multichannel measurement is done offline by merging the raw data files into one synchronized data file. The raw data files are defined with a header, coordinated universal time timestamp (UTC) and the effective power of each phase P_1, P_2, P_3 as well as the resulting effective power P_{eff}. The timestamp is set for each channel separately and depends on the sensor read request and value write time. The read and write time is dependent on the operating system. In the following case Microsoft Windows 7 was used where a real-time data read and write due to a non-realtime software system cannot be guaranteed. Due to internal process priority settings, IO functions and read and write function on hard drive or from serial port, are set on interrupt. That means that other kennel processes can interrupt this function to guarantee system stability and multitasking functionality of the operating system. Further reference is given to [218]. This also results to unequal time distance Δt_d between written values. Based on test measurements with a defined output sample rate of $5Hz$ the recorded time stamp values vary between $202\ ms$ to $235\ ms$, and an average of $+10.89ms$. This equals to an cross delay error of $\pm 5\%$. Figure 3.12 shows the analysis based on a multichannel measurement with 10 channels. The analysis shows that neither the sampling rate within one sensor, nor between other sensors is constant. Therefore a software-based resampling of the raw data is required.

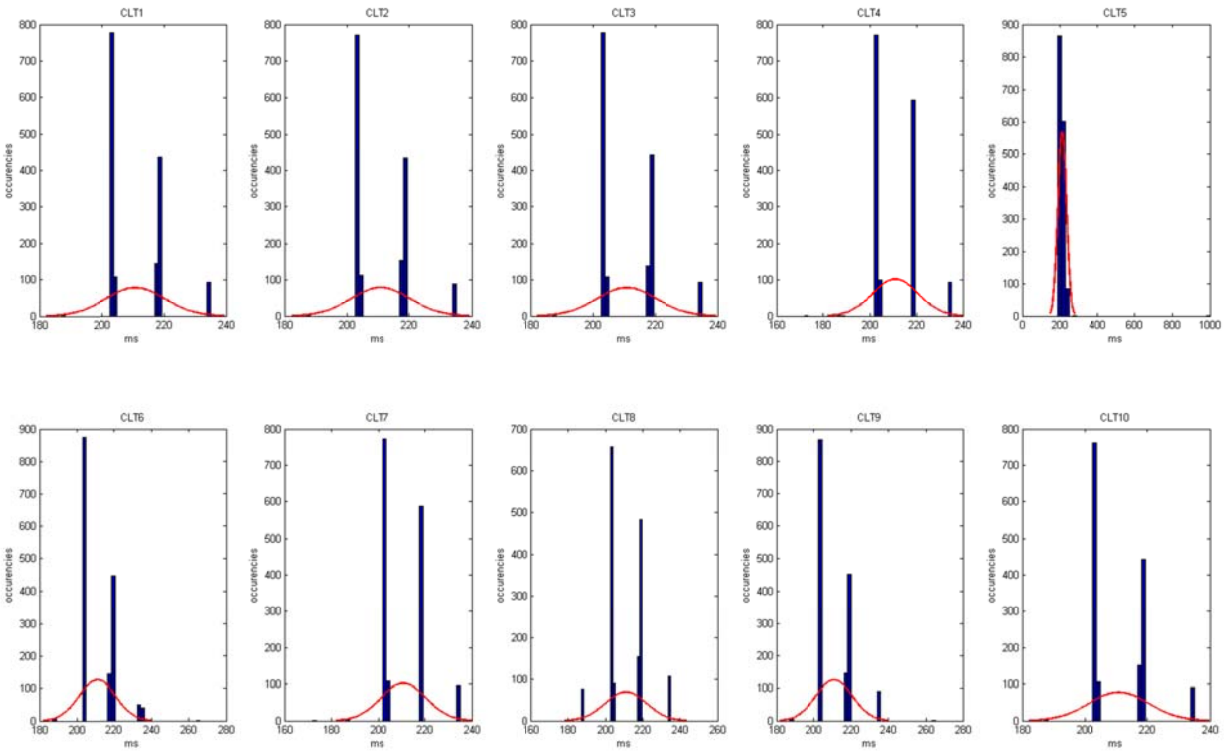


Figure 3.12: Analysis on time distance at sampling on CLT sensors with 5 Hz.

The time synchronization of the sensor data is therefore of particular importance to guarantee appropriate analysis functionality.

The effective power values P_{eff} of each device are written in a new matrix A_s :

$$A_s = \begin{bmatrix} P_{eff1.1} & \cdots & P_{eff1.n} \\ \vdots & \ddots & \vdots \\ P_{effm.1} & \cdots & P_{effm.n} \end{bmatrix} \tag{3.8}$$

Whereas each column of the matrix specifies the sensor or device number and each row the effective power of each device. The values are low pass filtered by the maximal effective power ($P_{eff,max}$) and negative effective power values. This is required as individual values might be missing. Missing values are possible due to the above mentioned process priority management of the operating system. Furthermore, the values need to be changed or multiplied by an amplification factor if the current transformer direction is wrong or CTs for certain channels are used.

The values are resampled with the fixed timestamp of $200ms$, preprocessed by interpolation between each measurement point and set to the new timestamp as shown in Figure 3.13. This preprocessing procedure guarantees a reliable synchronization of all sensor channels and can be further used for data analysis.

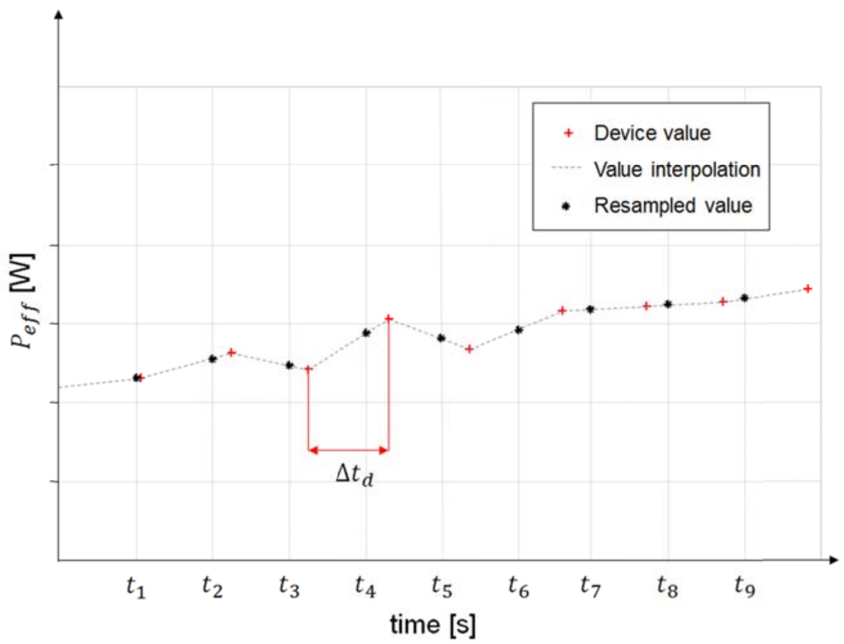


Figure 3.13: Preprocessing and resampling of measured values for data synchronization.

Based on this synchronization a resampling of the values is possible in an n-fold sampling output rate. For this reason a calculated sampling rate $> 10\ Hz$ is possible based on value interpolation. Therefore the values can be synchronized to any other sensor with a higher or lower sampling rate.

3.8 Sensor comparison and selection

Most of commercially available sensors are designed to measure aggregated measurement points, e.g. entire machine tools, production lines or divisions. O'Driscoll and O'Donnel [213] provide a review on available smart meter system for 3-phase electrical measurements on the unit process level. According to the authors five sensor parameters for the specification and selection of sensors are important.

Sampling rate: The sampling rate defines the samples that are taken in a defined time unit. The higher the sampling rate is, the more frequent the zero crossing detection can occur and the process analysis can be performed with a higher resolution.

Accuracy: The accuracy is dependent on the measurement settings, e.g. use of CTs and related standards according to which the sensor is assessed. Generally the accuracy for the sensors is defined in the standards IEC 62053, IEC 60051, and ANSI C12.20.

Resolution: The resolution, output or refreshing rate defines the interpolation of the pre-sampled values. The output rate is an important cost factor. Therefore, the selection of appropriate sensors must consider the requirement for the dynamic energetic behavior for the component which needs to be monitored.

Costs: Limited costs represent a dominating requirement for the selection of sensors in industrial environments. Nevertheless, the cost of the sensor must not be related to its accuracy, features, or supported protocols. In the case of multichannel measurements costs are of particular importance.

Communication: For manufacturing environments it is recommended to use digital outputs. Sensors with analog outputs are cheaper but susceptible to EMC which can lead to measurement noise and affect the measurement accuracy. Therefore, only sensors with integrated A/D convertor are evaluated. The common industrial protocol is Modbus via RS485.

In addition to the above mentioned factors, sensor types can be distinguished. Handheld multimeters, e.g. Fluke 179, can measure voltage and current values but a commonly only used for testing. Build-in multimeters for aggregated measurement points fulfill multiple analysis functions and communication requirements but are often designed for the application in building infrastructure. The Siemens Sentron represents a measurement device which is commonly used in manufacturing on aggregated measurement points, e.g. systems and subsystems including several dependent and independent components. In research, power quality analyzers are used for network analysis and sensor calibration, e.g. Yokogawa WT3000. These sensors provide sample rates of more than $1Mhz$ and precision of up to $\pm 0.01\%$ on the voltage and current measurement but are expensive and limited to one or only a few measurement channels. For the multichannel measurement system several multimeters with build-in A/D converter and digital output were evaluated and tested (Appendix A.3):

Table 3.3 defines the following specification for the multichannel measurement sensors based on the above mentioned requirements and needed analysis features:

Table 3.3: Required specification for the selection of sensors in the multichannel measurement.

Measurement principle	**3-phase effective power up to 600V via hall effect with digital output**
Sampling rate and output rate	4000Hz, refreshing output rate min. 5Hz
Input signals	3 phase alternating current with 220-240V per phase, min current 16A per phase
Communication	RS232 / RS485, Modbus, open communication system

Output signals	Effective power P1, P2, P3 and P_{tot} , Voltage per phase U1, U2, U3 and current per phase I1, I2, I3. Apparent power S1, S2, S3 and idle power Q1, Q2, Q3 are optional
Dimensions	As small as possible and suitable for ISO rack according to DIN EN 50022 or DIN 46277
Safety category	IP20, DIN EN 60529
Measurement category	CAT II DIN 61010-01

For the sensor selection the sensors CLT310 from Christ Elektronik [219], Acuvim II from Accuenergy [220], and Pilot PMAC903 [221] in a price range from 70 CHF to 400 CHF were compared. The sensor comparison was performed by a power measurement on a grinding spindle to evaluate the sensitivity on parametrization as shown in Figure 3.14.

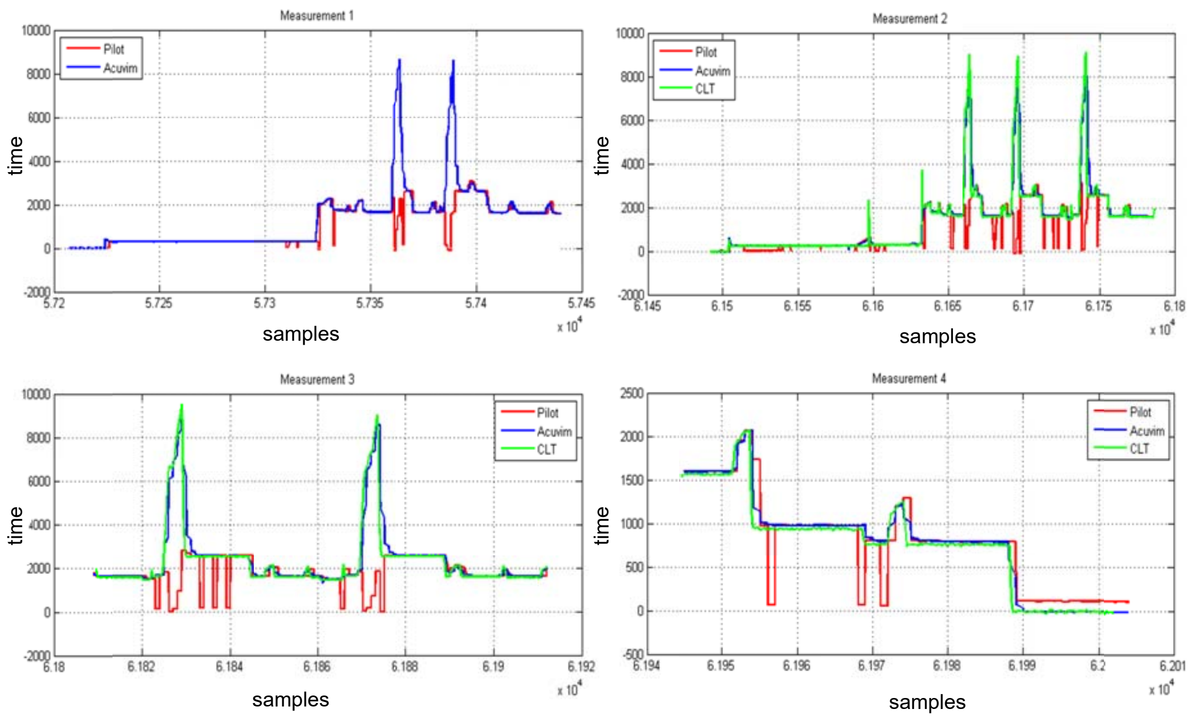


Figure 3.14: Comparison measurement on a grinding spindle with Pilot PMAC903, Accuenergy Acuvim II, and Christ Elektronik CLT310.

Measurement 1 and 2 show the spindle start up on the rotational speed of $1650\ 1/min$ and two grindings operations in measurement 1 and 3, and three grinding operations in measurement 2. Measurement 4 shows the machine tool switch off. The measurements show the dynamic behavior of the sensor and resulting effective power P_{eff} measurement. It can be seen that the refreshing rate of the Pilot PMAC903 is not sufficient and leads occasionally to zero values. This is case when the software-based data pull does not receive a valid value from the sensor. Furthermore, an electric inertia which is caused by the inductivity and internal resistance of the sensor can be seen in measurement 4. Acuvim II and the CLT310 show a similar behavior, whereas the peak detection and refreshing on the CLT310 is faster and suitable for dynamic analysis as shown in measurement 2 and 4.

According to the CLT data sheets [219] the sensor accuracy is indicated with ±1.0% on voltage and current and ±1.5% for derived parameters such as active and reactive power or the power factor. Based on the sensor comparison a detailed analysis on the accuracy of the active power on the CLT device was done.

Three 100 W consumers were connected to a three-phase 230V/400V electric power system. For the evaluation of the sensor accuracy and related dependencies, the following modification and parametrizations were done during the measurements:

- Change in the load from symmetric to asymmetric,
- Connect and disconnect of the neutral conductor,
- One or all devices were connected in series.

This results into the following measurement settings:

Table 3.4: Test setup for detailed accuracy measurement on CLT310.

Load	Neutral Conductor	In series
Symmetric (ABC)	No	No
Symmetric (ABC)	Connected	No
Symmetric (ABC, BCA, CAB)	No	Yes
Asymmetric (L1, L2, L3)	No	No
Asymmetric (L1, L2, L3)	Connected	No
Asymmetric (L1, L2, L3)	No	Yes

Each measurement was done during $t = 500\,s$ with a refreshing rate of $5\,Hz$ resulting to 2500 data samples per measurement. For the symmetric load each 100 W - consumer was connected to a different electrical phase. For the asymmetric load, all 100 W - consumers were connected in parallel to on electrical phase, while the other phases are left unconnected.

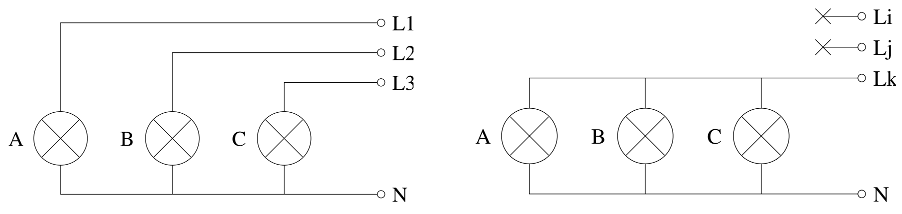


Figure 3.15: Cabling of the three 100W consumers (A, B and C) for symmetric load (left) with the three phases (L1, L2 and L3) and asymmetric load (right).

The result of the performed measurements shows the statistical analysis of all measurements (Figure 3.16). On the x-axis the device number is listed over the active power, normalized power or reactive power on the y-axis. The central mark represents the median with the 25th and 75th percentiles. Points are drawn as outlines if the if their value exceeds 150% of their 25th to 75th percentiles distance.

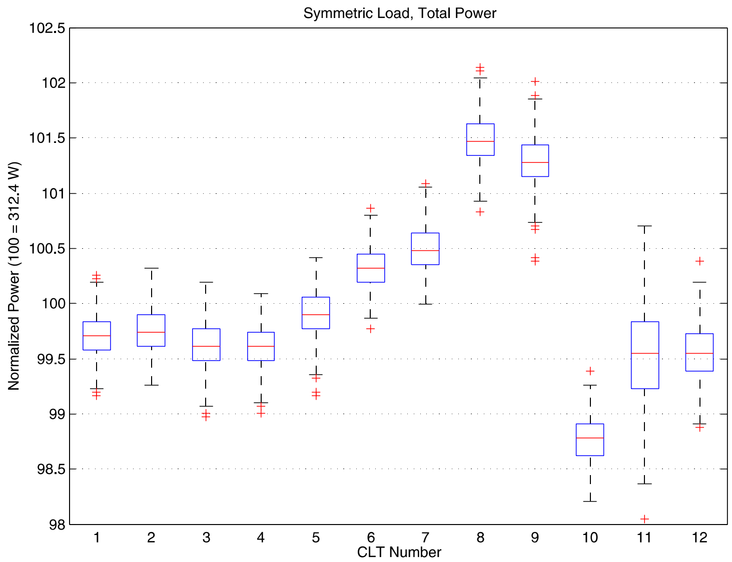


Figure 3.16: Overview of measurement with symmetric load and disconnected neutral conductor. The results are normalized to the mean value of all CLTs median value (100 ≙ 312.4W).

The following observations can be made:

- The devices show a deviation in their variance and value. Same dependency can be observed with the measurement of the symmetric load and the neutral conductor connection.
- The total power values of the devices vary between $\pm 1.5\ \%$ from the overall mean which confirms the manufacturers' specification.
- For the symmetrical load the connection or disconnection of the neutral conductor does not have any effects on the accuracy of the device.
- For the asymmetrical load the active power values of the phases vary between $\pm 3\ \%$ with connected neutral conductor. With disconnected neutral conductor an accuracy of $\pm\ 5\%$ can be observed.

Thus, an overall accuracy of $\pm 5\%$ on the power values within a multichannel sensor setting can be revealed. The overall sensor comparison shows that the deviations between the sensors result from the fabrication quality and secondly dependents on the load and the adequate connection with the neutral conductor.

3.9 Compressed Air Measurement

3.9.1 Introduction

Based on its importance and the positive properties such as clean application, safe usage and storability, compressed air is used in many industrial applications. More than three-quarter of the total financial life cycle costs of compressed air supplies are represented by energy costs, besides capital and maintenance costs [146, 147]. In machine tools, energy in the form of compressed air is generated by integrated equipment or - more often - supplied by the shopfloor. Air supplies at the shopfloor are often designed as centralized systems with long distribution networks and are therefore particularly vulnerable for leakage and pressure drops. Moreover the generation of compressed air is given by a low efficiency factor as indicated by Gauchel [222]. In comparison to electrical energy and depending on the pressure ratio between system pressure p_1 and environment pressure p_0, compressed air requires up to eight times more energy than electrical energy for comparable work, e.g. lifting movement. For this reason the costs of electrical energy used by compressed air can exceed the capital costs within a year [223]. For the measurement and monitoring application of compressed air, the following requirements can be revealed:

- ***Comprehensive measurement:*** A comprehensive measurement of machine tools and production systems contains different energy forms. For this reason the consolidation and comparison of compressed air with other energy form must be guaranteed.
- ***Universal application***: Compressed air measurements must be available on various machine tool and production system configurations. Therefore, all applied measurement approaches, simulations, data processing and analysis must be designed system independent.
- ***Industrial application***: Measurement equipment and used methods should be applicable to the industrial infrastructure. Parametrization of simulations, measurement system setup and analysis should be as easy, fast and reliable in their application. This requirement also covers the limitation of complexity and costs for compressed air measurements and monitoring.

3.9.2 Conversion factor

Manufacturing systems and machine tools are designed for individual applications and machining processes. In those processes different energy forms are used predominately represented by electrical energy and compressed air. Thus, electrical energy and compressed air must be comprised into the energetic balance.

A consolidation is required as it enables the indication of improvement potentials within a machine tool or production system. For this reason a transformation unit between electrical power (kW) and flow (m^3/h) must be applied. As electrical power represents the most dominant energy form in manufacturing, comprising high exergy, the transformation reference is given with kW.

The conversion from compressed air flow (m^3/h) in electrical equivalent (kW) can be done by a linear multiplication with an equivalent factor C_{Air}. This equivalent must be adaptable for various conditions and parameters, e.g. different pressure levels, system characteristics, operational schedules and degrees of system integration. In literature different energy equivalents can be found depending on the compressor type, capacity, pressure and temperature level. Hinsenkamp et al. [224] indicate the specific power consumption of a screw compressor for an industrial $6\ bar$ supply is given with $C_{Air} = 0.1006\ kWh/m^3$) at a capacity of 90%. This value rises to $C_{Air} = 0.1286\ kWh/m^3$) at $50\ \%$ capacity. Further reference to energy equivalents in compressed in the range from $0.09 - 0.14\ kWh/m^3$ is given in [223, 225-227].

The following procedure was developed, partly published in [228], and introduces a model based approach for the conversion factor description. This approach considers heat sources and sinks within the compressed air generation and enables the individual calculation of the compressed air conversion equivalent.

The model inputs consist of the demanded amount of compressed air V_n and inlet air conditions, represented by pressure p_{in} and temperature ϑ_{in}. The outputs of the model are given with the required electric energies W_{el} and thermal losses Q_{th}. Given this dependency the energy equivalent in this approach is defined as:

$$C_{Air} = \frac{\int_j^n W_{el,j} + \sum_i C_{th,i}(Q_{th,i})}{V_n} \qquad (3.9)$$

By the assumption of an isothermal and isobaric expansion, and the application of the first law of thermodynamics the calculation can be simplified to:

$$C_{Air} = R_S \cdot \rho_n \cdot \vartheta_{in} \cdot \ln\left(\frac{P_{comp}}{P_{in}}\right) \cdot C_{sys} \cdot C_{op} \cdot C_{leak} \qquad (3.10)$$

By combining the electric energy consuming components the function $C_{th,i}(Q_{th,})$ describes the energy required to treat the i-th thermal loss $Q_{th,i}$. The revealed conversion equivalent is strongly dependent on the given system parameters and conditions, e.g. leakage. For an individual calculation of the conversion factor C_{Air} a validation measurement was performed. The compressor with a rated power of $15\ kW$ and throughput of $2.11 \frac{m^3}{min}$ is combined with a vessel with $250l$ under a pressure of $10 - 11\ bar$. For the validation measurement a defined orifice with a constant flow rate of $3.75l$ was applied. According to the compressor data sheet the compressor operates, based on this configuration, at the average duty cycle of $20\ \%$ during stationary consumption. The power consumption of the compressor was measured at the main input with an expected relative error of $\pm 4.5\%$ for the power measurement and ± 3.5 % for the flow measurement.

$$\overline{C_{Air}} = \int_{t_1}^{t_2} \bar{P} dt \Big/ \int_{t_1}^{t_2} \dot{\bar{V}} dt \approx 0.55\ kWh/m^3 \tag{3.11}$$

The measurement value is further compared with the calculation as given in equation (3.11) by using conditions of the DIN1343 and the ideal gas properties, the conversion equivalent results to:

$$C_{Air} \approx 0.57\ kWh/m^3 \tag{3.12}$$

This results into a relative error of $\pm\, 4\ \%$ and shows that the defined model can be used in order to calculate the conversion equivalent C_{Air}, for compressed air flow into kilowatts, for individual compressed air systems. Nevertheless, this approach requires complex parametrization and is therefore only suitable to a limited extent for the application in industrial settings. A simplified approach for the calculation of the conversion equivalent C_{Air} based on the assumption of an adiabatic change of state during compressed air generation and neglecting the HVAC system, is represented in [216].

Assuming an adiabatic change of state and ideal gas, the compression work $P(t)$ in relation to the massflow of compressed air $\dot{m}(t)$, dependents on the specific heat capacity c_p, the intake temperature ϑ_{in}, in- and outtake pressure (p_{in} and p_{comp}) and the isotropic exponent for air κ is represented by:

$$P(t) = W(t) \cdot \dot{m}(t) = c_p \cdot \vartheta_{in} \cdot \left[\left(\frac{p_{in}}{p_{comp}} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right] \cdot \dot{m}(t) = C_{Air} \cdot \dot{m}(t) \tag{3.13}$$

Due to the uncertainties in the in- and outtake air temperature, humidity, thermodynamic behavior, and in- and outtake air pressure, the simplification in equation (3.13) is reasonable for industrial applications. The deviations within the air flow signal acquisition is given with $\pm 10\%$. The simplification leads to an infrastructural dependent transformation with major influence on the pressure ratio p_{in}/p_{comp} and intake temperature ϑ_{in}. Based on the defined system around the machine tool, the value of $6.5 - 7.5\ (kW)\ /\ (m^3/min)$ for C_{Air} is reasonable. Examples for numerical evaluations of the compressed air equivalent according to Hirano et al. [229] and Züst et al. [228] are shown in Table 3.5, where different efficiencies, pressure levels, and degree of system integration are compared. The comparison shows that the equivalent values are within the range of $0.08 - 0.90\ kWh/m^3$. For high efficient systems, the estimated equivalents are given at $0.08 - 0.20\ kWh/m^3$.

Table 3.5: Examples of estimated compressed air electric energy equivalents for different systems, pressure levels and system integration (low efficient: u=20%, ε=2, η=30%; high efficient: u=60%, ε=4, η=80%) according to Hirano et al. [229] and Züst et al. [228] the units of the listed equivalents are kWh/m^3 at normal conditions.

	No secondary thermal treatment	**Air-Air heat exchange**	**Connection to HVAC, moderate climate**	**Connection to HVAC, cold climate**
Description	Only electrical power has to be taken into account, since no secondary treatments of heat sinks and sources are required.	Heat loss is exhausted to the ambient air, which is conditioned by the HVAC of the building.	The compressor is connected to the HVAC system of the building. During six months per year the excess heat is used for heating.	The compressor is connected to the HVAC system of the building.The excess heat is used to heat the building.
6bar				
low efficient	0.55	0.65	0.50	0.45
high efficient	0.11	0.13	0.10	0.08
8bar				
low efficient	0.63	0.75	0.58	0.53
high efficient	0.12	0.15	0.11	0.10
10 bar				
low efficient	0.70	0.84	0.64	0.58
high efficient	0.14	0.17	0.12	0.11
12 bar				
low efficient	0.75	0.90	0.69	0.63
high efficient	0.15	0.18	0.13	0.12

It is obvious that the conversion equivalent depends on different parametrization and applied system boundaries. For this reason the following approaches for the conversion of compressed air in power equivalent for further consolidation are chosen:

1. Standard benchmark factor of $0.12\ kWh/m^3$ (or $0.72\ kW/(m^3/min)$).
2. Individual calibrated conversion equivalent of the industrial site.
3. Model dependent on system parametrization according to equation (3.13).

As a comparison has to be established and applicable within an industrial setting, the first method is preferred in the following procedure and applied in the given measurements.

3.9.3 Measurement equipment

For the compressed air measurement the flow rate $\dot{V}$, pressure $p,$ and temperature ϑ for a given flow are required. The reference conditions are given by DIN ISO 1343 [230] within a standardized industrial $6\ bar$ air supply. Based on the measuring method, e.g. calorimetric measurement, turbulences in the flow can influence the measurement results. Therefore, an upstream pipe length of 20 times the pipe diameter, and a respective downstream length of five times is required. Various measurement systems with different physical background are present in industry (Table 3.6). A comprehensive summary of given approaches is presented by Fraunhofer [225].

The selection for an industrial selective measurement and monitoring application leads to the following requirements:

- Measurement principle selection depending on requested accuracy.
- Universal application, adaptable on industrial infrastructure for $6 - 10bar$ compressed air supply.
- Reasonable cost-to-benefit ratio.
- Measurement of flow rate and pressure for up to $250m^3/h$ with up to $10bar$.

Measurement equipment for compressed air and coolant flow is strongly dependent on the individual throughput rate. In most machining application, e.g. milling processes with $P_N \leq 100kW$, an air flow rate of up to $250\ m^3/h$ and a coolant flow of $100\ m^3/h$ can be expected. The most convenient measurement method for air and gas measurements is given by the calorimetric measurement principles [231]. Liquids, e.g. cooling fluid, are commonly measured by rotameters amongst other principles. In principle, flow measurements can be differentiated in direct and indirect measurement principle. Direct measurements require the sensor built-in existing compressed air supplies, whereas indirect measurements can be applied by clamp-on solutions without the manipulation on the existing infrastructure. For the compressed air measurement indirect measurement principles are neglected due to their poor accuracy and related costs.

Table 3.6: Sensor types according to required variables.

Measurement variables	Type of sensor
pressure	manometer
volumetric flow	calorimetric
mass flow	coriolis
volumetric flow, leakage	ultrasonic

The working principle of the calorimetric measurement approach is given by a thermal change on the sensor tip. The heat is dispatched from the tip and the resistance adjusts to a reference value. So the output voltage U_{out} changes with the flow velocity [178]:

$$U_{out} = k \cdot \lambda \cdot \rho \cdot \omega \cdot (\vartheta_{Sensor} - \vartheta_{Fluid}) \tag{3.14}$$

where k is a sensor geometrical constant, λ the thermal conductivity of the gas, ρ the density of the gas and $(\vartheta_{Sensor} - \vartheta_{Fluid})$ the measured difference in temperature. With

$$\dot{V} = \omega \cdot A \tag{3.15}$$

The volumetric flow $\dot{V}$ can be computed with the fluid velocity ω and tube area A. Together with the flow measurement it is required to consider the pressure drop in the pipe. Generally compressed air follows the ideal gas equation.

$$p \cdot V = n \cdot R \cdot \vartheta \tag{3.16}$$

With pressure p, fluid flow $\dot{V}$ in relation to substance quantity n, specific gas constant R and absolute temperature ϑ. A comparison measurement of the flow rate and pressure was performed on an open pipe at a $6\ bar$ industrial supply. The measurement consists of a flow measurement with a calorimetric flow sensor and a pressure measurement based on a DMS ceramic sensor. Figure 3.17 shows a pressure drop of $0.4 - 0.5 bar$ at a flow rate of $33\ m^3/s$.

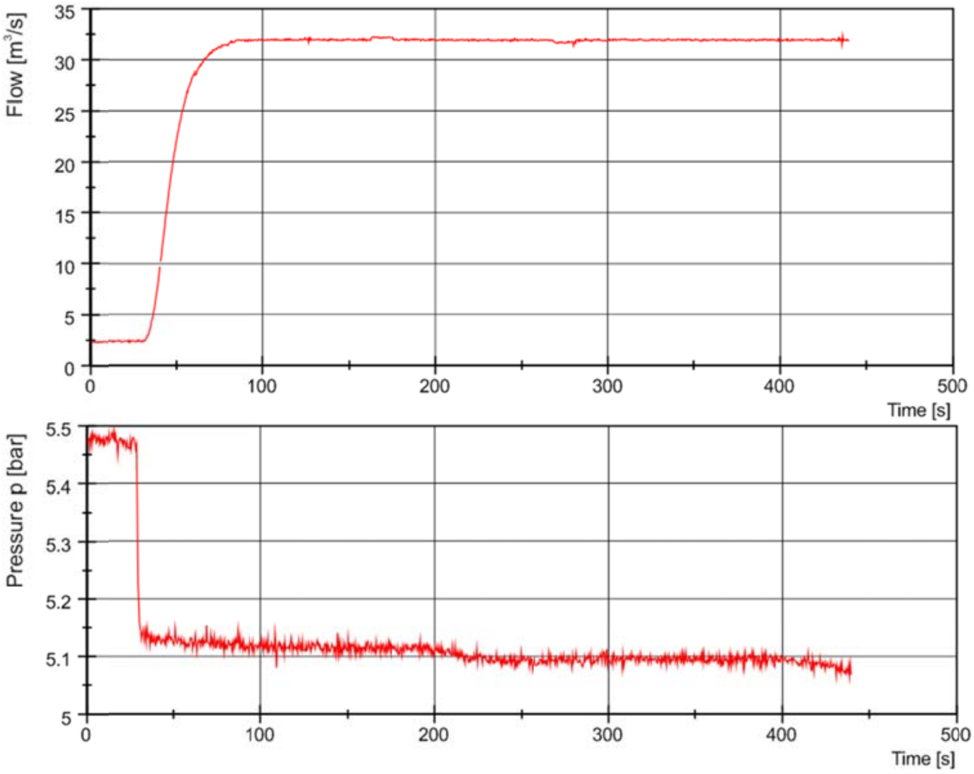


Figure 3.17: Measurement of volume flow and pressure within an open pipe at a 6bar industrial supply.

The measurement represents a full open pipe. This is usually not the case within industrial applications and represents therefore a uncommon maximal pressure drop. Furthermore, for the calculation of the compressor effectivity, parameters such as fluid humidity, mass flow and fluid temperature need to be measured. This requires are complex measurement setup. For this reason the pressure drop measurement and related reduced compressor effectiveness are neglected for the multichannel measurements.

3.9.4 Sensor comparison

In order to find adequate measurement equipment, two flow sensors based on the calorimetric measurement principle were chosen with the following specification (Table 3.7).

Table 3.7: Flow sensor selection for sensor comparison.

Device	Refreshing rate	Output signals	Communication	Accuracy	Price
Postberg+CO Compact 104s	5Hz	4 - 20mA / with internal A/D	RS485 / MODBUS (optional)	Measurement class 1,according to ISO 8573.1	~CHF 1400

VPFlowMate	2Hz	4-20mA / with internal A/D	RS232	0.5%	~CHF 1300

The following test setup was used Figure 3.18:

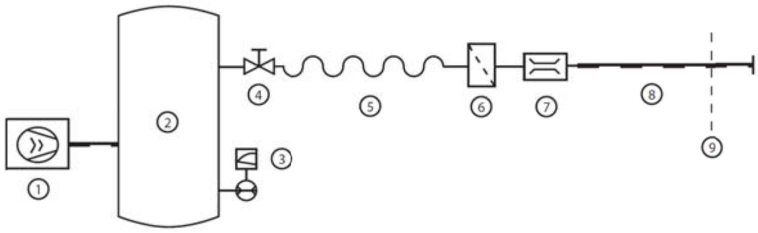


Figure 3.18: Test setup for sensor comparison test with 1. Compressor, 2. Tank, 3. Analog pressure manometer, 4.Ball valve, 5. Hose, 6. Filter,7. Sensor 1 and 2, 8. Pipe, 9. Open pipe.

Both sensors are connected with a hose which is also connected to one of the couplings at the end of the compressed air system. The air leaves the system through a fully open pipe. The initial and ambient conditions are given in Table 3.8. The air pistol is left open until the compressor has filled up the tank three times.

Table 3.8: Initial, ambient and other conditions of the sensor measurements.

Parameter		**Unit**	**Value**
Tank temperature	ϑ_T	K	295
Initial tank pressure	$p_{T,init}$	bar	10.70
Maximal tank pressure	$p_{T,max}$	bar	11.00
Response pressure difference	Δp	bar	0.50
Ambient temperature	T_{amb}	K	293
Ambient pressure	p_{amb}	bar	1.013

The comparison of the sensors is hampered as the Postberg & Co Compact 104s (1) sensor samples with a frequency of $f_1 = 5Hz$ and the VPFlowMate (2) with $f_2 = 2Hz$. Furthermore, the pipe is opened manually. Therefore, the time vectors need to be synchronized and adjusted to each other.

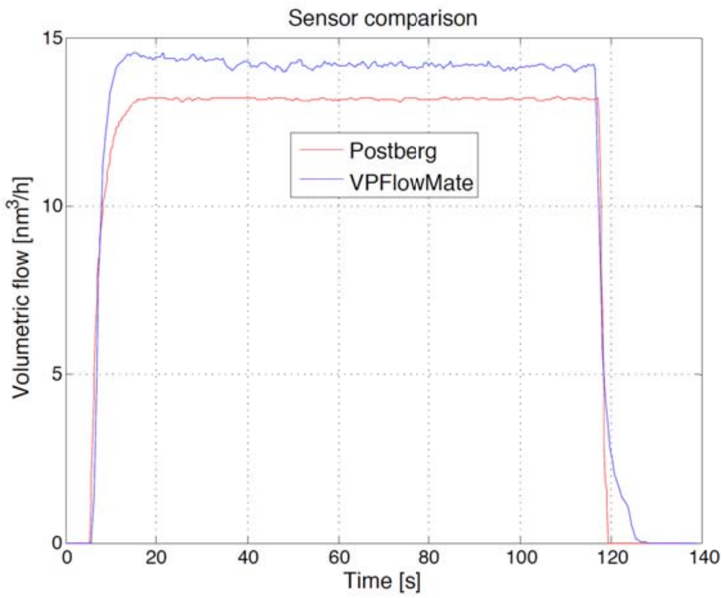


Figure 3.19: Sensor validation and comparison of Postberg&Co Compact104s and VPFlowMate.

Based on the sensor comparison Figure 3.19, the following observations can be made:

- Both sensors have the same response delay. The values rise fast to the maximum whereas the flow values remain constant. The ascent is equal for both sensors and they are congruent until they reach their peak value. Also the closing of the air pistol shows the same curve. The negative gradient is congruent. In the end the sensor 2 shows a higher inertia towards zero.
- In the stationary phase when the air pistol is fully opened one can see a difference in the flow value of the two sensors. Sensor 2 has an average deviation of 7% in comparison to sensor 1.
- Sensor 2 shows a small overshoot in the beginning. This overshoot lasts for several seconds where it comes into the stationary state afterwards. Sensor 1 shows no overshoot and remains constant over the whole period.
- With a look on the curve of the sensor 2, one can observe a stronger noise than on the sensor 1. The sensor 1 shows a smooth behavior in every situation. It has to be considered, that the sampling rates aren't the same. This results in less measuring points for sensor 2.

The variance in the curve at the end of the measurement shows an imprecision of sensor 2 in respect of small volumetric flows. This is because pipe valve was not opened exactly the same as with sensor 1.

Furthermore, the range of the VPFlowMate (sensor 1) is bigger. Hence it makes the sensor more inaccurate for small volumetric flows.

The deviation in the stationary phase leads to two perspectives. The allowed measurement error given by the manufacturer is $\pm 1\%$. In the comparison measurement the relative mean deviation between sensor 1 and sensor 2 is 7%. This requires recalibration of the sensor. The measurement shows also that sensor 2 reacts fast to strong volumetric flow changes but needs more time to stabilize and approach to a steady phase. This also explains the slower decrease in the end of the measurement.

3.10 Measurement methodology

The procedure for the detailed multichannel measurement was further defined in ISO 14955 [29] and consists of the following 5-steps methodology.

1. Identification of measurement points: According to the machine tool architecture and individual configuration, relevant measurement points are selected based on the machine tool E-scheme. In accordance to ISO 14955, minimum 80% of all components must be measured. Energetically relevant components are defined as minimum 5% of the total effective power P_{tot} in each machine tool mode.

2. Measurement system Implementation: Each channel of the measurement system can be either connected directly through an external implemented connector to the machine tool or through CTs as shown in chapter 3.4.

3. System configuration and tests: Based on the measured component and related direct or indirect measurement the measurement system needs to be configured accordingly, e.g. setting of used CTs. A system test is performed to check phase balancing, correct wiring, CT direction validation, and completeness of the required measured components.

4. Measurement of reference process: The reference process represents a typical part and process combination for the intended machine tool operation in the field. It is recommended to define a reproducible process for further comparison. The measurement is further performed in all possible machine tool modes.

5. Data analysis: Finally, the collected and preprocessed data can be used for further analysis. The raw data of each measured channel is synchronized in the preprocessing and merged into a common file for further analysis.

The electrical and compressed air measurement can be combined to the multichannel measurement as shown in Figure 3.7. The main requirements for the appropriated machine tool measurement can be summarized to five requirement groups as listed below. Furthermore, the requirements refer to the analysis features based on the multichannel measurement data.

- **Safety:** All measurements need to be performed with safety equipment based on EN61010 [189]. Besides the wiring safety appropriate measurement equipment and measurement points need to be chosen.
- **Measurement points:** Measurement points need to be accessible and its wiring should not be changed. For warranty and safety issues, changes at the machine tool electric circuit are forbidden. Where possible standard taping, e.g. for voltage, should be used.
- **Machine downtime:** The machine tool downtime should be limited to a minimal duration for the measurement preparation. Due to safety reasons the machine tool must be switched off and disconnected from the power outlet.
- **Analysis:** The measurement should cover all relevant machine tool components. Measurement data should be further used for the analysis and further indication on optimization measures. This also includes all required energy forms within the machine tool system boundary. The measurement must further be based on the intended machining process.
- **Costs:** The costs for the measurement service, including the measurement preparation, measurement, and analysis must be appropriate towards the potential benefit of the measurements.

Based on the industrial requirements and the measurement equipment the following measurement methodology was developed.

3.10.1 Measurement preparation

The preparation of the measurement equipment covers all machine tool energy supplies and is based on the E-scheme of the machine tool. The selection of the relevant machine tool is done in dependency of the ratio of the machine tool rated power P_r and the effective power of each machine tool component $P_{eff,n}$.

$$P_r \leq 0.1 \cdot P_{eff,n} \tag{3.17}$$

If the effective power of each component equals 10% of the machine tool rated power, the component is relevant and needs to be covered by the measurement. This verification must be true for the machine tool standby and processing mode. As the effective or rated power of a component might be not known, the maximal current at the fuse I_{sec} together with the power factor $cos\varphi = 1$ and the effective total power on the machine tool $P_{eff,t}$ can be taken as an indication for the relevance of machine tool components.

$$P_{eff,t} \leq 0.1 \cdot 400V \cdot I_{sec} \cdot cos\varphi \tag{3.18}$$

Form this pre-selection of potential components and measurement points the measurement system needs to be prepare for 1, 2, or 3-phase measurement settings.

3.10.2 Machine tool preparation

The measurement can be performed by a direct or indirect measurement principle as shown in Figure 3.5. The direct measurement leads to higher measurement accuracy but requires the implementation of connectors and results in changes on the machine tool electrical circuit. The compressed air flow sensor needs to be built in in line with the machine tool air supply. An example of the allocation of all required measurement points with used CTs is shown in Table 3.9.

Table 3.9: Example of measurement configuration at an EDM machine tool.

Name	Measurement point	Sensor	Remark
Total power supply 400V	At MT input	Acuvim 8	CT 100/5A
24V DC supply	NF4 (e-scheme)	Acuvim 3	CT 50/5A
Generator	NF2 (e-scheme)	Acucim 4	CT 50/5A
200V AC supply	NF0 (e-scheme)	Acuvim 5	CT 100/5A
Drives	FP2	Acuvim 6	direct
Filterpump	KM2	Acuvim 1	direct
Feed pump	FP1	Acuvim 7	CT 50/5A
Cooling pump	KM7	Acuvim 2	direct
Compressed air	External	Cair 00	direct

After the measurement points are defined and the sensors connected, several measurement system tests need to be performed to guarantee valid data. This includes the test for the appropriate phase assignment and CT direction by the phase balancing and plausibility check with

$$P_{1,n} + P_{2,n} + P_{3,n} \geq P_{eff,n} \tag{3.19}$$

To check the correct CT direction, the effective power of each component must always be positive. Furthermore, a checksum of all measured phases P_1 to P_N is compared to the total effective power $P_{eff,t}$.

$$P_{eff,n} \geq 0 \text{ and } \sum_1^n P_{eff,n} \leq P_{eff,t} \tag{3.20}$$

These tests ensure the correct measurement results of the implemented sensors.

3.10.3 Machining processes

As indicate in the state of the art the evaluation of the machine tool depends not only on the machine tool configuration but also on the individual use. The machine tool use and resulting energetic behavior is defined by the duration and sequence of the given machine tool states. The machine tool states are defined by the mode of operation. Modes of operation represent the machine tool behavior according to the safety standards, e.g. manual mode, automatic mode, setting mode. Based on this definition the energetically relevant machine tool operating states can be defined in; *OFF*, *Startup*, *Standby*, *Ready*, *Processing*. This definition is also given in ISO 14955 [29]. For the measurement the following operating states are chosen (Table 3.10).

Table 3.10: Machine tool operation modes

Name	Mode	Description
OFF	OFF	Machine tool in *OFF* mode
Startup	OFF--> ON	Turn on main switch of machine tool
Standby	STBY	Machine tool in *standby* mode
Ready	RDY	Machine tool in *ready* mode
Process	PR	Machine tool in *process* mode
Switch off	ON --> OFF	Turning off machine tool

Machine tool mode *OFF*

The operation mode "OFF" represents the machine tool when the main switch is turned off. This machine tool mode can be performed on all machine tools and production systems and indicates active but not needed components or energy loss, e.g. external monitoring devices, or compressed air leakages. The measurement is performed for $t_m = 180\ s$. This observation period in combination with the measurement resolution of $5Hz$ results in minimal 900 measurement points and is required to detect any periodical component power consumption, e.g. periodic air compressor activity or valve control. The measurement duration is valid as all auxiliary devices are expected to be switched off. As this mode represents a stationary energetic machine tool behavior, the power average value $ØP_{off}$ is considered as a valid and commonly applicable Energy Performance Indicator (EnPI).

Machine tool mode *Startup*

The operation mode *Startup* represents the machine tool mode where the main switch is turned on and the machine tool is starting up. In this machine tool mode the system software, control and individual components are starting up and the control behavior is measured. This mode can include operations for the component heat up, e.g. spindle pre-lubrication. The observation period is manufacturer-specific and depends on the individual startup times. As this mode represents a transient machine tool behavior, the power average value $ØP_{setup}$ is restrictedly suitable as an EnPI.

Machine tool mode *Standby* and *Ready*

Some machine tools have multiple standby state levels. The operation mode *Ready* is one possible standby state and machine tool manufacturer-dependent. The machine tool mode is given when the main drives are activated and the actual machining process could be started immediately. The observation period is fixed to minimum $t_{stby} = 180\,s$ to detect any periodical component power consumption, e.g. cooling compressors or hydraulic pumps. The observation period is valid when the periodic energetic behavior is known and adequately represented, e.g. at least two full periodic cycles, in the given observation period. As this mode represents a stationary energetic machine tool behavior, the power average value $ØP_{stby}$ or $ØP_{rdy}$ represents a valid and commonly applicable EnPI.

Machine tool mode *Process*

The operation mode *Process* represents the machining process during a defined reference process. The reference process or a set of relevant reference processes, represent all relevant machining operations which are required for the intended use of the given machine tool. The reference process represents therefore a typical machining process, including process forces and/or process-required energies, tool and workpiece handling and use of required fluids and/or process gases. The observation period is not fixed as the machining process is individually defined, machine tool and application-dependent. As this mode represents a transient machine tool behavior, the power average value $ØP_{PR}$ is restrictedly suitable as an EnPI.

Machine tool *Switch off*

The operation mode *Switch off* is given when the machine tool is switched off according to OEM specification. In this machine tool mode the individual, automatic or semi-automatic component switch off and control behavior is measured. This can include operations for the component cooling or cleaning, e.g. fans or exhauster. In accordance to *Startup* measurements, *Switch off* measurements indicate the energetic machine tool component behavior. The observation period is machine tool dependent. As this mode represents a transient machine tool behavior, the power average value $ØP_{swo}$ is restrictedly suitable as an EnPI.

The entire measurement including the measurement equipment implementation takes up to four hours and requires a minimal machine tool downtime, due to safety reasons, of currently $30min$. This application fulfils the industrial requirement of a comprehensive and efficient machine tool evaluation. The resulting data from the performed measurements are further used in the analysis which is explained in chapter 5.

3.11 Measurements and resulting findings

In the following measurement examples for the above mentioned machine tools states are shown. Figure 3.20 shows a multichannel measurement of a grinding machine tool during the off state. As the main switch is off the measurement shows a stationary compressed air leakage of $4.08\,m^3/h$ or $0.52\,kW$. In the following case the leakage is exceptionally high in comparison to other machine tools.

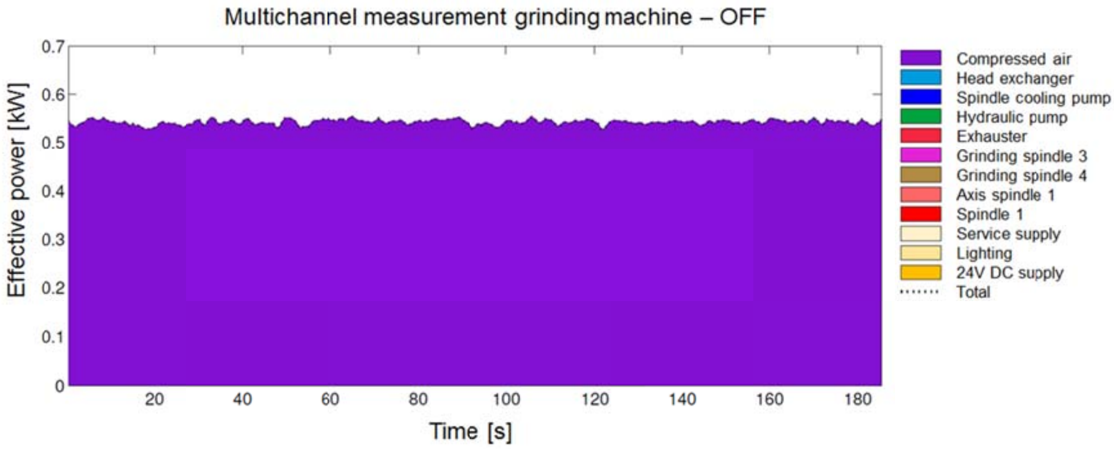


Figure 3.20: Multichannel measurement on grinding machine tool in machine state "OFF".

Figure 3.21 shows the machine tool startup and the energetic behaviour of the active components in this machine tool state. The startup time in the given case is 170s followed by an axes referencing process. During the machine tool startup a power peak of $\mathbf{13.6\ kW}$ was reached. Furthermore, the measurement shows that the machine tool can be used after 430s.

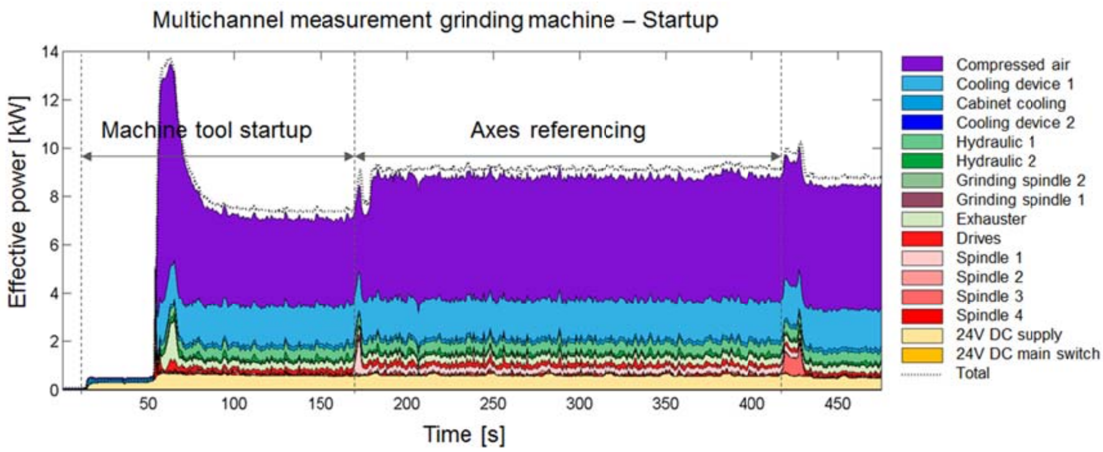


Figure 3.21: Multichannel measurement on grinding machine tool in machine tool startup.

One of the most common machine tools states is represented by the standby state as shown in Figure 3.22. The following machine tool state shows a high demand on compressed air of $9.3\ kW$ and a total power consumption at the machine tool standby of $11kW$. The standby state shows some activity on external monitoring devices.

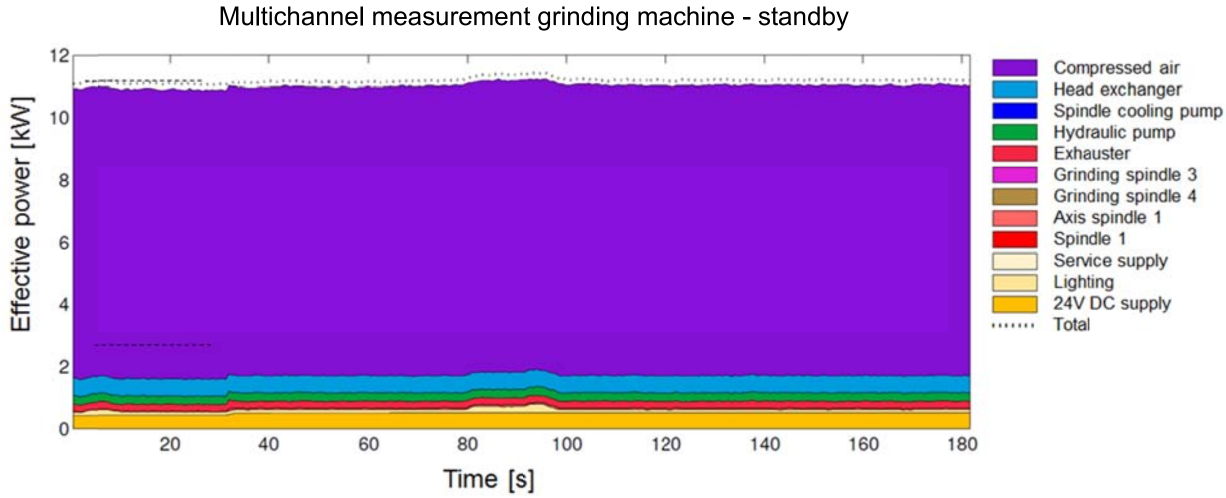


Figure 3.22: Multichannel measurement on grinding machine tool in machine tool state “standby”.

The machining process is machine tool and application dependent. In grinding operations auxiliary components are dominating in comparison to the drives. Figure 3.23 shows the machine tool switch off mode. In the given case all components except the 24V supply and the cooling fan are switched off immediately. The measurement of the switch off mode is required as some components might continue to run. Especially after grinding operations mist extraction through exhausters is necessary. In the given case this is not given.

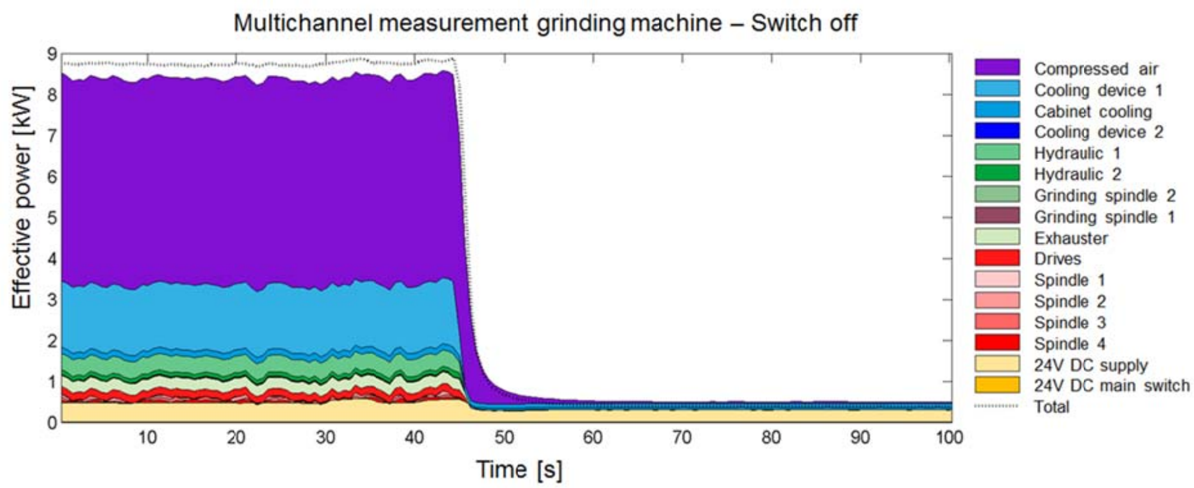


Figure 3.23: Multichannel measurement on grinding machine tool during switch off.

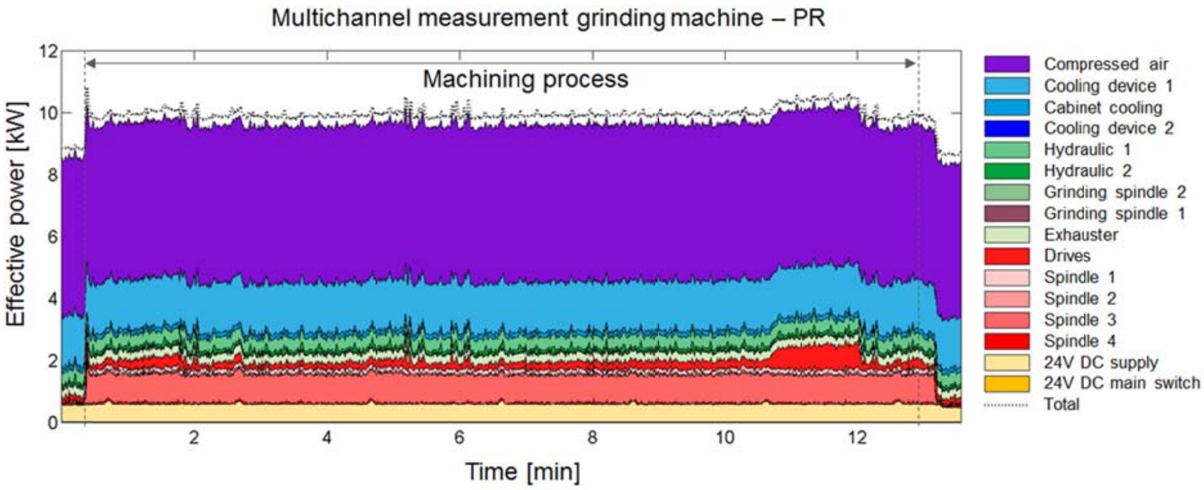


Figure 3.24: Multichannel measurement on grinding machine tool in machine state “process”.

Another observation from the measurement in Figure 3.23 is the inertia of the compressed air. The machine tool switch of is controlled by a stop valve in less the 0.5s and often leading to a pressure surge within the compressed air supply. This pressure drop and immediate stop is not measured as the measurement system does not show dynamic fluid changes.

Figure 3.24 shows a reference process on a grinding machine tool with a total duration of $480s$ including tool changes and dressing operations. The measurement shows that auxiliary equipment, e.g. cooling devices, hydraulic system, and the 24V DC supply, dominate the power consumption in this phase in comparison to the drives. The measurement and resulting area chart shows that the auxiliary components remain constant and on the same power level as in non-productive machine tool modes, e.g. standby, while changes on the axis and drives can be seen.

4 Simulation

4.1 Introduction

As shown in the chapter 2, simulation and modeling is applied to support the evaluation of resource and energy and are used for further analysis and optimization. In the following thesis models represent the mathematical and stochastic description of a system, whereas simulation use these models in relation to the time sequence to indicate the model behavior. Various statistical, physical, and hybrid modeling approaches on different system levels from machining to manufacturing processes exist. A modular approach or parameterizable macro models which is based on only a few essential parameters for the assessment and prediction of energy consumption with the inclusion of auxiliaries, does not exist. Furthermore, most simulation and model approaches for data evaluation are represented in research rather than in industry. In the following the application of simulation approaches is reviewed to be used for industrial measurement and monitoring tasks.

The goal of this chapter is to find suitable replacement of sensor and measurement information for the application in energy and resource monitoring in industry in accordance to available modelling approaches. Simulations should also be used for predictive applications as unnecessary and cumbersome measurements on the machine tool periphery installation can be avoided. In relation to the multichannel measurement approach, the application of supportive models is required to save costs and implementation effort in monitoring applications. Based on the selected approaches a validation in measurement and monitoring is performed to assess the benefit and required accuracy.

4.2 Energetic modeling approaches

A survey among Swiss SMEs [232] revealed available machine tool models in research and industry. Few models are applied on the machine tool level and are specifically designed for a particular parameter set as shown by Altintas et al. [233] and Eisele et al. [183]. The simulation approaches were classified according to the model classification of Domschke and Scholl [180] and the system application level as introduced by Neugebauer et al. [44] and combined in Figure 4.1.

This classification shows that several approaches are given but descriptive models on machine tool level are missing in research and industry. These models are required to replace sensors in monitoring applications. The study revealed further that the most important aspect for the simulation of energy on the machine tool is the possibility for optimization followed by the required information on the energetic behavior of the machine tool component. It can be therefore seen that various approaches of energetic machine tool models exist, whereas only a small share focuses not only on the process zone but also considers the auxiliary devices.

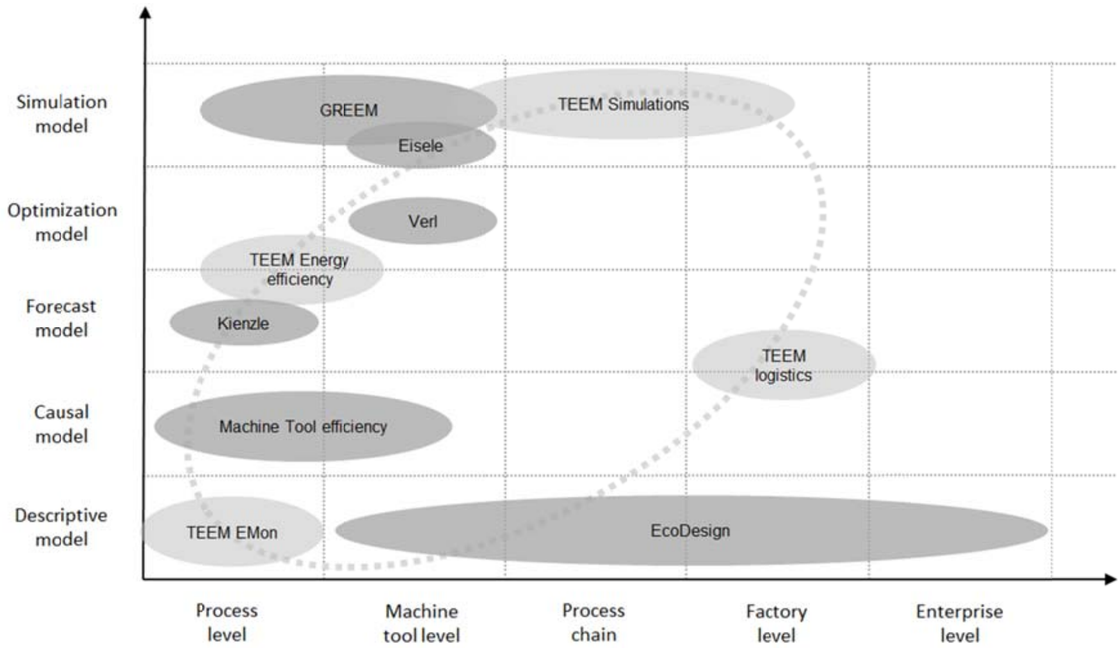


Figure 4.1: Available simulation approaches related to the evaluation of energy and resource consumption.

The major requirement to evaluate different machine tool types and configurations concludes that the concept of modular models is reasonable as indicated by Verl et al. [188]. Shnayder et al. [234] show an approach in the field of sensor network simulation for the test and development of sensor networks. This approach shows that sensors can principally be replaced by adequate models.

In summary, different approaches can be distinguished which are focused on optimization. For optimization procedures on the entire machine tool system, the interconnection and interoperability of components as well as accuracy of the component models are of special importance. Furthermore, the energetic behavior and its dependencies must be understood. These requirements are currently not sufficiently answered in literature. A large majority of the reviewed approaches base on existing and specific machine tools and manufacturing systems. The universal adaptation and parametrization of other components in order to replace sensor and for optimization measures at machine tools is not supported by simulation today.

4.3 Requirements

The review of available simulation approaches and the survey among Swiss SMEs [232] lead to the following requirements for the application of simulations and modelling approaches in the machine tool evaluation and application in measurement and monitoring. These requirements are taken as a reference for the application of modelling approaches for the machine tool evaluation and monitoring.

- **Purpose:** The interaction and the energetic behavior of the machine tool components must be quantified. Special focus for simulation approaches is given on the machine tool auxiliary as it can represent a major share of the total energy consumption and might also be process-independent.
- **Adaptability:** Analysis and optimization indication based on data analysis must be applicable. The application of simulation must lead to clear optimization and evaluation results.
- **Simplicity:** In order to the useful application in the industrial environment, model and simulations approaches need to be covered by an useful and simplified application. This covers the complexity of the model, the type and quantity of needed parameters, as well as the input mask or user interface. The parametrization effort should be limited while retaining the required accuracy. For this reason, effects with minor relevance to the energy demand, e.g. vibration or friction effects, should be neglected.
- **Effectiveness:** Only a s can be fully revealed mall number of input parameters is required. Simulation approaches must be based on only a few and accessible parameters, e.g. from the component data sheet.
- **Accuracy:** By using models in order to replace sensor for measurements the accuracy needs to be sufficient. Results from the modelling approach must meet the accuracy requirement which equals the given sensor accuracy of at least $\pm 5\%$.
- **Flexibility:** Modeling approach must be applicable for various machine tool setups and configurations. A flexible and modular approach is therefore required.
- **Modularity:** Due to the large variety of different machine tool types, configurations, component setting and parametrization models and simulations need to be adjusted and be configurable in order to describe the reality and the individual setting as accurate as possible.
- **Level of detail:** The simulation should focus only on the essential information. As models are used to replace sensors, the same or equal information is required. Information should be used for further comparison to measurement data and analysis.

4.4 Electrical component modeling

The following chapter is partly published in [235]. Two approaches for the energetic machine tool modeling, *EMod* (Energy Modelling approach) and *Teach-in*, were developed and reviewed in order to be used to replace sensors in monitoring applications for electrical machine tool components.

The modelling approach *EMod* primary addresses the evaluation of the entire machine tool and its components in an early development phase. For this reason a physical machine tool system is not required for the parametrization. The approach represents the significant physical effects and the energetic behavior of the machine tool system. It contains a configuration procedure based on given inputs as a component database which is linked to a physical model library. The actual simulation leads to an analysis procedure and further outputs in accordance with the above mentioned requirement of the industry. This approach generally fulfills the requirements of a primarily small number of input parameters and flexibility for the model implementation on various machine tool systems.

The second approach, *Teach-in*, is based on a given physical machine tool system. Therefore, pre-measurements are required in order to define the appropriate parametrization and to fulfil the accuracy requirements. This approach focusses on maximal accuracy with limited parametrization effort. The energetic behavior of machine tool components, in particular transient operations, can be fully revealed. This modelling approach is also fully independent of physical assumptions and simplifications as it is based on a cause-effect logic. The approach relies on input parameters, e.g. "*component on"* or "*component off"*, which needs to be pre-defined on a given machine tool system and related machine tool components.

Both modelling approaches are assessed and compared in order to substitute sensor in measurement and monitoring application by suitable simulation according to the given requirements.

4.5 EMod

Emod represents a modelling framework for the machine tool and its components within the system boundary as defined in ISO 14955 [29]. It is based on the mathematical relation and composed with Matlab Simulink. Special focus is given on the modularity and potential application in measurement and monitoring application. Figure 4.2 shows the basic structure and procedure of the energy model framework *EMod* [14]. It contains a configuration procedure based on given inputs as a component database which is linked to a physical model library. The actual simulation leads to an analysis procedure and further outputs in accordance with the above mentioned requirement of the industry.

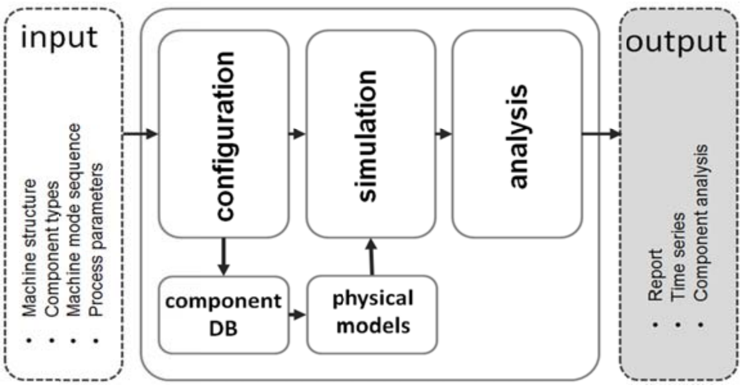


Figure 4.2: Structure of the modelling framework EMod. Input is represented by parameters given from the machine tool component data sheets. The output can be used for further data analysis.

An essential element of this approach is the modularity and interchangeability of the machine tool component models. The model has been designed and evaluated upstream the energy flow, starting from the initial cutting process. This energy demand is described mathematically by the application of the Kienzle cutting force model. Input parameters of each modelled machine tool component are therefore directly or indirectly dependent of the initial machining process.

Thus, in accordance with Guzzella and Sciarretta [236], a quasi-static simulation (QSS) is applied. For this reason it is essential to describe the machining process, in particular, the required forces or process energy at the TCP. Transient activities represented by peak values, e.g. spindle startup, are neglected in this model approach because of the following reasons:

- Some transient activities, e.g. spindle startup, are represented by dynamic forces and inertia. Therefore additional models of the mechanical relations are required which are not present in the given approach.
- Transient activities are dependent on the control of the system. The given approach does not cover the system component control.
- A peak value at the startup of the component infringes the fundamental assumption of the QSS of a quasi-static behavior.

QSS can reduce the simulation times in comparison to a dynamic simulation within a complex environment. This is due to the reduced number of differential equations. Investigating the causalities of the power consumption on the level of components, the input energy flow is driving the output energy flow. For example, the input, voltage and current, to a drive determine its output power. In QSS, this relationship has to be inverted:

$$P_{out} = f(P_{in}) \Leftrightarrow P_{in} = f^{-1}(P_{out}) \tag{4.1}$$

Hence, QSS requires an invertible mapping function of the input to the output power. To achieve the requested modularity of the simulation approach, generic components are used. A generic component can be represented for instance by a motor with pre-defined inputs, e.g. rotational speed and torque, and outputs, e.g. consumed power and heat loss. Subsystems of the same generic type have the same interfaces and can be replaced by another generic component of the same type. In the following, relevant generic machine components for the electro-mechanical part are derived.

Constant consumer: Based on an operating state, the consumption, e.g. power or material flow, is stationary. The input signal is given by the operating state, whereas the output is represented by a constant power consumption.

Motor: A given rotational speed and torque demand is mapped to a power demand. Dependent on the point of operation and related motor efficiency map, the effective power is calculated.

Pump: A pump moves an incompressible fluid. For a given mass flow demand and a state of operation, the requested power is calculated. Furthermore, the effective power is calculated. In cases where the pumping system includes storages – i.e. a pressure tank – the inlet flow rate may differ from the demanded outlet flow rate. In this case, the inlet flow rate is calculated additionally.

Fan: A fan is used to move a compressible fluid over small pressure gradients. The operational level of the fan is given as an input. The power demand and the resulting mass flow are calculated.

Figure 4.3 shows an example of the total interrelation of components with different generic types and their in- and outputs on an example of the turning machine tool Schaublin 42L.

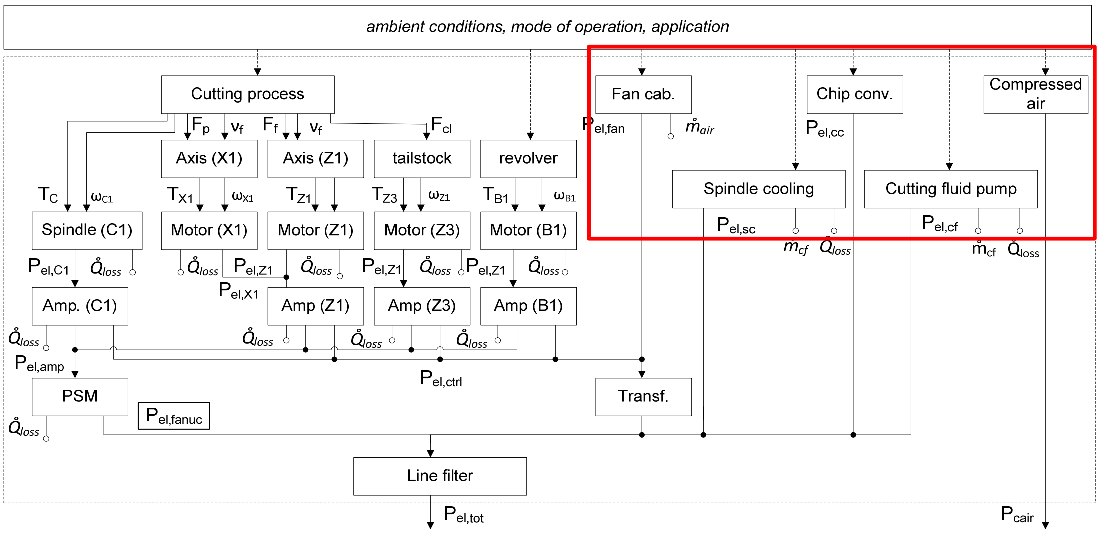


Figure 4.3: Example topology of a machine tool system. The red box represents auxiliary components which are fully or partly independent from the machining process.

The application of the *EMod* modelling approach for the measurement and monitoring purpose is focusing on auxiliary components as marked in red in Figure 4.3. Table 4.1 shows the selected generic components and related in- and outputs.

The initial energetic behavior of the auxiliary is initialized directly or indirectly by the actual cutting process at the TCP as shown in Figure 4.3. For the validation of the modeling results, the machine tool energy model was applied on a turning process and is mainly based on static cutting parameters.

Table 4.1: Types of generic components and their inputs and outputs.

Generic component	Inputs	Outputs
Constant consumer	S_{cmp} [-] state of the component	P_{tot} $[W]$ resulting consumption
Motor	T $[Nm]$ required torque ω $[rpm]$ required rotational speed	P_{tot} $[W]$ resulting consumption $\dot{Q}_{loss}[W]$ thermal losses η $[-]$ current efficiency
Pump	S $[-]$ operational state $\dot{m}_{dmd}[^{kg}/_{s}]$ required mass flow	P_{tot} $[W]$ resulting consumption $\dot{m}_{in}[kg/s]$ mass flow into the pump $\dot{Q}_{loss}[W]$ thermal losses
Fan	$u[-]$operational level (0…1)	P_{tot} $[W]$ resulting consumption $\dot{Q}_{loss}[W]$ thermal losses $\dot{m}_{in}[kg/s]$ created mass flow
Hydraulic	$F_{dmd}[N]$ demanded force $v_{dmd}[m/s]$demanded displacement speed	Resulting pressure $\dot{m}[kg/s]$ resulting mass flow

The following turning process parameters are considered: Rotational speed of the main spindle ω_C, the translational speeds of the z-axis v_z and x- axis v_x, and the cutting depth α_p. Moreover, parameters on the workpiece material, cutting tool and angle of setting κ between the work piece and cutting tool are needed. Relevant parameters can be found as statistical data in literature. As these parameters are strongly dependent on the individual work piece and tool relationship as well as cutting edge condition, force measurements are required to define specific Kienzle parameters for the given test case scenario and to reach a simulation accuracy of $\pm 5\%$.

According to this approach the cutting force F_C, feed force F_f and passive force F_p can be calculated. By neglecting the bearing friction caused by side forces, F_C is the most relevant for the torque calculation of the spindle.

$$F_c = b \cdot h^{1-z_c} \cdot k_{c1.1} \tag{4.1}$$

When applying the equation to the model, the relation between rotational speed ω_C, feed rate v_z and chip dimension have to be made, while constant chip dimension with constant diameter and no z-movements are given.

With the applied assumptions and further geometrical simplification, the resulting cutting force F_C is represented by:

$$F_c = \frac{a_p}{\sin\,\kappa} \cdot \left(\frac{2 \cdot \pi \cdot v_c}{\omega_c} \cdot \sin\,\kappa \right)^{1-z_c} \cdot k_{c1.1} \tag{4.2}$$

$b\ [mm]$:	Chip height	$v_c\left[\frac{mm}{s}\right]$:	Cutting speed
$a_p\ [mm]$:	Cutting depth	$\omega_c\left[\frac{rad}{s}\right]$:	Rotational speed
$\kappa\ [deg]$:	Setting angle (static)	$z_c[-]$:	Corrective factor
$k_{c1.1}\left[\frac{N}{mm^2}\right]$:	Unit specific cutting force coefficient		

Constant consumer

The energetic component behavior is derived from the machine tool operation mode and/or the initial cutting process. Within the *EMod* simulation the timing for the machine tool operation has to be assumed or combined with other machine tool components. A certain state of the component causes a defined output P, where the component state S_{mch} is caused by the machine state S_{mch}. The set of states of the machine tool are given as $S_{mch} = \{S_{mch,i} | i = 1,2, \dots, N_{mch}\}$ and the states of the component as $S_{cmp} = \{S_{cmp,j} | j = 1,2, \dots, N_{cmp}\}$, where $N_{mch} \geq N_{cmp}$. The relationship between S_{mch} and S_{CMP} is defined in a 1-to-1 relationship. In order to simulate the component behavior two state mappings are required. First the mapping of the machine state to the component state $\sigma(S_{mach})$, second the mapping of the component state to the output $\sum(S_{cmp})$. This leads to the equations for a constant component:

$$S_{cmp}(t) = \sigma(S_{mch}(t)) \quad \text{and} \quad P_{tot}(t) = \sum(S_{cmp}(t)) \tag{4.3}$$

Furthermore, each machine tool component state $S_{cmp} \in \{1,2, \dots, N\}$ with N component power levels needs to be defined. The mapping can be realized by a vector $\vec{P} = [P_1, \dots, P_N]^T$. The states can be taken from the component data sheet or need to be assumed when a physical system component is not present.

Asynchronous motor

Within the machine tool system various types of electrical motors exist, e.g. synchronous or asynchronous motors. The motors reprent fans, pumps or filter motors. For the asynchronous motor with given rotational speed $\omega(t)$ and torque $T(t)$, the mechanical power is calculated according to:

$$P_{mech} = \omega(t) \cdot T(t) \tag{4.4}$$

For a particular operation point (ω, T) and further ambient influences, the motor requests a certain effective power P_{el} from the NC unit (Figure 4.4). In most cases asynchronous motors are running at constant rotational speed $\omega(t) = const$, not controlled by frequency converters.

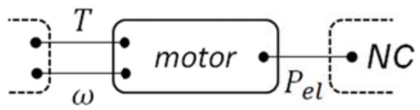


Figure 4.4: Component interconnection with the power-line $\boldsymbol{P_{el}}$ and to the transmission of mechanic power by $(\boldsymbol{\omega}.\boldsymbol{T})$.

The effective power P_{el} and resulting efficiency, depend on the operational point (T, ω) and on ambient conditions, such as temperature ϑ_{amb}. Furthermore, a motor has several losses, such as static friction, dynamic friction, thermal effects and others. For an overview on the modelling of losses further reference is given to Vanhooydonck and Kalenda [237]. Effects with a limited impact on the energetic behavior and power consumption are summarized in the component efficiency η. The motor efficiency η is defined by:

$$\eta(t) = \eta\big(T(t), \omega(t)\big) = \frac{P_{mech}}{P_{tot}} \Leftrightarrow P_{tot}(t) = \frac{T(t) \cdot \omega(t)}{\eta(T(t), \omega(t))} \quad (4.5)$$

With known $\eta(T, \omega)$, the effective power demand $P_{eff,n}$ can be calculated with the mechanical power demand P_{mech}. The input vector $\vec{u} = [\omega, T]^T$ and the output vector $\vec{y} = [P_{tot}, \eta]^T$result from the interrelation of ω and T, from an efficiency map. The motor efficiency from an available efficiency map might be given for punctual operation points in the catalogue data or must be measured. Based on the available information missing efficiency information for a given $\eta(T, \omega)$ can also be approximated by using linear interpolations within the efficiency map and known data points.

Servomotor

In difference with a motor from the section above, a servomotor is assumed to be a synchronous motor connected to control electronics, e.g. amplifier as shown in Figure 4.5. The amplifier supplies the motor with a variable armature voltage $U_a(t)$ and current $I_a(t)$. The motors characteristics is fully described by the armature resistance R_a, speed constant κ_i and torque constant κ_a.

Given now as input the requested torque $T(t)$ and the requested rotational speed $\omega(t)$. The torque given by the motor has to be the requested torque plus the friction torque. According to the standard model for synchronous drives as shown by Guzella and Sciarretta [236], the behavior of the servomotor can be described as:

$$T(t) = \kappa_a \cdot I_a(t) \qquad and \qquad U_i(t) = \kappa_i \cdot \omega(t) \tag{4.6}$$

With the equations above, the armature current $I_a(t)$ and the EMF voltage $U_i(t)$ can be calculated, as the armature voltage $U_a(t)$ and the voltage drop over the internal resistance can be calculated by using Kirchhoff's current law:

$$U_r(t) = I_a(t) \cdot R_a = \frac{T(t) + T_{fr}}{\kappa_a} \cdot R_a(t) \tag{4.7}$$

$$U_a(t) = U_i(t) + U_r(t) = \kappa_i \cdot \omega(t) + \frac{T(t) + T_{fr}}{\kappa_a} \cdot R_a \tag{4.8}$$

The input vector $\vec{u} = [\omega, T]^T$ with the input parameters rotational speed ω and required torque T can be read out from the NC. The output vector $\vec{y} = [P_{tot}, \eta]^T$ results from the following interrelation:

$$P_{tot}(t) = U_a(t) \cdot I_a(t) \tag{4.9}$$

$$\eta(t) = \frac{\omega(t) \cdot T(t)}{P_{tot}(t)} \tag{4.10}$$

Amplifier

To realize various speed and torque combinations on electric drives, amplifiers are required. As shown in Figure 4.5, the electric power P_{el} required by the motor is summplied by the connected amplifier. To do so, the amplifier requires the power P_{amp} for which $P_{amp} \geq P\_el$ generally holds. This is for two reasons: First, the amplifier shows a power dependent conversion efficiency $\eta(P_{mot})$. Second, the electronics of the amplifier require a constant energy flow P_{const}.

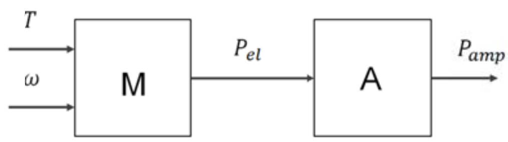


Figure 4.5: Generalized modelling of asynchronous motor with the elements motor (M) and the amplifier (A).

With this information, the amplifier power demand can be calculated as

$$P_{tot} = \frac{P_{mot}}{\eta(P_{mot})} + P_{const.} \tag{4.11}$$

With

P_{mot}: Mechanical power

T: Motor torque

ω: Angular velocity

$\eta(P_{mot})$:Efficiency map of amplifier

$\eta(T, \omega)$: Efficiency map dependent on T and ω

P_{tot}: Total resulting effective power

$P_{const.}$: Constant power consumption at amplifier

Hydraulic system

According to Dürr and Wachter [238] hydraulic systems consists in general of the following elements which need to be considered when simulated (Figure 4.6).

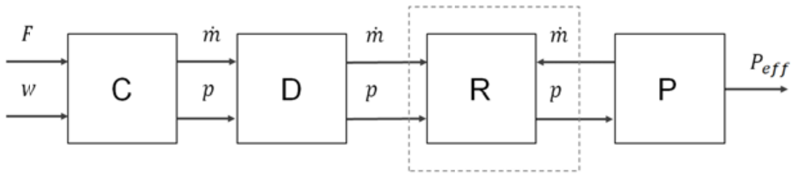


Figure 4.6: Generalizes modelling of the hydraulic system with the elements comsumer (C), distribution (D), reservoir (R), and the pump (P).

Each element of the hydraulic system has specific in and outputs which are given by the force $\boldsymbol{F}$ and velocity $\boldsymbol{\omega}$ as the input parameters for the cylinder (C). The cylinder generates the output parameters required mass flow $\dot{\boldsymbol{m}}$ and required pressure $\boldsymbol{p}$ which are further used as inputs for the distribution system (D), e.g. pipe or valves, and the pressure reservoir (R). Finally the pump and resulting effective power $\boldsymbol{P_{eff}}$ and the mass flow supply to the reservoir $\dot{\boldsymbol{m}}$ can be calculated in relation to the given pressure $\boldsymbol{p}$. General parameter of the hydraulic system is the hydraulic oil and its specification.

Cylinder

According to the conversion of mass for defined system boundaries the change of the mass flow $\dot{\boldsymbol{m}}$ within the cylinder is given with:

$$\frac{dm}{dt} = \rho \cdot w \cdot A_1 - \dot{m}_{leak} = \dot{m} - \dot{m}_{leak} \tag{4.12}$$

with

ρ: fluid density $[kg/m^3]$

w: fluid velocity $[m/s]$

A_1: cylinder cross section $[m^2]$

$\dot{m}_{leak}$: mass flow leakage at cylinder edge $[kg/s]$

According to the conversion of momentum, given with:

$$m \cdot \frac{d^2}{dt^2} x = \sum_{i=1}^{n} F_i \tag{4.13}$$

The relation of the cylinder surface and required force equals in:

$$m \cdot \frac{d^2}{dt^2} x = p_1 \cdot A_1 - p_2 \cdot A_2 - F - F_R \tag{4.14}$$

with

m: Mass $[kg]$

x: control variable $[-]$

p_1: pressure in cylinder chamber 1 $[Pa]$

A_1: cylinder cross section, chamber 1 $[m^2]$

p_2: pressure in cylinder chamber 2 $[Pa]$

A_2: cylinder cross section, chamber 2 $[m^2]$

F: cylinder force $[N]$

F_R: Friction force $[N]$

As the friction force can be replaced by the hydraulic-mechanical efficiency which is available from the manufacturer's datasheet and the dynamic term is neglected as it is considered as energetically not relevant, equation (4.14) can be simplified to:

$$p_1 = \frac{F}{A_1 \cdot \eta_{hm}} + p_2 \cdot \frac{A_2}{A_1} \tag{4.15}$$

As $p_1$represents the pressure in the cylinder chamber one the pressure in cylinder chamber 2 p_2 results from the Bernoulli resistor equation in:

$$p_2 = \frac{\dot{m}^2}{2 \cdot \rho \cdot k^2 \cdot A_{pipe}^2} \tag{4.16}$$

The relation between the input and output is given with the piston radius r and drilling hole radius R:

$$\dot{m} = \rho \cdot w \cdot A_1 + \frac{\Delta p \cdot \pi \cdot (R + r) \cdot (R - r)^3}{12 \cdot \nu \cdot b} \tag{4.17}$$

and

$$p_1 = \frac{F}{A_1 \cdot \eta_{hm}} + \frac{A_2}{A_1} \cdot \frac{\dot{m}^2}{2 \cdot \rho \cdot k^2 \cdot A_{pipe}^2} \tag{4.18}$$

Distribution

The distribution of hydraulic oil is represented by a pipe. The pressure drop within a pipe dependents on the diameter and the friction coefficient λ. This relation is given in the Darcy-Weisbach equation:

$$p_{loss} = \frac{\rho \cdot w^2}{2} \cdot \lambda \cdot \frac{l}{d} \tag{4.19}$$

The friction coefficient is dependent on the flow regime which is defined by the Reynolds number:

$$Re = \frac{w \cdot d}{\nu} \tag{4.20}$$

It is assumed that the flow is turbulent. Furthermore, the surface roughness is neglected due to the assumption of smooth pipe and a wall velocity of zero, which leads to the following equation:

$$\lambda = \frac{0.3164}{Re^{0.25}} \tag{4.21}$$

Pump and reservoir

Pressure tanks consist of two chambers, one with the pressurized oil and the other with compressible gas with an adjustable pressure value as shown in Figure 4.7.

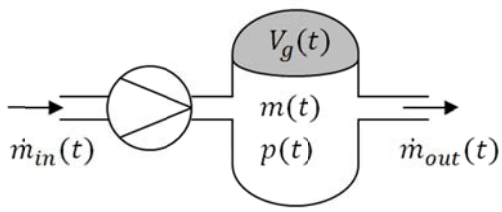


Figure 4.7: Pump with pressure tank. The compressed gas is represented by the grey area. A mass $\boldsymbol{m(t)}$ and pressure $\boldsymbol{p(t)}$ within the tank is given.

The balance of mass for the chamber with the fluid is given to:

$$\frac{d}{dt} m(t) = \dot{m}_{in}(t) - \dot{m}_{out}(t) \tag{4.22}$$

Since incompressibility is assumed, the total oil mass m(t) in the tank can be represented by its column $V(t)$. The relation of the tank V_t and the pressure chamber V_g at time t is:

$$V_g(t) = V_g + V_t - V(t) \tag{4.23}$$

with

$\dot{m}_{in}(t)$: Mass flow input $[kg/s]$

$\dot{m}_{out}(t)$: Mass flow output $[kg/s]$

V_g: Volume of fluid in pressure chamber $[m^3]$

V_t: Volume of fluid in tank $[m^3]$

$m(t)$: fluid mass $[kg]$

ρ_t: fluid density $[kg/m^2]$

With the assumption of an ideal gas and by neglecting the influence of fast dynamics of the fluids the pressure in both chambers are equal. Thus, the pressure of the fluid equals to:

$$p_t(t) = p_g \cdot \frac{V_g}{V_g(t)} = p_g \cdot \frac{V_g}{V_g + V_t - \frac{m(t)}{\rho_t}} \tag{4.24}$$

The relation between the mass flow and pressure gradient is described by the pump map f_{map} from the manufacturer in relation to the pressure difference $p_t(t) - p_{amb}$. For the simulation it is important to consider if and when the pump is turned on and off based on the minimal pressure $p_{t,min}$ and maximal pressure $p_{t,max}$ which are used for the hydraulic pump control. For this reason the following relations for the $\dot{m}_{in}(t)$ need to be considered:

$\dot{m}_{in}(t) = f_{map}(p_t(t) - p_{amb})$ if $p_t(t) < p_{t,max}$ and pump was on

$\dot{m}_{in}(t) = f_{map}(p_t(t) - p_{amb})$ if $p_t(t) \leq p_{t,min}$ and pump was off

$\dot{m}_{in}(t) = 0$ if $p_t(t) > p_{t,min}$ and pump was off

$\dot{m}_{in}(t) = 0$ if $p_t(t) \geq p_{t,max}$ and pump was on

The pump state is shown in the state diagram Figure 4.8. The function f_{map} includes the pump specific mass flow given a pressure difference over the pump, also known as pump map.

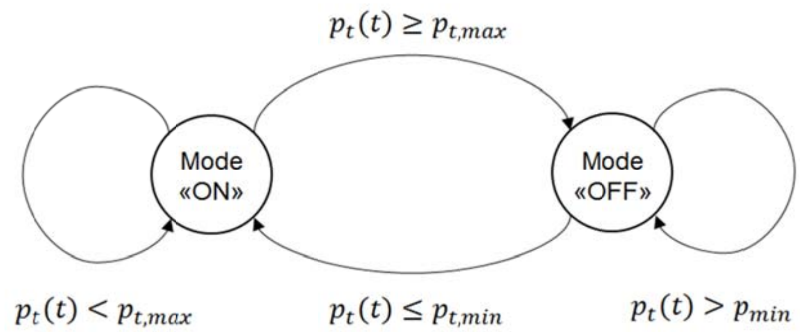


Figure 4.8: Example of the functional state of the pump depending on the hysteresis control.

Based on this differentiation $f(\dot{m}_{in}(t))$ the power of the pump and reservoir results in:

$$P_{tot}(t) = f(\dot{m}_{in}(t)) \cdot P_{tot,pump} \tag{4.25}$$

The following parameters for the simulation of the hydraulic system are used (Table 4.2 - Table 4.5):

Table 4.2: Parameters chosen for the pump.

Parameter	Unit	Value		
Pressure	$p[Pa]$	5900000	6000000	7000000
Power	$P[W]$	650	650	700
Power	$P[W]$	950	950	990
Volumetric flow (idle)	$\dot{V}[l/min]$	6	6.5	6.6
Volumetric flow (flow)	$\dot{V}[l/min]$	8.5	9.5	9.6

Table 4.3: Parameters for the reservoir.

Parameter	Unit	Value
Reservoir volume	$V[m^3]$	0.01
Initial gas pressure	$p_{init}[Pa]$	6000000
Initial liquid volume	$V_t[m^3]$	0.0005
Maximum pressure	$p_{t,max}[Pa]$	7000000
Minimum pressure	$p_{t,min}[Pa]$	6000000
Ambient pressure	$p_{amb}[Pa]$	100000

Table 4.4: Parameters for the cylinder.

Parameter	Unit	Value
Piston cross section 1	$A_1[m^2]$	0.085
Piston cross section 2	$A_2[m^2]$	0.025
Piston thickness	$b[m]$	0.01
Efficiency	$\eta_{hm}[-]$	0.95
Stroke	$p_{t,max}[Pa]$	0.032
Fluid density	$\rho[kg/m^3]$	878

Table 4.5: Parameters for the pipe.

Parameter	Unit	Value
Pipe length	$l[m]$	1
Pipe diameter	$d[m]$	0.05
Initial liquid volume	$V_t[m^3]$	0.0005
Maximum pressure	$p_{t,max}[Pa]$	7000000
Minimum pressure	$p_{t,min}[Pa]$	6000000
Fluid density	$\rho[kg/m^3]$	878

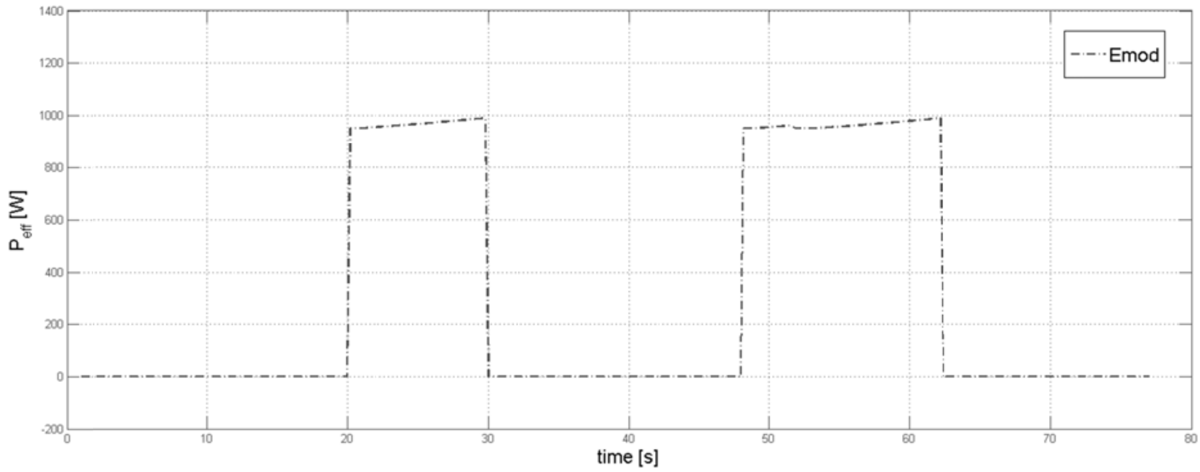


Figure 4.9: Simulation of the hydraulic system with a pressure reservoir on a MAG NDM200.

Figure 4.9 shows the simulation of the effective power of the hydraulic system P_{tot}. One can see that the pump is running periodically according to $f(\dot{m}_{in}(t))$ as defined in equation (4.25). The simulation shows an increasing power demand while the pump is operating and increasing pressure the pressure level in the pressure reservoir and results in a higher torque on the pump motor. The buckling in $t = 52s$ results from a parametrization error as more supporting points within the pump map are required to calculate the effective power P_{eff} in peripheral areas. An asynchronous energetic behavior as shown in Figure 4.9, with different operational durations of the two filling operations, is given. This cumulative effect is increasing over time.

4.6 Teach-in

The *Teach-in* modelling approach represents a selective component representation focused on constant and controlled-constant consumers as indicated in chapter 5. Multiple components can be covered as long a physical entity or machine tool component is present which provides a state signal, e.g. PLC status. A high accuracy can be reached if all relevant dynamic and non-dynamic machine tool component activities are mapped and quantified accordingly. Figure 4.10 shows the basic structure of the *Teach-in* approach. It contains a component measurement which is the input for the component analysis. Together with a defined machine component state definition and external machine tool signal the required information can be revealed. The simulation leads to outputs in accordance with industrial requirements.

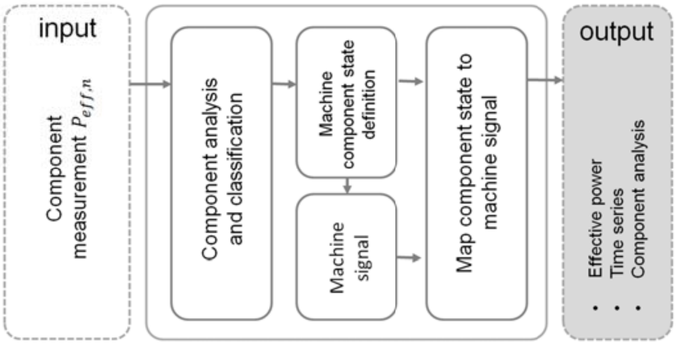


Figure 4.10: Structure of the modelling framework Teach-in.

The approach is machining process independent and therefore applicable on all machine tool components. The direction of evaluation within this model is given with:

$$P_{in} = f(P_{out}) \Leftrightarrow P_{in} = f^{-1}(P_{in}) \tag{4.26}$$

Therefore this approach represents the opposite approach in comparison to the *EMod* approach and relies on the input parameters.

4.6.1 Machine tool component selection and measurement

It is required to allocate the energetic machine tool component behavior. This requires a component measurement as indicated in chapter 3. The following components for the electro-mechanical part are identified to be most suitable for the application within the *Teach-in* approach. The components have the same inputs and outputs.

Constant consumers

The model can be applied on components with a stationary energetic behavior in dependency of a definite machine tool signal, e.g. PLC. In a first step the identified component for the *Teach-In* application need to be measured. Figure 4.11 shows a measurement of a typical constant consumer. According to the measurement the machine tool component can be classified in constant or controlled-constant with n defined energetic states. In the given example two component states can be identified.

$$f(P_{out}) \in \{0, n\} \tag{4.27}$$

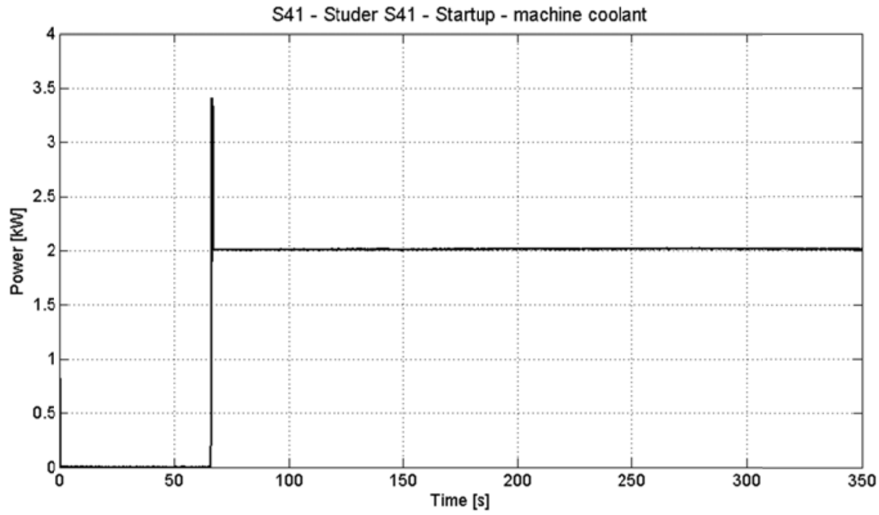


Figure 4.11: Effective power measurement of the cooling fan.

Machine tool operation states

The *Teach-in* approach strongly depends on the definite input of the machine tool control which results in a define machine tool component state. For this reason it is necessary to receive the input information from the PLC. To access the machine tool PLC information further reference is given to Siemens [239]. The PLC has defined inputs which, dependent on the PLC-programming, lead to defined outputs. These outputs define electrical, mechanical, pneumatic, or hydraulic actuators. For this reason two basic cases can be distinguished:

Case 1: $PLC_1\colon 0 \rightarrow 1$: Leads to a direct actuator signal, which controls the component energetic behavior, e.g. coolant fan turns on.

Case 2: $PLC_2\colon 0 \rightarrow 1$: Leads to an approval or unlocking information only. This information only unlocks the component control. The energetic machine tool component behavior might still be dependent on other entities, e.g. thermostat signal.

Contrary to the *EMod* approach, the machine tool operational state and related component behavior is clearly defined by the PLC state and relation as shown in equation (4.28). For the implementation within a monitoring strategy the PLC status of each machine tool component is continuously monitored to trigger the simulation.

$$\sigma(S_{PLC}) \in \{0,1\} \tag{4.28}$$

4.6.2 *Teach-in* example

Asynchronous motor

In the *Teach-in* approach the effective power of the consumer is measured as shown in Figure 4.12. Thus, all required dynamic component behavior are quantified. The measurement shows the energetic behavior of a cooling fan with a nominal power of $P_{nom} = 1kW$. Based on the machine tool state and from the performed pre-measurement of the machine tool components in all energetic relevant states, the energetic component behavior together with transient states, can be classified in four areas as indicated in Figure 4.12 and applied depending on the given PLC status ($\sigma(S_{PLC})$).

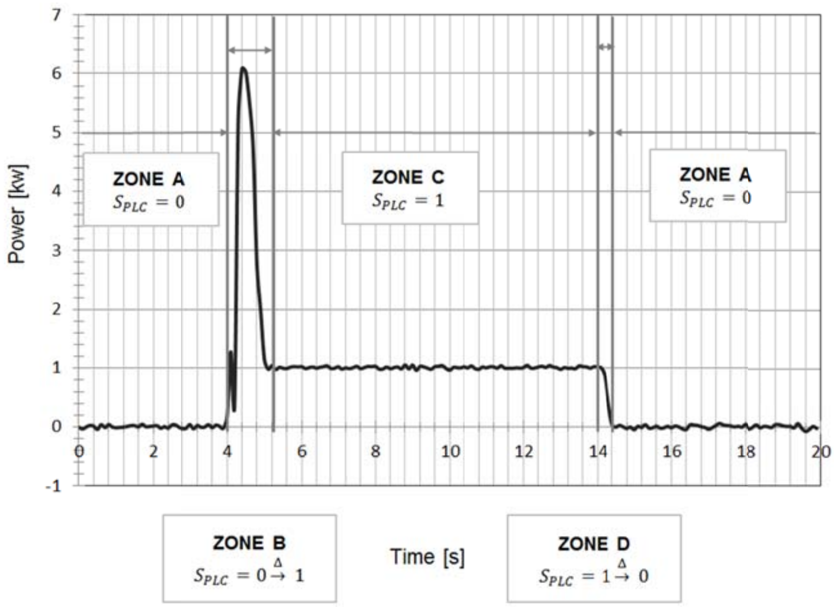


Figure 4.12: Component and classification of the energetic machine tool component behavior in operational modes.

The P-t-measurement of the controlled-constant component shows four areas that are defined as follows:

Zone A: The component state is defined by the PLC state $S_{PLC} = 0$. The resulting vector is static and given by $\vec{P} = 0$.

Zone B: This zone represents the machine tool component startup peak which can have an energetic relevance caused by inductive elements in the machine tool component. Therefore, a sampling rate of $5Hz$ is required, as indicated in chapter 3 and 5. Figure 4.12 shows that the component is turned on in second four. This leads to a PLC signal change from $S_{PLC} = 0$ to $S_{PLC} = 1$. The resulting peak is resolved by at least five measurement points. In the simulation and in the following example the vector $\vec{P}_B$ is represented by $\vec{P}_B = [0.33,\ 5.45,\ 6.01,\ 5{,}88,\ 3{,}47]^{0,2}$.

Zone C: The component status is defined by the PLC status $S_{PLC} = 1$ and represents a static machine tool behavior. In this phase the machine tool component is active. Due to possible changes of the power consumption, recalibration of the machine tool component, e.g. exhaust suction device, is required. However the component energetic behavior is defined by the nominal power as indicates in the data sheet or pre-measurement.

Zone D: The zone represents the machine tool component switch-off peak which could also lead to a power feed in back to the system. In the following case the machine tool component turn from "*on*" to "*off*" without a peak. In the simulation the vector $\vec{P}_D$ is represented by $\vec{P}_D = [3.63,\ 3.62,\ 3.34, 0.00,\ 0.00,]^{0,2}$.

Hydraulic system

The application of the *Teach-in* approach on the hydraulic system is fully independent of and component or subcomponent analysis. In general the effective power is given by the electric input of the hydraulic pump which is further dependent on the hysteresis value $p_{t,min}$. In the first step the effective power $P_{eff,tot}$ of the given system needs to be measured (Figure 4.13) and the relevant PLC signal needs to be revealed S_{PLC}.

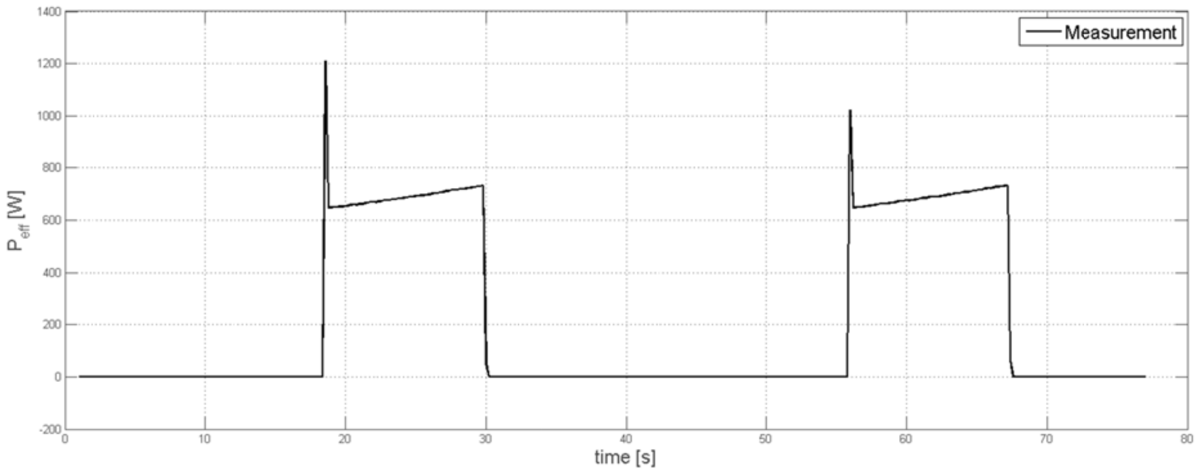


Figure 4.13: Measurement with the multichannel measurement of the effective power of the hydraulic system at the NDM200.

The measurement shows the typical startup behavior of a startup peak followed by a constant increase until the pressure tank is filled. The pump is active for $t_{pmp} = 12s$ during tank filling and turns on periodically after $t_{off} = 25s$. During t_{off} the machine tool is in standby mode and the pressure change in the hydraulic system is only given by pressure leakage at the valves. This behavior is therefore not process-dependent.

In the second step the PLC address of the hydraulic system is read. In the following case and based on the Siemens Solutionline NC, this information can be revealed from the machine tool individual Step 7 project and assigned R-parameters. The behavior of the hydraulic system can be separated into four segments:

A: For $S_{PLC} = 0;\ P_{eff} = 0$

B: For $S_{PLC} = 0 \rightarrow 1;\ \vec{P}_{eff} = [0,\ 1210,\ 649.9, 648.4]^{0,2}$

C: For $S_{PLC} = 1\ ;\ P_{eff}(t) = \frac{10.4}{81} t + 648.4$ for $\Delta t_{0 \rightarrow 1}$

D: For $S_{PLC} = 1 \rightarrow 0;\ \vec{P}_{eff} = [730, 732.6;\ 53.5,\ 0\ ]^{0,2}$

The four segments represent the energetic behavior of the hydraulic pump accordingly to the given signal from the PLC S_{PLC} and result in Figure 4.14:

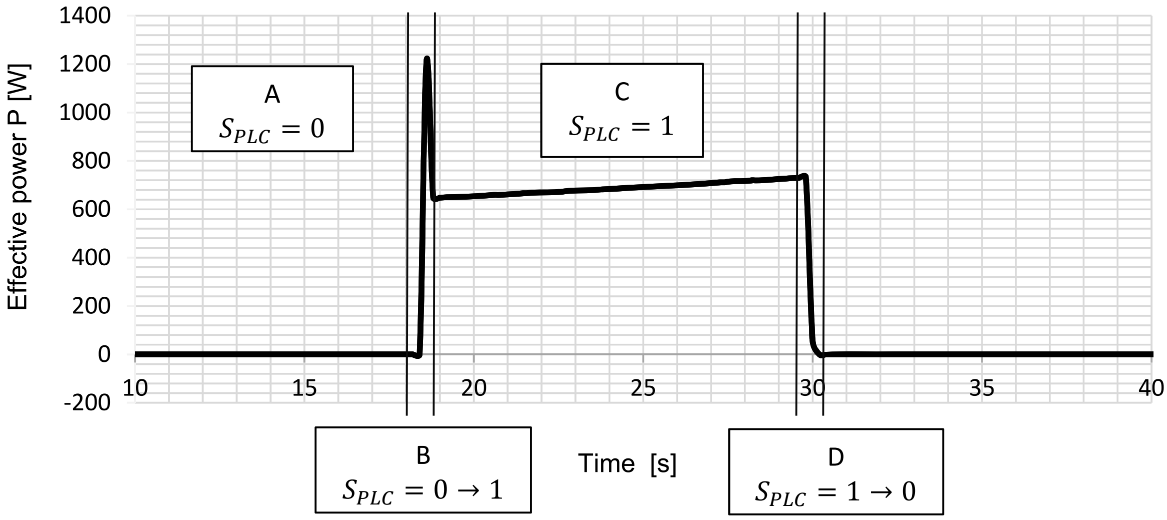


Figure 4.14: Segmentation of hydraulic pump measurement for Teach-In modelling.

The input parameter of the *Teach-In* approach is given by the PLC signal S_{PLC} which is continuously monitored over a PLC readout. The accuracy of the model depends on the sampling rate of the pre-measurement.

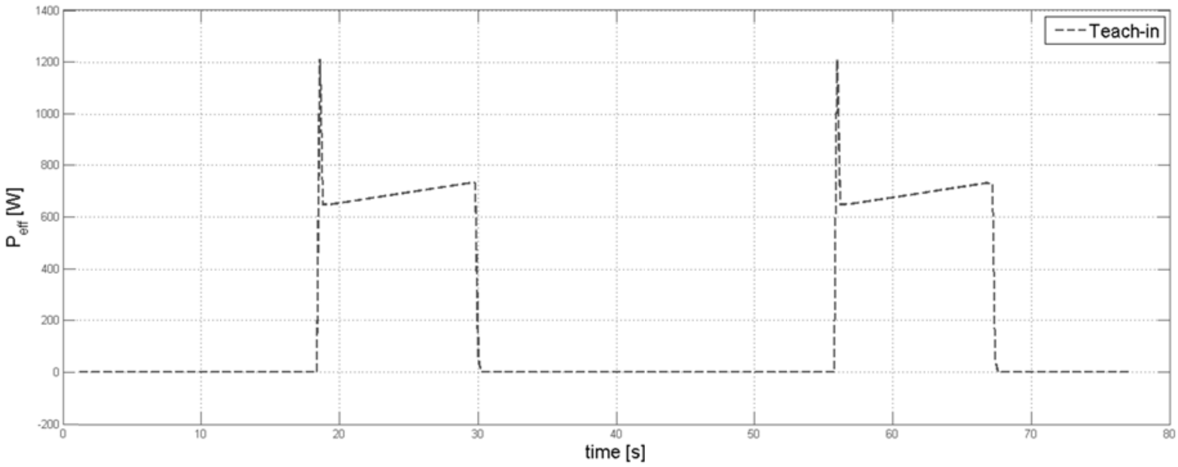


Figure 4.15: Simulation of the hydraulic system with a pressure reservoir by Tech-In on a MAG NDM200.

Figure 4.15 shows the simulation according to the sections as defined above. The energetic behavior of the simulated hydraulic pump is symmetrical. The stat-up peak is given accordingly to the measurement. Segment C is based on a linear pressure increase which is valid for incompressible fluids within the given system. In the following the *EMod* and *Teach-In* simulation is compared to the actual measurement.

4.7 Comparison and conclusion

The approaches are compared together in Figure 4.16. Both approaches have in common, that a pre-selection of the relevant consumers for the replacement of sensors through simulation has to be done. This can either be done by assumption of the consumer behavior as done in the *Emod* approach, or by pre-measurements and measurement analysis as done in the *Teach-in* approach.

The *Teach-in* approach further represents a simulation method based on a pre-measurement with an accuracy of minimal $\pm 5\%$, including all transient and dynamic energetic component operations. This model is applicable for constant and controlled-constant consumers, provided that they are controlled and clearly defined by a PLC signal S_{PLC}. This ensures the representation of the component dynamics and the appropriate timing for the energetic behavior. Due to the pre-measurement, a separate parametrization is not required.

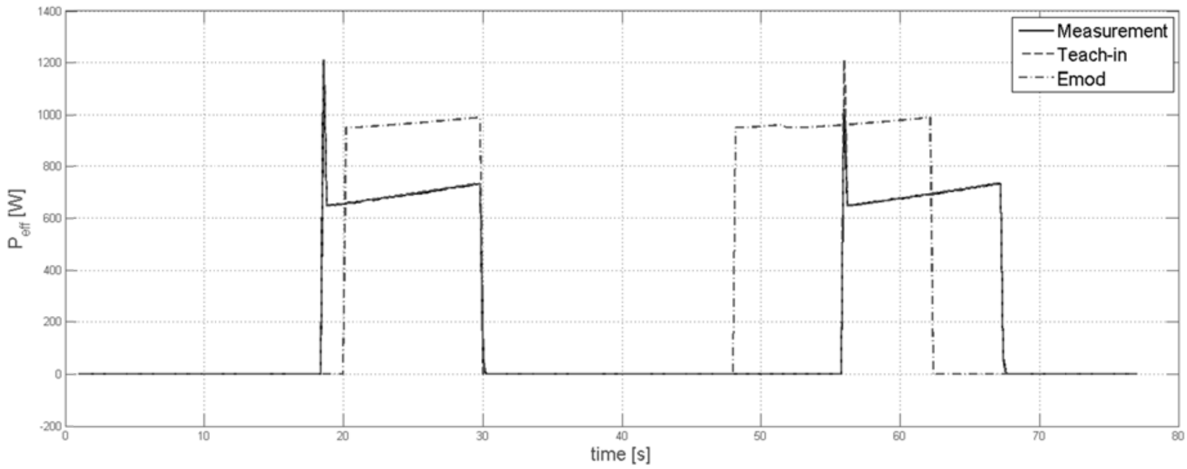


Figure 4.16: Comparison of the effective power measurement with the Teach-in and Emod approach based on synchronized time plots and known parameter set.

The *EMod* approach is based on mathematical methods and the physical relation within the considered components. This approach is suitable when the target application for the monitoring implementation is unknown or has to be applied on not yet available consumers or where pre-measurement is not possible, e.g. in an early development state. Main application is the prediction of the effective power for a certain machining process. The simulation is based on the ideal physical relationship based on assumptions as well as comprehensive simplifications. These simplifications enable the application of only a few given parameters but impede the application of this model approach for measurement or monitoring, as the required accuracy of $\pm 5\%$ cannot be guaranteed. For instance, the simplifications neglect dynamic effects, e.g. motor startup. Because of the unknown timestamp and inaccurate parameters, an increase in the simulation duration increases also the simulation error as showed in Figure 4.16. Therefore, this approach can only be used for the exchange for particular channels within a multichannel measurement, in order to simulated components, which are not present or measureable. Thus, this method is not applicable for trusted monitoring data.

Both methods represent a reading of vector elements which fully describes the constant component model with input $u = S_{cmp}$ and output $Y = P_{tot}$. For the application in measurement or monitoring both methods require a reference value as a checksum if the model is still accurate. For the checksum the effective measured power $P_{eff,m}$ at the total machine tool input needs to be smaller or similar to the sum of all simulated effective power value of each component P_{eff,n_sim}:

$$P_{eff,m} \geq \sum_{1}^{n} P_{eff,n\_sim} \tag{4.29}$$

For the quantification of the data accuracy of the simulation, the applied models are compared to actual and trusted power measurements which are performed by the multichannel measurement system as introduced on chapter 3.

According to the given requirements on the simulation of the machine tool components in order to replace sensors for the energy and resource monitoring in chapter 4.3 the following conclusions can be made:

Purpose: Both simulation approaches fulfill this requirement as the simulations are applied on machine tool components and subcomponents and the overall machine tool auxiliary.

Adaptability: The result of both simulation approach result in effective power values with a defined time stamp. Based on the applied sampling rate analysis methods can be applied on the *EMod* and *Teach-in* approach. In order to detect power peaks the *Teach-in* approach needs to be used.

Simplicity and effectiveness: As shown by Table 4.2 to Table 4.5, and despite some simplifications and subsystem complexity, more than 23 parameters are required in to set up the *EMod* component model on the hydraulic system. Those parameters are either not given or inaccurate. The *Teach-in* approach requires a pre-measurement and a PLC signal. This is not always possible.

Accuracy: The *Teach-in* model showed that an accuracy of $\pm 5\%$ can be achieved as it primary depends on the applied measurement. As the energetic behavior of the machine tool components might change over time, e.g. through wear, a continuous comparison with measurements and recalibration must be performed in order to guarantee an adequate optimization indication. The accuracy of the *EMod* approach is highly dependent on the parametrization. For a monitoring approach the accuracy of $\pm 10\%$ is considered as not sufficient.

Flexibility: Both models can be applied on machine tool components and subcomponents. For the *EMod* modeling the application and related accuracy strongly depends on the available parameters. The *Teach-in* approach is applicable on components with a stationary energetic behavior with a clear signal indicating the operational mode.

Modularity: The *EMod* simulation strongly depends on the available parameters. While a physical entity is required in the *Teach-in* approach. Therefore, the level of modularity with the *Teach-in* approach is considered higher compared to the *EMod* simulation approach.

Level of detail: The comparison of the two approaches with the actual effective power measurement proofs that the *Teach-in* approach fulfils all required details for a further analysis and monitoring. However, only the sampled signal is reflected. Therefore, the correctness of the initial and measured signal is of high importance and the measurement value must be approved by independent external sensors. The *EMod* approach can be used as a quantitative tool as it indicates the basic energetic behavior without a direct validation and approval of correctness.

In summary Table 4.6 shows both methods in comparison to the defined requirements.

Table 4.6: *Comparison of method Teach-in (Method A) and EMod (Method B) in relation to the given industrial requirements.*

Characteristic / requirements	Fulfillment Method A	Fulfillemt Method B	Comment
Accuracy	●	◐	Method A represents an accuracy depending on the performed measurement accuracy
Modularity	◐	◐	Both methods represent approaches for different constant and constant controlled machine tool components
Complexity / Parameterization	●	○	Method B rquires more parameters and information from data sheets, wheres as method A bases on measurements
Pre-measurement	○	●	Method A rquires a running physical system to perform pre-measurements, whereas method B do not need a physical system.
Duration of implementation	◐	○	Due to the required data sheets in method B and input into the framework the implementation time is higher.
Needed recalibration	◐	○	Both methods require a recalibration, whereas method A can be done by measurements.

● = good fulfillment, ◐ = medium fulfillemt, ○ = poor fulfillment

4.8 Compressed air simulation

The following chapter was partly published in [22] and represents possible modeling approaches for compressed air systems.

The generation of compressed air is accompanied with conversion losses. The losses are given by thermal effects during the compression. Despite of the importance [225, 231] and costs [240] of compressed air, careless use of compressed air for multiple applications can be observed in industry. As shown in previous measurements [216] and Figure 3.22, the energy demand of a machine tool in the form of compressed air can be significant. Furthermore, the measurement of compressed air is expensive and requires an inline flow and pressure measurement. Thus, energy assessment through a sensible combination of measurements with simulations based on detailed knowledge of the physical behavior of the components of compressed air systems to replace sensors was developed. The added value of a modelling approach for compressed air systems is an insight analysis of available or not yet available systems without excessive efforts for measuring on the component level, a step which is time consuming, costly and at times difficult to implement.

Energy oriented simulations on the manufacturing level including the simulation of compressed air are introduced by Herrmann [241] and Thiede et al. [242] while simulation approaches on the machine tool level are given by Avram [243] and Gontarz et al. [235]. For the analysis and evaluation of compressed air systems the software tools AirMaster+ [244] and AirSim [245] are available. The available software approaches are either too detailed and thus require multiple parameters and detailed measurements, or are only valid for a particular system layout, generally limited to the specific compressor provider and related components, and thus cannot be used for the replacement of sensors within a measurement or monitoring setting.

For this reason it is necessary to understand the energetic behavior of a compressed air system to develop a universal model in order to replace flow sensors by accurate models for the monitoring application. According to the measurement requirements for compressed air, the following requirements are given for the simulation of compressed air systems:

- **Accuracy:** The simulation approach requires at least an accuracy of $\pm 5\%$ in comparison to the measurement equipment. This is required for further analysis and optimization indication.
- **Parameters:** The quantification of pressure $p_{loss}(t)$ and flow losses $\dot{Q}_{loss}(t)$ is required as they represent the most important losses within a compressed air system.
- **Relevance:** It is required to implement a simulation approach within the machine tool system boundary according to ISO 14955 [29]. As compressed air is generated in most cases decentralized, multiple losses with increasing complexity outside the system boundary occur.
- **Modularity:** The key function for simulation approaches within this thesis is the application in energy- and resource monitoring of machine tools. For this reason a modular application for measurement and monitoring purposes which can be adopt on different systems is required.

The compressed air system including the compressor and the distribution in the machine tool can be separated in two main groups: *Processing* and *distribution*. These two groups can be further subdivided into six subsystems for the evaluation and quantification of inefficiencies in the form of flow $\dot{Q}_{loss}$ and pressure losses p_{loss} as indicated in Figure 4.17.

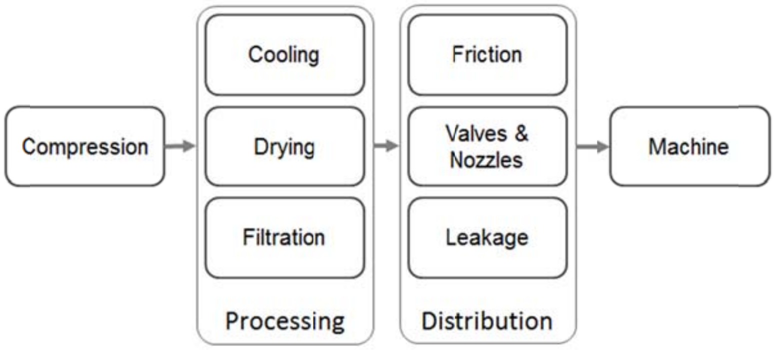


Figure 4.17: General structure of a compressed air system.

The generation of compressed air, including the compression and processing, is in most cases outside the system boundary as defined in chapter 3.3 and ISO14955 [29]. The focus is given on the simulation for flow loss, caused by leakage and pressure drops due to flow friction within the system distribution.

4.8.1 Distribution system

The distribution system is understood as the supply installation of the compressed air within the machine tool system boundary. This includes tubes and fittings. A pressure drop of $1bar$ in the distribution system can lead to annual costs of up to 10% of the total costs as shown by Ruppelt [246]. In the following the pressure drop in the distribution system is calculated.

A first step an incompressible air flow ($\rho = const$) is assumed. For the validation of this assumption an essential variable is the Mach number:

$$Ma(x) = \frac{w(x)}{a(x)} \tag{4.30}$$

with $w(x)$ as the local velocity and $a(x)$ the local speed of sound. For ideal gas, the speed of sound is defined as:

$$a = \sqrt{\gamma \cdot \frac{p}{\rho}} = \sqrt{\gamma \cdot R_{air} \cdot T} \tag{4.31}$$

The Mach number is not constant as it depends on the thermodynamic state of the fluid. It in- or decreases with a change of temperature. The Mach number is required for the considerations of the fluid density. According to Kleiser et al. [247] the relation of the actual density to the density at the initial state or rest is given for an isentropic flow:

$$\frac{\rho}{\rho_0} = \left(1 + \frac{\gamma - 1}{2} \cdot Ma^2\right)^{-\frac{1}{\gamma - 1}} \tag{4.32}$$

The density at fluid rest is given with $w = 0$, representing a static condition. This occurs in big vessels or in the stagnation point of a body which is exposed in a flow. A series expansion of the equation (4.32) can be written as a function of Ma:

$$\frac{\rho_0 - \rho}{\rho_0} \approx \frac{1}{2} Ma^2 + \theta(Ma^4) \tag{4.33}$$

For small Mach numbers $(Ma \to 0)$, equation (4.33) can be rewritten to:

$$\frac{\rho_0 - \rho}{\rho_0} \approx \frac{1}{2} Ma^2 \quad for \quad Ma \to 0 \tag{4.34}$$

With $\gamma = 1.4$, $R_{air} = 287.058\, J/kgK$ and $T_{amb} = 293.15\, K$ into equation (4.34) one obtains $a = 343.237\, m/s$. This can be seen as a typical value in a compressed air distribution system. Varying the velocity in (4.34) results in the values as given in Table 4.7. Thus, up to a value of $Ma \approx 0.3$ the relative change of density is below 5%. This confirms the assumption of incompressible flow for compressed air. As recommended by Barber [248] the air velocity w should not be higher than $w = 15\, m/s$ to avoid too high friction at the pipe wall. The velocity within a compressed air distribution is between $w = 1\, {}^{m}/_{s}\ and\ w = 6\ {}^{m}/_{s}$. The change of density is therefore negligible.

Table 4.7: Relative change of density at low Mach numbers at a temperature of $\boldsymbol{T_{amb} = 293.15K}$.

$w[m/s]$	$Ma\,[-]$	$\frac{\rho_o - \rho}{\rho_o}$
1	0.0029	$4.2 \cdot 10^{-6}$
5	0.0146	$1.06 \cdot 10^{-4}$
10	0.0291	$4.24 \cdot 10^{-4}$
20	0.0583	0.0017
50	0.01457	0.0106
100	0.2913	0.0424
150	0.4370	0.0955

For the pressure drop, caused by friction, in a straight tube (Figure 4.18) the Bernoulli for incompressible flow can be applied as given in:

$$\left[p_1 + \frac{\rho}{2} \cdot \overline{w}_1^2 + \rho g h_1\right] = \left[p_1 + \frac{\rho}{2} \cdot \overline{w}_2^2 + \rho g h_2\right] + \Delta p_{12} - \Delta p_{ext} \tag{4.35}$$

The mean velocity is calculated as $\overline{w} = \frac{\dot{m}}{\rho \cdot A}$. Since for an ideal tube the volumetric flow remains constant within a constant cross section, the mass flow is constant as well. Thus, the velocity applies as:

$$\overline{w}_1 = \overline{w}_2 \tag{4.36}$$

For gases, the potential energy $E_{pot} = \rho g h$ can be neglected and equation (4.36) simplifies to:

$$\Delta p_{12} = p_1 - p_2 = \Delta p_{12} - \Delta p_{ext} \qquad (4.37)$$

Δp_{ext} describes the possible influence of an energy input or output. These are for example continuous-flow components, e.g. pumps or turbines. The expression Δp_{12} contains two parts, the friction in a straight pipe $f\left(\frac{L}{D}\right)$ and fittings in the distribution system $f(\sum \zeta)$:

$$\Delta p_{12} = \Delta p_{friction} = \frac{\rho}{2}\overline{w}^2 \cdot f(\frac{L}{D} + \sum \zeta) \qquad (4.38)$$

Within the simulation approach, the friction is represented by the Darcy-Weisbach equation. L represents the characteristic length of the straight pipe, D the inner pipe diameter and f represents the Darcy friction factor.

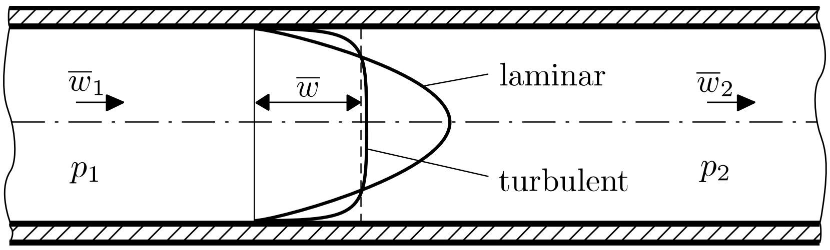


Figure 4.18: Model of a straight pipe with a laminar and turbulent velocity profile

For the calculation of factor f the flow behavior must be considered. Figure 4.18 shows the velocity distribution in a straight pipe for laminar and turbulent flow. The friction factor is determined by the Reynolds Re_D number which leads to different pipe surface friction:

$$Re_D = \frac{\overline{w} \cdot D}{\upsilon} \qquad (4.39)$$

$\overline{w}$ is the mean flow velocity and υ represents the kinematic viscosity. Up to the critical Reynolds number $Re = 2300$, a laminar flow is given and the friction factor results in:

$$f = \frac{64}{Re_D} \qquad (4.40)$$

For turbulent flow, $Re > 2300$, f depends not only on the Reynolds number but also on the pipe surface roughness k_s. For smaller Reynolds numbers and smooth surface roughness $\omega \cdot {}^{k_s}/_{\upsilon} < 5$, where ω describes the velocity gradient equation is used:

$$\frac{1}{\sqrt{f}} = 2 \cdot \log\left(Re_D \cdot \sqrt{f}\right) - 0.8 \tag{4.41}$$

For the model implementation, various supporting points were calculated numerically and implemented into a lookup table. Based on this table, linear interpolation is used in the simulation. To obtain f for very rough pipes with $\omega \cdot {}^{k_s}/_{\upsilon} > 70$, von Karman's explicit formula is used:

$$\frac{1}{\sqrt{f}} = 1.14 - 2 \cdot \log\left(\frac{k_S}{D}\right) \tag{4.42}$$

As transitional roughness is often observed in the entire distribution system, for the quantification of the roughness Colebrook and White [249] developed a curve fit. An alternative for the roughness modeling is used with the explicit Chen approximation according to Brkic [250]. Together with the known pipe length and the gas properties, the pressure loss can be calculated for constant pipe diameter as shown in (Appendix A.2). In order to quantify the pressure loss at fittings in this simulation, an empirical method is chosen. Depending on the fitting geometry an equivalent straight pipe length L can be obtained which represents the same pressure loss p_{loss}. Forder [251] and Miller [252] tabulated the values for different pipe diameters. All losses obey the same functional dependency on the flow velocity. The given model approach corresponds to the values of the pressure drop in straight pipes and fittings.

4.8.2 Modeling of Leakage

In compressed air systems, leakage causes the biggest part of energy losses. It can be found throughout the entire compressed air system. Leakages often represent a significant cost factor, as shown in Table 4.8 within an industrial 6 bar supply based an electrical equivalent power of $P_{eq} = 7kW/(m^3/\text{min})$. The values are given for an operation time of 8760 h per year and an electricity price of 0.15 € per kWh according to [32].

Table 4.8: Examples of the costs for an air leak through a hole with different diameters.

Hole diameter	Air consumption	Leakage loss	
mm	M3/min	kW	€/year
1	0.065	0.46	604
2	0.257	1.80	2364
4	1.03	7.21	9474
6	2.31	16.17	21247

The following options for leak evaluation can be found in research and industry today:

A) Determination of the leakage volumetric flow $\dot{V}_L$. According to Fraunhofer [225] the time while the air tank empties from a start pressure p_s to an end pressure p_e is measured. This measurement can be used for the quantification of leakages.

$$\dot{V}_L = \frac{V_t \cdot (p_s - p_e)}{t} \tag{4.43}$$

B) Evaluation of the leakage with an ultrasonic gauge or with infrared thermography. This measurement can be used for the detection of leakages as shown by Ruppelt et al. [253].

The available quantification methods do not allow a predictive estimation of leakage of a system before installation or monitoring purpose; therefore the physics of leakage were further evaluated. Figure 4.19 shows an idealized leak model. State 1 represents a fully developed laminar flow without any influences of the leakage, while state 2 represents the orifice point by the flow downstream the leakage. Ambient conditions are assumed outside of the pipe.

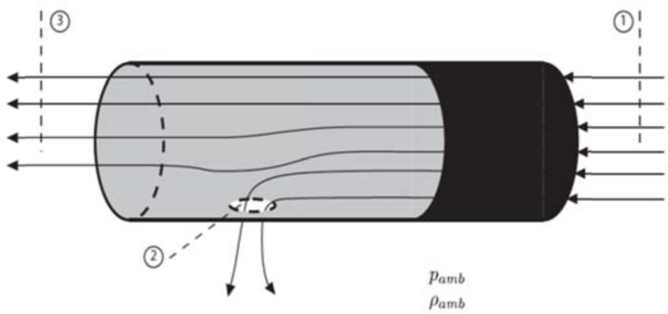


Figure 4.19: Model of an idealized discharge through a leak orifice.

Figure 4.19 shows an idealized leak with the air flows with the velocity w_1 and w_3 in the tube and w_3 at the orifice with the area size A_2 into the atmosphere. To study the discharge behavior, the Bernoulli equation for compressible flow is used. For a flow with small velocity the fluid can be assumed as incompressible. In the case of a leakage the fluid accelerates with high velocities. Thus, compressible fluid is assumed to describe leakage.

$$w_1 \approx w_3 \quad and \quad w_1 \ll w_2 \tag{4.44}$$

For the discharge behavior the Bernoulli equation for a compressible fluid is used:

$$\frac{\gamma}{\gamma - 1}\frac{p_1}{\rho_1} + \frac{w_1^2}{2} = \frac{\gamma}{\gamma - 1}\frac{p_2}{\rho_2} + \frac{w_2^2}{2} \tag{4.45}$$

Given with the adiabatic coefficient γ, pressure p, media velocity w and density ρ. This equation can be further simplified according to Siekmann and Thamsen [254] by assuming a free jet at orifice with the same ambient conditions, pressure $p_2 = p_{amb}$ and density and $\rho_2 = \rho_{amb}$ of the fluid. As the velocity at the orifice w_2 is assumed to be much higher in comparison to the velocity in the tube w_1, w_1 can be neglected. With assumption of an adiabatic process with $p/\rho^{\gamma} = const$ the velocity of the fluid at the orifice w_2 can be described as:

$$w_2 = \sqrt{\frac{2\gamma}{\gamma-1} \cdot \frac{p_1}{\rho_1}(1 - \frac{p_{amb}}{p_1} \cdot \frac{\rho_1}{\rho_{amb}})} = \frac{\sqrt{2\rho_1 p_1}}{\rho_{amb}} \cdot \underbrace{\sqrt{\frac{\gamma}{\gamma-1} \cdot \left[\left(\frac{p_{amb}}{p_1}\right)^{\frac{2}{\gamma}} - \left(\frac{p_{amb}}{p_1}\right)^{\frac{\gamma+1}{\gamma}}\right]}}_{Discharge\ function\ \Psi} \tag{4.46}$$

According to the law of conservation the highest velocity occurs at the smallest orifice. According to [247] the area velocity relation is given with:

$$\frac{dw}{w} = \frac{1}{Ma^2 - 1} \cdot \frac{dA}{A} \tag{4.47}$$

This results in the critical pressure relation where $Ma = 1$ is given and to

$$\left(\frac{p_{amb}}{p_1}\right)_{crit} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{4.48}$$

The discharge function Ψ remains constant for the critical pressure relation $(p_{amb}/p_1)_{crit} \leq 0.528$ and represents the so-called *choked flow*. The maximum value with $(p_{amb}/p_1)_{crit} \leq 0.528$ and $\gamma = 1.4$ is $\Psi_{max} = 0.48418$. The desired leakage volumetric flow is ultimately obtained by multiplying the outflow velocity w_2 with the orifice cross section A_2 with:

$$\dot{V}_L = w_2 \cdot A_2 \tag{4.49}$$

For the consideration of friction and non-ideal effects at the orifice, a correction factor c_d needs to be considered and determined empirically. This leads to equation:

$$\dot{m}_L = c_d \cdot \rho_{amb} \cdot w_2 \cdot A_2 \tag{4.50}$$

Conclusion and Validation

For the validation of the findings and implemented models a defined leakage test was performed. As shown in Figure 4.20 a defined 2mm (8) and 4mm leakage was measured and compared against the defined model. The entire electrical power input on the compressor (1) against the flow (7) was measured. The tank (2) was filled up to a system pressure at the manometer (3) to 10.6 bar. A ball valve (4) was opened and released the stored compressed air through a high pressure hose (5) and filter (6) to a test pipe with the defined leakage (8).

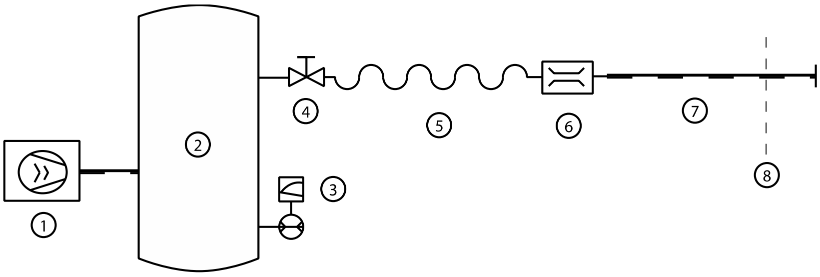


Figure 4.20: Piping and instrumentation diagram of the leakage measurement setup.

The parameters for the validation measurement are shown in Table 4.9.

Table 4.9: Parameters of the measurement setup as shown in Figure 4.20.

Number	Component	Parameter	Value
1	Compressor	Kaeser SK25	-
2	Tank	Volume [m^3]	0.25
3	Pressure manometer	Measurement Range [Pa]	0 - 15000000
4	Ball valve	-	-
5	Hose	Length [m], diameter [m]	0.55, 0.00127
6	Filter	-	-
7	Sensor	Length [m], diameter [m]	0.7, 0000254
8	Pipe	Length [m], diameter [m]	0.5, 0.000254
9	Leak	Position [m], diameter 1 and 2 [m]	0.4, 2, 4

Additional parameters for the simulation are shown in
Table **4.10**:

Table 4.10: Initial, ambient, and other conditions of the leakage measurements. The measurement conditions were the same as for the sensor measurement.

Parameter		Unit	Value
Tank temperature	T_T	K	293 – 300
Initial tank pressure	$p_{t,init}$	PA	10700000
Maximal tank pressure	$p_{t,imax}$	PA	11000000
Response pressure difference	Δp	PA	200000
Ambient temperature	T_{amb}	K	293
Ambient pressure	p_{amb}	PA	101300
Leak diameter	d_L	mm	2 and 4

The measurement of the leakage was accompanied by an effective power measurement at the compressor. For the leakage measurement the distribution line was opened at the filter. The ball valve was opened manually. The response pressure difference of the hysteresis control of the compressor was changed to $p = 2bar$ to avoid a refilling of the compressor tank. The air flew out until the ball valve was closed again until the minimal pressure p_{min} was reached. This procedure was executed two times for each leak diameter.

The leakage model was written in Simulink. The comparison of the simulation with the measurement are shown in Figure 4.21.

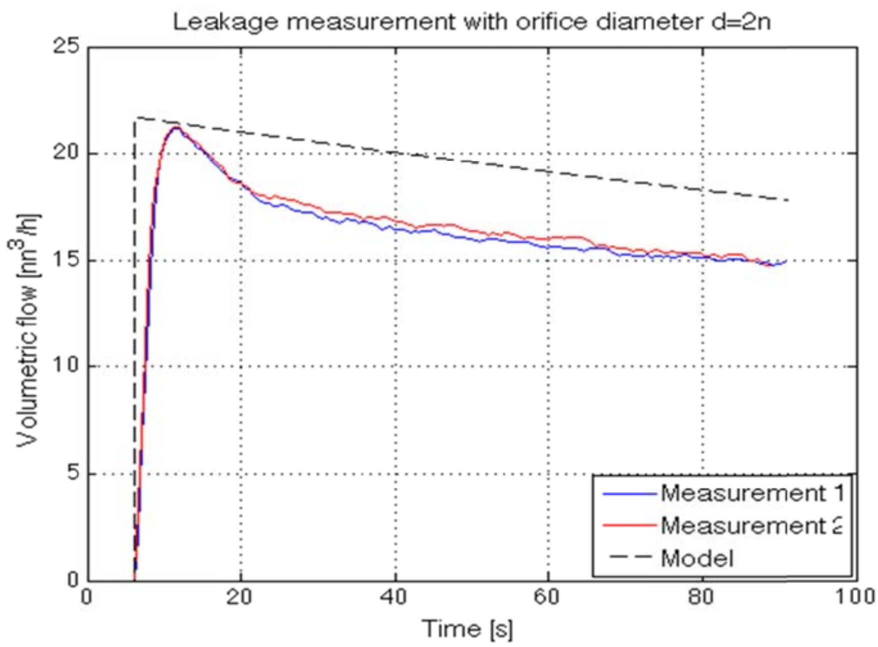


Figure 4.21: Comparison of the measurement on a 2mm orifice in comparison to the leakage model (dashed line). Measurement 1 and 2 represent the same measurement with the same parameters.

The leakage model reflects correctly the volumetric flow over time (Figure 4.21). As friction and the dynamic accumulated pressure behavior are not modeled the model does not reflect an initial transient behavior and produces an offset in the long run. The offset is caused by the neglected friction and the measurement accuracy on the flow sensor. The given approach and developed model is based on the fundamental physical behavior of the subsystems of the compressed air system and has illustrated that it is possible to estimate the needed compressor dimension and predict its power consumption according to defined parameters.

The given model reflects the most important loss on compressed air system. For the use as a sensor replacement the given modelling approach is not applicable as the accuracy of at least $\pm 5\%$ cannot be reached. Furthermore, the given approach relies on several parameters that might be not available or not sufficiently precise. Other losses in the system are strongly dependent on the actual use and volume flow $\dot{V}$. For the monitoring purpose, compressed air is considered as too important to be evaluated through a modelling approach based on few parameters. Therefore measurement of compressed air is recommended for monitoring applications.

4.9 Conclusion

For electric components, e.g. motors, the *EMod* and *Teach-in* approaches were developed and validated against the effective power measurement. For the compressed air supply a compressed air simulation was applied and validated with flow measurements. It can be revealed that the given simulation approaches are only partly applicable for the adaption of a sensor within a monitoring application. The comparison shows that the implementation and parametrization effort in order to reach the required value accuracy is high. Based on this requirement the *Teach-in* approach is seen as a promising solution. Still it can be only used for the replacement of constant and controlled-constant components with a direct relation to the PLC. The *EMod* approach and the related compressed air simulation can indicate the qualitative energetic behavior of the system in order to predict the energy consumption of a component and machine tool system, but requires parameters which are partly not given or not accurate enough in order to indicate optimization potential and/or measures. This missing parameter set leads to false timestamps and effective power value output. Therefore, an implementation in the industrial setting is not applicable. The modeling approach *EMod* reaches an accuracy of $\pm 20\%$ and is therefore hardly applicable for the monitoring, analysis and indication of energy efficiency potentials within a machine tool system.

Thus, the EMod and compressed air simulation approach are reasonable where physical systems are not given and for a first estimation. This approach does not cover the given industrial requirements towards accuracy, implementation effort, and general applicability. For the industrial application the developed modelling approach *Teach-in* can be used on constant and controlled-constant components as it covers the industrial requirements in accuracy and applicability.

5 Analysis and Optimization

5.1 Introduction

Based on the multichannel measurement and simulation strategies for data acquisition, effective power and other energetically relevant data on the component level is available. Based on this data acquisition, data analysis approaches are developed to indicate the optimization potential and resulting technically and economically proven optimization measures. During the research a measurement database based on the multichannel data acquisition (chapter 3) with more than 52 multichannel measurements on multiple machine tool types were performed. The analysis as introduced in this chapter is based on the findings of these measurements. The following chapter addresses data analysis which is required to define effective and specific optimization strategies for energy efficiency on machine tools and production systems as shown in Figure 5.1. The focus is given on optimization activities in manufacturing that address the combination of economic and environmental goals. Furthermore, a case study on the measurement use and related findings in industry is shown.

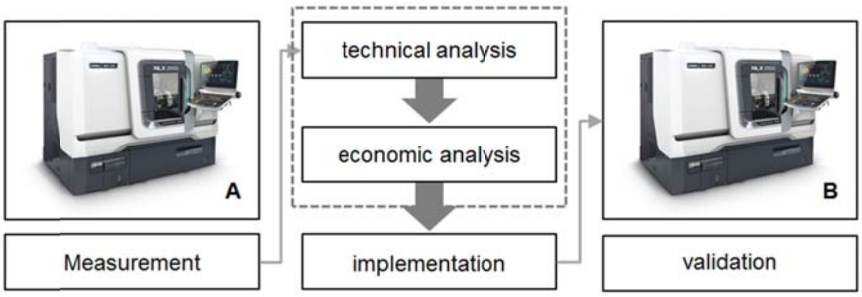


Figure 5.1: Principal procedure for the measurement, analysis, and optimization of a machine tool A to an optimized machine tool B. The area within the dashed lines represents the technical and economic analysis for measurement data as introduced in the following chapter. Picture source: DMG Mori.

Data analysis is understood as a detailed evaluation of acquired data and information for the indication of improvements and findings. According to Bellinger et al. [255] data, and related analysis, is seen as the foundation for information and further knowledge. This can be principally achieved by mathematical methods, e.g. statistical methods or algorithms.

The amount and variety of available analysis approaches based on various evaluation and optimization goals (chapter 2.3), requires a structured classification. Vijayaraghavan and Dornfeld [43] introduced a classification of measurements and optimization based on the application level in macro and micro-process planning. According to this level segmentation, optimization approaches in this work are classified in micro and macro-optimization as well. Micro-optimization defines all optimizations related to the machine tool parametrization as well as the control and configuration of the machine tool components and is related to all optimization measures within the machine tool system boundary as defined in ISO 14955 [29]. Macro-optimization comprises parametrization related to the manufacturing process, factory logistics, and production scheduling without changing the configuration or control of the machine tool components. Thus, it is related to all optimization measures outside the machine tool system boundary.

The basis for all developed analysis approaches in this research is given on grounds of the multichannel measurement system as introduced in chapter 3.4. The raw data consists out of a data header with a UTC time stamp and the effective power for each measured phase P_1- P_3 and the overall effective power for each device $P_{eff}[W]$ as shown in Appendix A.4. Other values, e.g. $cos\varphi$, reactive power P_{VAR}, or apparent power P_{VA} are collected if specifically required for further analysis. The raw data of each machine tool component is furthermore synchronized according to the given time stamp of the main supply in UTC.

In general optimization approaches aim to increase the efficiency of a system. Efficiency can be increased by either increasing the output, or minimize the input for a certain process as defined in ISO 9000 [38] and shown in:

$$e_{PR} = \frac{E_{in}}{E_{out}} \tag{5.1}$$

The analysis and optimization procedure within the following chapter follows the minimum principle as introduced by Pehnt [39]. Thus the goal of the following selective methods is to reduce resources to a minimal required amount (input) by maintaining a constant process output, e.g. quality and quantity which results to an increased machine tool efficiency.

5.2 Analysis of Measurement Findings

In principle, the energetic behavior and resulting individual optimization findings are primary defined by the machining process, system configuration, component parametrization, as well as the individual use of the machine tool and production system. For instance, grinding processes, in particular in finishing operations, require low process forces at the main drives, whereas the auxiliary equipment, e.g. cooling or fluid filtering, dominates the energetic behavior of the production system (Figure 5.3). On the other hand, roughing cycles in milling operations show high forces and resulting effective power P_{eff} demand at the main drives with a limited effective power share of auxiliary devices $P_{eff,aux}$. Furthermore, the individual machine tool usage and related machine tool mode are influencing factors on the energetic behavior of the entire machine tool. Table 5.1 shows the performed multichannel measurements in this research.

Table 5.1: Overview of performed multichannel measurement.

Type	Measurements
Grinding (incl. 4- and 5-axis grinding centers)	15
Milling (incl. 4-, 5-, and 6-axis milling machining center)	13
Wire EDM	4
Production center (incl. overall production, machining center)	4
Laser (incl. Laser sintering and laser cutting)	4
Auxiliary (e.g. isolated compressed air supply)	1
Turning (e.g. lathe)	2

Based on the performed measurement in Table 5.1 the following observations and findings for the energetic behavior or machine tools can be made.

High Compressed air share: Independently from the machine tool type and operation modes, a high share of compressed air consumption can be seen throughout various machining processes and applications. The share of compressed air in comparison to the effective power from electrical components can be calculated and further compared as introduced in chapter 3.2. Predominately in milling and grinding applications, compressed air is used as sealing air for main drives, glass scale cleaning, and for process cooling. In most cases this function is process independent and occasionally active in sleep, standby modes, or even at emergency stops. Figure 5.2 shows the measurement of a grinding machine tool in different machine tool modes. It can be seen that the compressed air share is dominant independently of the machine tool state.

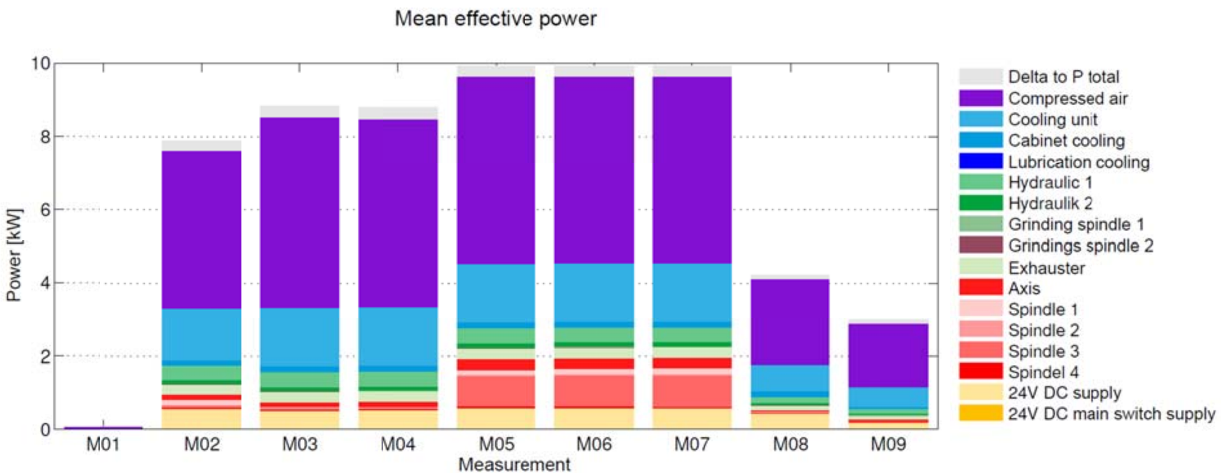


Figure 5.2: Measurement of a grinding machine tool in different machine tool modes (M01 = OFF, M02 = startup, M03 and M04 = Standby, M05-M07 = Processing, M08 = Switch off, M09 = emergency stop).

Load of main drives: In grinding processes, the actual needed force at the spindle complies only for up to $5 - 10\%$ of the actual spindle rated power. Especially in finishing processes with low process force, the auxiliary components, e.g. cooling and fluid filtering, are dominant. Spindles with higher rated power run in a part load cycle with lower efficiency. Besides the process relevance the dimensioning of the main drives are chosen to guarantee flexibility in torque and rotation speed according to the given spindle characteristic. The rated spindle power is therefore required to guarantee the dynamic spindle behavior, e.g. start and stop operations of spindles for tool change. A minimal spindle acceleration time requirement can lead to n-fold effective power peak in comparison to the rated spindle power and requires the given spindle dimensioning.

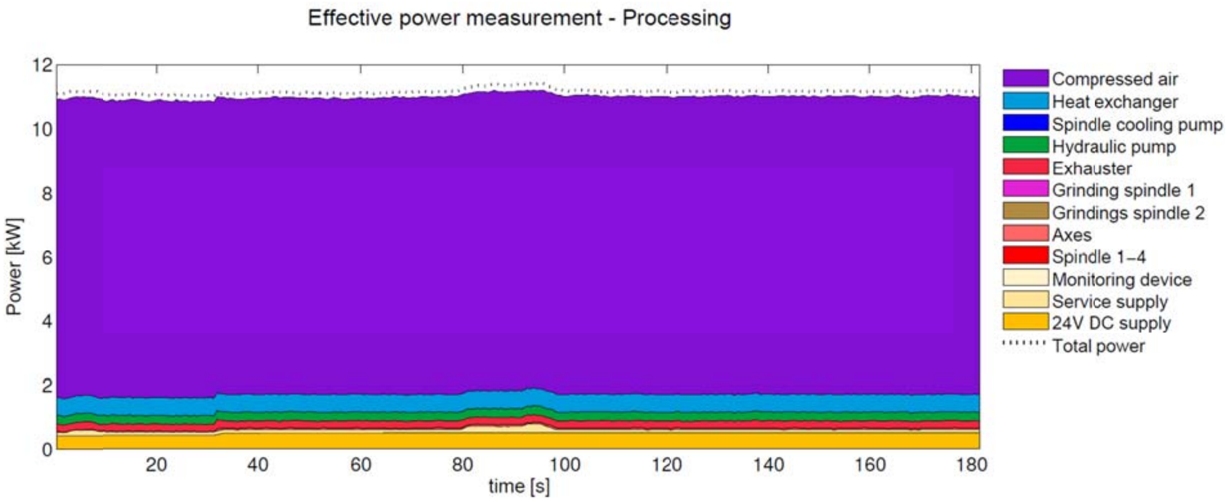


Figure 5.3: Multichannel measurement of the effective power and compressed air supply of a grinding machine tool during processing with a spindle of 30 kW rated power and a typical grinding operation.

Dimensioning of main drives: Similar to the above mentioned low load of main drives, the dimensioning of spindle systems of today is cumbersome and mainly driven by process reliability and safety, as mentioned by Maeda et al. [256] and Abele et al. [257]. This requirement can be also confirmed for auxiliary equipment with process stability, safety and reliability. Especially in milling operations with dynamic processes and frequent tool change, spindles need to stop and start immediately ($t_t \rightarrow 0s$) (Figure 5.4). This requires high torques in combination with required rotation speed, which results in spindle systems with high rated power. In the overall machining operations, during constant cutting, this power is not required as shown above. The peak power can reach up to 8 times the rated power of the spindle.

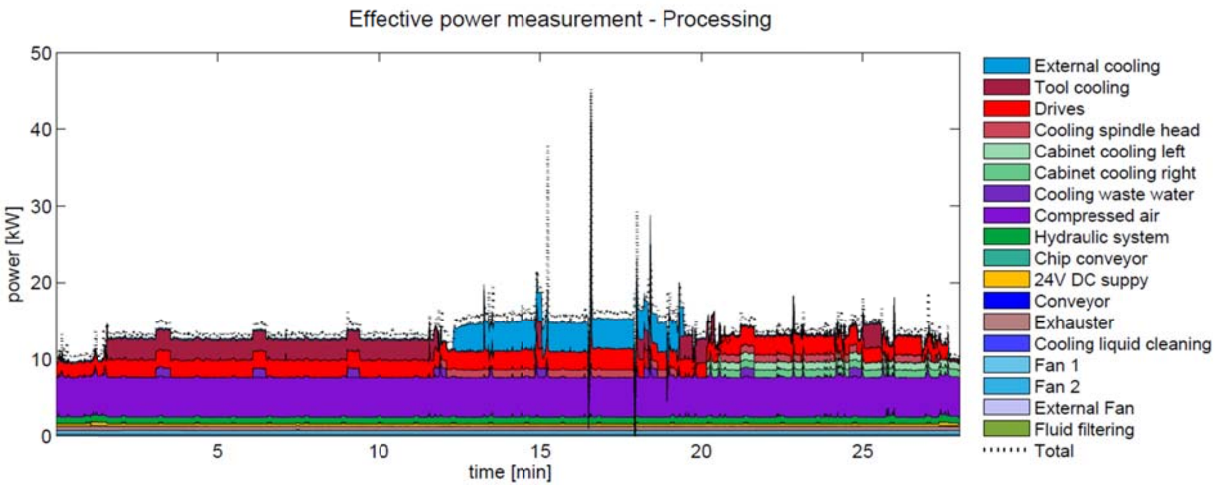


Figure 5.4*:* Multichannel measurement of the effective power and compressed air supply of a milling machine tool during processing with a spindle of 35 kW rated power and tool change at $\boldsymbol{t_{t1} = 15min}$ and $\boldsymbol{t_{t2} = 16min}$ and $\boldsymbol{t_{t1} = 16.5min}$.

Dimensioning of cooling: In relation to the above mentioned findings, the effective power of main drives, for instance of the spindle system, is generally expected to be below the rated power. However, cooling systems are dimensioned against the rated spindle power to guarantee sufficient cooling of the motors and drives for all possible machine tool modes. In most cases a process-dependent controlled loop is not given for cooling units or other auxiliaries for conditioning, e.g. filter pumps or fans. The effective power of cooling units is considered as constant. It can be further observed that cooling systems are often over-dimensioned compared to their actual need during processing (Figure 5.2). This is mainly caused by safety and reliability reasons and to guarantee and maintain a constant temperature with low temperature gradients.

Process dependencies: In accordance to the uncontrolled cooling applications in milling and grinding, the same effect can be observed in other machining processes, e.g. EDM, where auxiliaries are not process-dependently controlled and adapted towards their actual need at the target application. This is mainly caused by safety and process reliability reasons and missing knowledge on the target application and process parametrization. Safety margins up to factor 5 are possible and present in industrial settings. Safety and reliability related machine tool design acquire a higher priority than energy efficiency measures and control optimization. For this reason and wherever possible cooling and supporting functions should be designed and controlled according to their actual need, which is defined by the machining process. Therefore, the analysis needs to quantify the actual auxiliary share in comparison to the machining process to define and indicate the needed and adequate component dimensioning and control.

Shares of variable and constant consumers: The performed measurements revealed that machine tool components can be principally classified by their energetic and control behavior into three groups; *Constant*, *controlled-constant*, and *variable* load as shown in Figure 5.5.

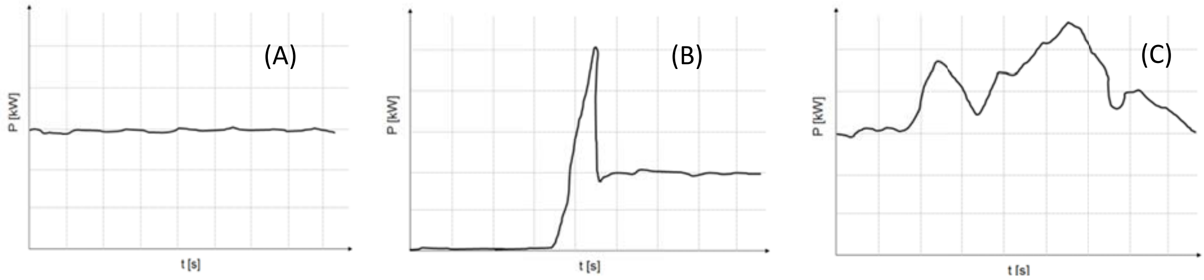


Figure 5.5: Figure A represents an effective power measurement of a constant component. Figure B represents a controlled-constant component and figure C represents a variable consumer.

The share of constant and uncontrolled consumers can be dominant. In most cases and especially in discrete part manufacturing, this decreases the overall efficiency of the system. In principle, the share of constant components in standby, setup modes, or in static machining processes with minimal forces is higher than the share of controlled-constant or variable components. Further reference to the component classification is given in chapter 4.4.

Share of constant consumers: Constant consumers are generally not process-dependent. Controlled-constant consumers can be independent of the actual load of the main drives as well. Observations from performed measurements revealed that auxiliary components are likely designed for the maximal possible demand, e.g. pressure or flow rate, to guarantee the reliable performance of the subsystem and entire machine tool system. This is caused mainly by poor process-dependent control or unknown process energy demand. For an efficiency improved system process supporting components, e.g. cooling system or filter pumps, should adapt continuously their power consumption to the intensity of the process, more precisely, to the variation of the cutting process parameters, e.g. cutting forces at milling processes. The power demand of each machine tool component is represented by the quality of control and the power share of the component. For this reason not only the fluctuation but also the share of each machine tool component must be measured.

Peak power: Spindle start and stop operations for instance at tool changes, can lead to power peak with an effective power up to 8 times of the rated power and a duration of 0.7 to 0.9 seconds. Depending on the machining process and related frequency of the spindle start and stop operations, spindle design, and spindle torques, peaks might have an energetic importance and need to be evaluated. Furthermore, it is observed that in the machine tool startup mode independent machine tool components are often switched on simultaneously. This can result to an intensification and overlapping of the startup peak. The result is a higher fuse dimensioning and related wire thickness. Figure 5.6 shows a multichannel measurement of an

EDM machine tool in the startup phase. The machine tool switches into standby mode after 6 min by a simultaneous switch on of all pumps a resulting power peak of $4kW$.

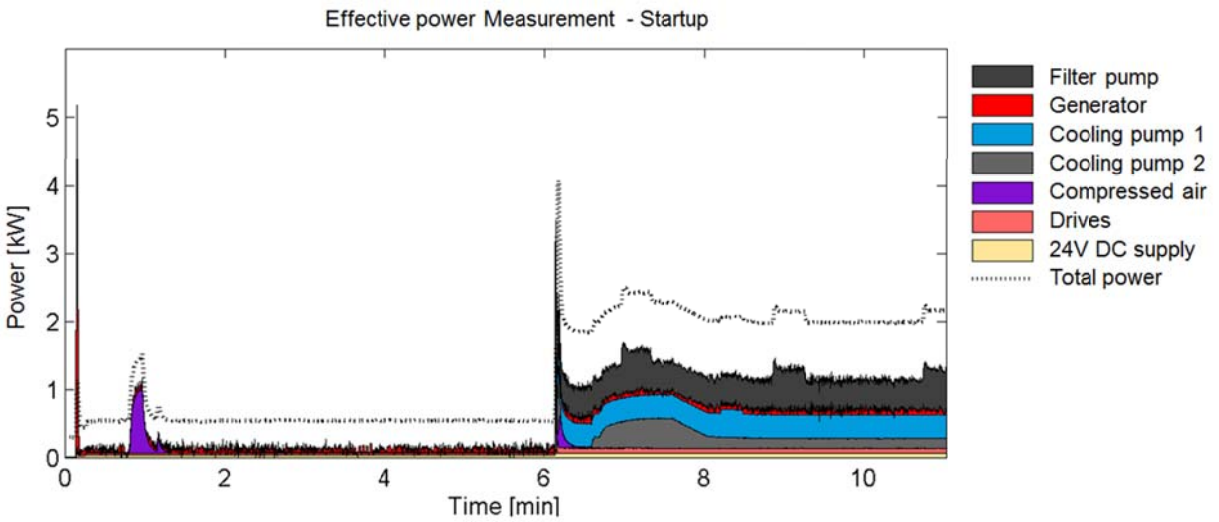


Figure 5.6: Multichannel measurement of an EDM machine tool with simultaneous component start up.

Machine modes "Off": The machine state "*OFF*" as defined by the ISO 14955 [29] and safety standard ISO 13849 [258] is indicated when the main switch of the machine tool is turned off. This machine tool state is very rare in medium and large-scale production. The analysis of this machine tool state is of special importance in shopfloor applications. Although external energy supplies are connected, it is expected that no resources between and within the system boundary are exchanged. Measurements during "off" mode revealed that still some machine tool activity and related energy demand can be observed. This is mostly given by leakage on the compressed air and the distribution system. Also external devices, e.g. monitoring systems or transformers can also show activity during the machine tool off state. Figure 5.7 shows a multichannel measurement of the 5-axis milling machine tool during *off* state. In the following case the analysis revealed that internal leakage due to open tool holder and sealing air caused a massive air flow of $15.4\ {m^3}/{h}$ or 2 kW electrical equivalent.

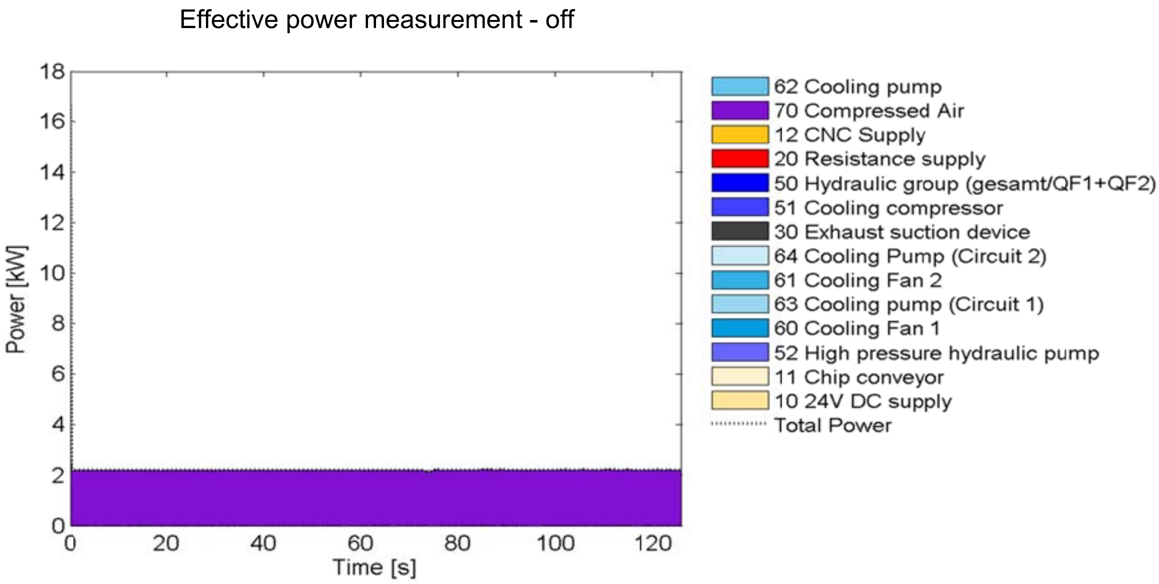


Figure 5.7: Multichannel machine tool measurement on 5-Axis milling machine during off state.

Undefined Standby Modes: The machine tool modes *off* and *process* are defined in ISO 14955 [29]. Furthermore, these states comply with the safety standard ISO 13849 [258] and can be clearly assigned to various machine tools. Machine tool modes as *standby* and *ready* are of particular importance for the energetic machine tool behavior. It can be observed that the machine tool mode *standby* is not universally described and can differ in multiple stages, e.g. various active machine tool components and control setting. Based on the variety of machine tools, it is obvious that a standardized standby mode definition, e.g. definition of active machine tool components, is cumbersome or not possible. Furthermore, a clear definition based on the individual machine tool system by the machine tool builder is not always present.

Hydraulic applications: Hydraulic systems represent important and common machine tool application and are mostly needed for tool or part handling and clamping operations. Hydraulic pumps are designed to maintain a constant pressure and represent a stationary load and resulting power consumption. In most cases, this constant load is not needed but defined as a pump system or hydraulic accumulator control is missing or too expensive. In most machine tool applications this constant and over-dimensioned load on hydraulic pumps is given to guarantee multiple tool change operations during machining. The dimensioning, control, and configuration of hydraulic as well as pneumatic applications is of special interest for the energetic evaluation and needs to be considered in the data analysis.

Ineffective modes: In addition to undefined standby modes it is useful to classify the active machine tool components during *standby* in value and non-value adding components and resulting functions. Depending on the manufacturing process, the machine tool mode *standby* must maintain a certain machine tool state, e.g. thermal stability. For this reason it is of particular relevance which components are active at any operation stage and for how long this state occurs as not all active components are quality or safety related. Further important information for the analysis and optimization is if the duration of the *standby* mode. A detailed *standby* time prediction can lead to an optimized machine tool component behavior. Thus, it is required to measure the power share of active components in standby mode, its duration, and occurrence.

Active components: The multichannel machine tool measurement enables the measurement of all active components. In accordance to ISO 14955 [29] all machine tool functions and subfunctions need to be measured which are relevant for energy supplied during different machine tool modes. Therefore, it is required to measure and analyze at least 80% of the total power supplied to the machine tool in all possible machine tool modes $P_{eff,tot}$. The sum of the effective power of all components $\sum P_{eff,i}$ must be equal or higher than 80% of the total power consumption $P_{eff,tot}$:

$$\sum_{1}^{i} P_{eff,i} \geq 0.8 \cdot P_{eff,tot} \tag{5.2}$$

The performed measurements show that the delta of the sum of the power of all components towards the total power ΔP can vary depending on the machine tool mode and even on the applied machining process by up to 25%. For this reason it is necessary to measure the total power input P_{tot} in comparison to the sum of all components $\sum P_{eff,i}$ to guarantee that all components are measured in all machine tool modes.

Internal dependencies: The subsystem control behavior is given by the PLC, process-related operations, external sensors, or manual inputs. It is observed that some machine tool components are interconnected, e.g. master and slave application. The energetic behavior is directly depended on the energetic behavior of other components. For this reason it is required to perform parallel measurements to detect given dependencies. Single channel and sequential measurements require a high synchronization effort to indicate these dependencies.

Component pre and overrun: Measurement for the machine tool startup and switch-off show that based on machine tool provider information, rule-based operations on the machine tool components are required. For instance, the oil temperature for cooling and lubrication needs to reach a certain thermal state and viscosity to provide the intended functionality and output. Other operations require staggered intervals for the spindle speed. After machining processes, in particular in grinding operations, it is needed that the process zone is free of any dust or oil mist. To guarantee this the exhaust system has to overrun for a defined duration after machining stop. These functions are machine tool safety and process quality related. Still, these operations require energy and resources during non-productive machining time and need to be measured and analyzed.

Comparison of machine tools: Even though machine tools are mostly designed to perform a specific machining task with individual parametrization, it might be still required to provide an adequate comparison of the energetic performance of a machine tool or production system, e.g. in order to evaluate a production scheduling or detect differences on the component level. This might be required for machining processes, that can be performed by different machine tools or aggregated reporting, for instance EnPI acquisition. The selection of measurement points on various machine tools revealed that components and subcomponents of machine tools can be classified in recurring consumer groups as indicated below:

- Cooling pumps
- Hydraulics
- Pneumatics
- Main drives / auxiliary drives
- 24V DC supply
- 230V AC supply
- Chip conveyor
- Exhausting systems
- Cabined cooling

The above mentioned observations and findings taken from the multichannel measurement show the need to focus the analysis on auxiliary components, non-productive time optimization, and dimensioning of subcomponents. As machine tool measurements can only reveal some of the above mentioned findings analysis tools for direct indication are developed. For this reason the above mentioned observations and findings are further transformed into the following requirements for data analysis tools.

5.3 Requirements for data analysis

Based on the performed measurements with the multichannel measurement system, in order to find inefficiency on the machine tool or production system, the following requirements can be revealed from the above mentioned observations:

- ***Classification / Evaluation:*** For the evaluation and comparison of similar machine tools a unified methodology is required. As machine tools are highly variant in the usage and configuration this requirement implies a method which is as detailed as possible while maintaining the unified application on different machine tools.
- ***Component measurement:*** It is required to measure all active and inactive components within the system boundary according to the ISO 14955 [29] definition. As the control and energetic behavior of machine tool components and subcomponent varies, it is needed to perform the measurement of all components to ensure and the sum of all components of 80% of the total energy input in all machine tool modes. This ensures a detailed analysis on all machine tool

components, e.g. fluctuation, share, and dependencies, for the indication of inefficiencies on the component level.

- ***Machine tool modes:*** The measurements must be performed in all possible machine tool modes. This ensures the analysis on possibly relevant machine tool states, e.g. *off* or *standby*, and guarantees the evaluation of all active and relevant components.
- ***Resolution:*** For the analysis of peak loads and dynamic component behavior, e.g. spindle start or stop, a minimal resolution of $5Hz$ is required. This requirement includes the detailed analysis on the component level in order to detect and quantify peak loads and synchronous component startups.
- ***Observation period:*** As the energetic behavior and component interrelation depends on the machining process, different machine tool modes, and thermal stability management, a representative observation period needs to be applied. This observation period must cover therefore all possible and relevant stages of the energetic machine tool behavior.
- ***Economic factor:*** The analysis should indicate inefficiencies and potential optimization measures. For a full evaluation besides the technical view, the analysis needs to encompass also an economic assessment. Based on the given information on the component level, economic assessment should be done. This information, among others, should be further used for service and maintenance reasons.

Based on these requirements and the multichannel measurement the following analysis and evaluation tools are developed in order to facilitate and indicate optimization measures on machine tools and production systems.

5.4 Analysis tools

5.4.1 Functional Component classification

In order to compare and evaluate machine tools and production systems an adequate evaluation method is required. In particular in macro optimization (Chapter 5.1), the comparison and evaluation of machine tools is required in order to quantify an aggregated efficiency and optimization evaluation on the machine tool level or for the comparison of similar machine tools for the same or similar product. A comprehensive comparability can set the basis for decision-making within manufacturing, e.g, type and selection of machine tools based on specific machining tasks and can represent an important indication of the machine tool purchase. In accordance to the European Energy Labelling of Productions Directive [259] an universal evaluation is required. Its definition, development and implementation is very cumbersome due to the heterogeneous application, design and configurations of machine tools. A unified classification approach as given in white ware [260] or automotive industry [261] in order to objectively classify and compare system with each other is requested from the legislative point of view. Schischke et al. [205] summarized the reasons for the challenging definition of a universal evaluation of machine tools:

- Undefined scope of the evaluation and definition of machine tools:
- Diversity in configuration and parametrization and machining process variety
- Diversity and complexity of machine tools
- Organizational applicability and energy wise classification
- Lacking of simplicity and inclusion of required relationships
- Transparency and reproducibility
- Missing completeness and agreements

A generally applicable evaluation method for machine tools and production system was developed based on the above mentioned requirements and challenges. The following method and related findings were adopted in the first part of the ISO 14955 [29] standard and are partly published in [262, 263] and [264].

A machine tool represents an assemblage of different components and subcomponents. Therefore, a comparability of energy and resource consumption and their resulting energy efficiency on different process technologies or machine tool configurations cannot be identified by applying a single component evaluation. Based on the above mentioned observations, it is obvious that the actual needed energy for the machining process, performed by the main drives, has a minor energetic influence. In other cases, the auxiliaries that disprove a common energetic comparison on the component level, dominate the total energy consumption as introduced by Dietmair and Verl [87]. From these findings, a comparison based on the chip-removal energy only is not applicable. Based on the findings from performed measurements, auxiliary components can be classified in component groups as specified above.

Depending on the machine tool mode and configuration, auxiliary components fulfill essential functionality without a direct added value. The goal of the following analysis and optimization measures is to minimize the power consumption of all components to the essential physical minimum by maintaining the output, flexibility, costs and quality of the machining process. The resulting component functionality, e.g. cooling, might be substituted by corresponding technologies or proper dimensions in order to increase energy efficiency. Therefore, an abstract view of the overall machine tool system, including the peripheral consumers, is chosen for the evaluation and resulting conclusions from the component power measurements. These evaluation statements can be reached by detaching from the component to a functional view of the system and represent a view detached from technical solutions or implemented components.

Function orientation is primarily represented in the development of complex technical systems with high variability, e.g. automotive sector. The development, testing, and evaluation of the system properties can be challenging since complex mechatronic or hybrid systems such as vehicles, buildings, and machine tools fulfill their defined functionality by subsystems.

A function is defined as the outcome, task, action, or attribute of an object or component as introduced by Pahl and Beitz [265]. In general a functional description is independent of the system design. As revealed from the performed measurements and component groups, machine tool components can be generally clustered to one of five main machine functions, as illustrated in Figure 5.8 (left) for a generic sample machine tool. The assignment of the machine tool components to the functions is specific for each case. Figure 5.8 shows the transition from total energy consumption via functional level and functional mapping to component level with hereby defined five main machine functions. The machine tool components are assigned to their related function by general rules and best knowledge of the user. If a component cannot be mapped completely to one function, its power consumption share is split and is assigned to several functions according to measurements or estimations.

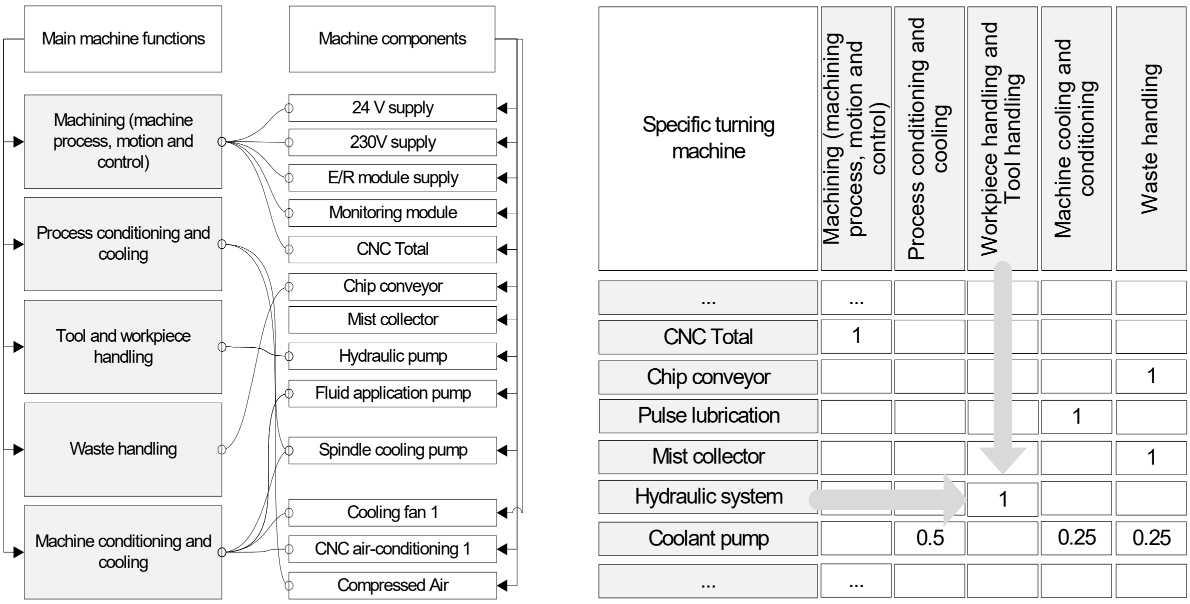


Figure 5.8: Selection and classification of machine tool components into machine tool functions. Left figure shows the classification of machine tool components and measuring points into five functions. Right figure shows the selection of the component share in each function.

In the following each machine tool function is defined and explained in detail.

Machining *- machining process, motion and control*

This function summarizes the target function of the machine tool and represents the energy demand which is required to realize the intended machining process, e.g. chip removal. For instance, it comprises the realization of cutting velocity, of an electro-discharge process, or of laser beam for cutting. Furthermore, it includes the needed energy for machine motion needed during machining, e.g. supporting axis. As this function is driven by a NC containing the NC kernel, drives, and amplifier, the PLC, HMI, 24V supply, monitoring systems, and measuring systems, except the cooling of these parts.

Process Conditioning and Cooling

Measurements show that cooling application can be distinguished in process and machine tool related cooling. The following function refers only to the machining process, e.g. cooling or lubrication of the tool. It also comprises conditioning, e.g. heating of the process zone within the machining process. This function encompasses needed power to maintain the temperature and other relevant conditions of the working volume, the tools, the fixtures and the workpieces within their default settings and limits. The function might interfere with the machine cooling and heating. Therefore, the share needs to be defined individually. Process cooling is indicated when a direct added value, e.g. workpiece surface quality or machining output, is given.

Workpiece and Tool Handling

The function, *workpiece and tool handling*, implies changing, grasping, clamping, handling, and lifting of the workpiece, the tool, or both; furthermore, it includes the infeed of raw material and the measurement of workpieces in the machine tool. Typical mechanical components for handling workpieces are robots, hydraulic fixtures, and pneumatic chucks. Typical mechanical components for tool handling include a turret of a turning machine and tool changer of a machining center. In some cases, this function must be separated into two sub functions*: workpiece handling* and *tool handling* as shown in ISO 14955.

Waste Handling

This function summarizes the handling of chips, cutting fluids, the separation and filtering, handling of dust and fumes, and handling of dirt, including the protection of machine components against ingress of harmful waste. Typical mechanical components for the function *waste handling* consist of a chip conveyor, filter systems, and exhaust systems. A common measure to protect components is to seal air for motors and measuring systems.

Machine Cooling and Conditioning

This function summarizes the energy which is required for all cooling and heating activities that are independent from the machining process. This function does not add direct value to the machining process. It is applied to keep thermal stability of the control cabinet within the operational limits to ensure that components are not damaged or distorted. This function can overlap with the *process cooling and conditioning*. One way to distinguish machine cooling from process cooling is to consider the location of the related components. *Process cooling* is directly connected to the workpiece and process area, whereas *machine cooling and conditioning* is apart of the machine tool auxiliary, e.g. control cabinet.

Components mapping

Based on the definition and classification in five generalized functions made above, various machine tool systems can be characterized, independently from their configuration or individual machining process.

With this abstract view it is possible to evaluate and compare similar but not identical machine tool configurations on a detailed level. For example, the main machine functions, *machine motion*, with the generation of relative movement of axes can be realized by different technologies, quantity, and type of components. The function remains the same and is independent of the individual machine tool configuration and dimension. Herewith the attribute power consumption of each energetic relevant component $P_{eff,i}$ must be summarized and clustered according to the functional component mapping as shown in Figure 5.8. The mapping of the components and their share to the intended function must be defined individually. The methodological approach as shown in this research should be performed in cooperation by the machine tool builder and user. The mapping is seen as an orientation and is done with the best knowledge and inspection by the machine tool builder and machine tool user. A certain imprecision is indispensable and deviations on the component shares are likely as the component mapping bases on a qualitative approach. The uncertainty is given as this classification combines a quantitative with a qualitative approach. In general a deviation within the mapping of $\pm 10\%$ is possible. As the total sum of the power demand P_{tot} is split on the given functions and all functions on the given components are considered vice versa:

$$P_i \rightarrow \{F | F_1, F_2, F_3, F_4, F_5\} \tag{5.3}$$

and

$$F_n \rightarrow \{P | P_1, \dots, P_i\} \tag{5.4}$$

Besides the mapping uncertainty, this qualitative approach is seen as an appropriate indication of the machine tool potential and importance of functions.

Most components represent a one-to-one relation to a certain function. A spindle is clearly assigned to the function *machine motion*. However, a coolant pump contributes not only to the process cooling but also to the *machine cooling* and *waste handling* as well. Consequently, the energy consumption of the coolant pump must be split into these three functions. The proper assigned share of the machine tool components indicates the ensuing evaluation and optimization and needs to be evaluated based on experience and by expert assumption, e.g. machine tool builder and machine tool user. The functional energy evaluation can be structured into a general and qualitative part which is valid for all machine tools, and a specific and quantitative part, which represents the individual machine tool configuration. The general approach is completely machine tool independent but implies the qualitative component mapping, whereas the machine tool specific part is based on a selected machine tool and quantitative evaluation according to multichannel measurements on the component level.

Example and application of the functional oriented evaluation

The developed methodology is part of the ISO 14955 [29] and is also used in the current SRM proposal. The example in Figure 5.9 shows the application of the methodology on two different machine tool types. The examples show that the function *process cooling* and *machine cooling* dominate the energetic behavior. The disproportion between these functions and the primary function *machining*, representing the energy initially brought into the machining process, indicates a potential inefficiency in the generation of these functions. In the following case the respective components for the cooling function might be oversized for the given specific machining process. The applied component configuration or the subsystem design might be inefficient.

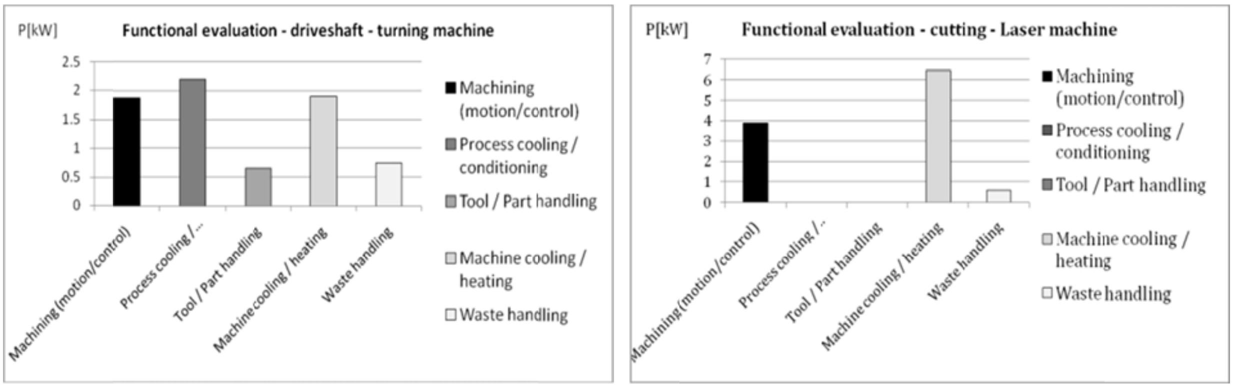


Figure 5.9: Functional oriented evaluation on different machine tools. Left figure represents a turning machine. Right figure represents a laser machine tool.

Function / Component	F1 Machining	F2 Process Cooling	F3 Tool / Part handling	F4 Machine Cooling	F5 Waste Handling
CNC Axis	100%				
Grindling spindle	100%				
Cooling fluid unit		20%		80%	
Fliter pump					100%
Exhauster					100%
Compressed air		80%			20%
Hydraulic system			100%		

Function / Component	F1 Machining	F2 Process Cooling	F3 Tool / Part handling	F4 Machine Cooling	F5 Waste Handling
CNC Axis	100%				
HF generator	100%				
Turbo blower	100%				
Laser cooling unit				100%	
Fan 1					100%
Fan 2					100%

Figure 5.10: Component to function mapping based on the component measurement and average effective power during processing on a turning machine (left) and a laser cutting machine (right).

The functional evaluation graph (Figure 5.9, right) represents a typical picture of a laser cutting machine. The main machine function is represented by the CNC drives, the high frequency (HF) generator, and the process gas turbo blower. In this machine configuration the *process cooling* and the *tool and part handling* function are not applied as there is no component within this configuration to fulfill this function. The evaluation shows that the *machine cooling* peripheral is dominant, whereas the *waste handling* function is low in comparison to other functions. This finding is true as in the following configuration *waste handling* is only represented by a constantly running exhaust fan. The functional analysis can be applied on a specific machine tool mode, e.g. machining process, other relevant machine tool modes or over a set of different modes resulting from a defined reference process. In the following case the *waste handling* function is the dominant function in standby mode. In consideration of the relevant time share of each machine tool mode within a given production, appropriate optimization measures might therefore be suitable within specific machine tool functions and related component relation.

The functional evaluation method was introduced in the SRM proposal to be able to evaluate and optimize machine tools and production system based on an unified methodology and to indicate specific optimization measures based on inefficiency detection and potential quantification. The SRM approach requires the applicability on various machine tool systems. A general acceptation of the SRM can only be reached by an easy to apply and comprehensive approach. The proposed functional oriented analysis procedure, based on the multichannel measurement is classified in four independent steps and described as follows.

Step 1: Measurement and functional evaluation

In the first step it is required to measure the machine tool based on the multichannel measurement or multi-selective measurement approach. It is considered as reasonable to measure a reference process which represents a typical machining process for a given configuration as defined in ISO 14955 [29]. This reference process should also take different machine tool modes and their individual time share into consideration. The measured values must be mapped accordingly to their function as indicated in Figure 5.10 resulting in Figure 5.9. It is possible to perform the measurement with conventional sequential multimeter measurements.

Step 2: Determination of scope

In the second step a relevance threshold is set for the indication of relevant machine tool function for further analysis and optimization. The threshold is required as it sets the focus level which functions and components should be further considered or not. The threshold value is variable but is oriented towards the connected load, the amount of active components, and effective power range during the machining process and / or reference process. The threshold level can be adjusted further accordingly to legislative requirements. As the performed measurements show that a connected load of $P_N = 100kW$ leads in most cases to an effective power average of $\emptyset P_{eff} = 6kW$ based on up to 12 to 15 active machine tool components within various machine tool modes, a threshold of $P_\Delta = 1\ kW$ or 10% on the total average effective power during machining process $\emptyset P_{eff,tot}$ is considered as reasonable. This threshold can be either defined by a relative value, e.g. $\geq 10\%$ of the total effective power $P_{eff,tot}$, or an absolute value, e.g. $\geq 1kW$. This threshold defines the relevance and level of detail for the further analysis and optimization of all functions and interconnected components.

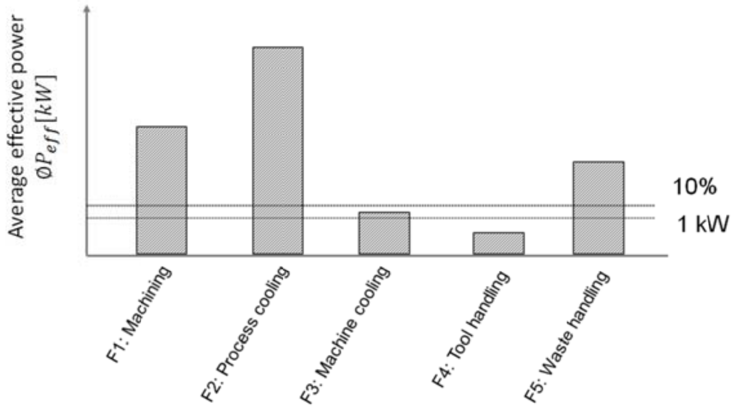


Figure 5.11: : Functional-oriented machine tool classification based on a reference process on a turning machine tool with 10% and 1kW threshold that indicates the optimization focus.

Step 3 Optimization of efficiency potential

Based on the defined threshold, the optimization potential can be addressed qualitatively or quantitatively. The qualitative evaluation for the indication of optimization measures can be applied to report against public entities in the SRM methodology as it refers only to relative values without a technical specification, individual or even confidential technical solution. Furthermore, this evaluation helps machine tool builders to indicate what has been optimized based on a standard machine tool configuration and reference process. For the optimization measures indication the quantitative analysis based on the given measurement should be used. In the following example (Figure 5.11) the functions *F1*, *F2*, and *F5* are of special interest and need to be further investigated for technical improvement. Function *F1*, is process-dependent. A change within this function will influence the process quality and output. For this reason it is refrained from direct measures within this function. The indication on function *F5* shows only little optimization potential. If no effective measures, for instance from ISO 14955 [29] are available, this function is not due to optimization measures. The example shows, that in the case of function *F2* an adequate optimization potential, given by the over-dimensioning of the process cooling, is given. A detailed technical assessment and further measurement is reasonable within this function, e.g. examination of the appropriateness for a frequency controlled cooling pump (Figure 5.12).

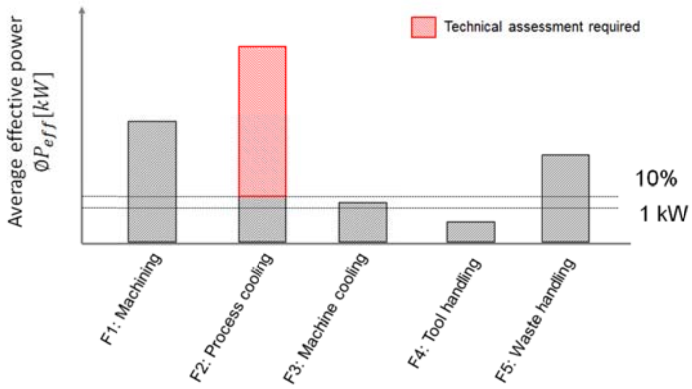


Figure 5.12: Functional-oriented machine tool classification based on a reference process on a turning machine tool with the indication on the machine tool process cooling.

Step 4 Measurement and comparison of optimized setting

In the final step the indicated and individual machine tool problem is assessed and an optimization measure is applied. Based on the given reference process, the improved machine tool configuration is measured again (Figure 5.13). This comparison measurement can also be performed on a qualitative basis, resulting to the relative improvement of the given machine tool and the proof of a defined optimization measure. Based on this optimization and the actual machine tool use, economic evaluations can be included.

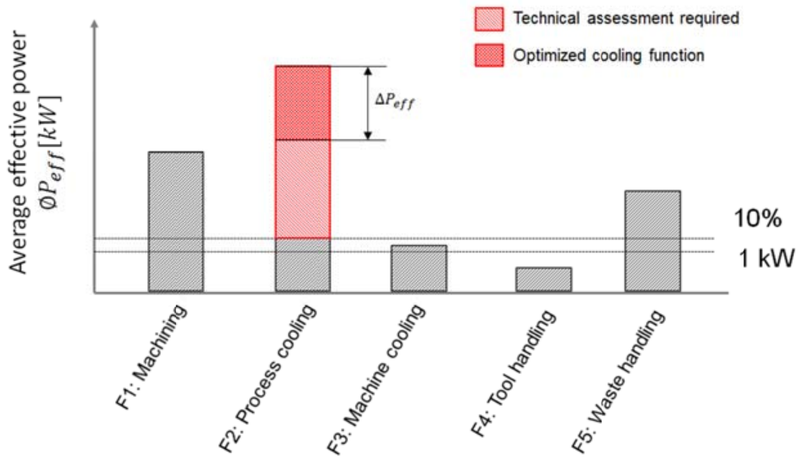


Figure 5.13: Functional-oriented machine tool classification based on a reference process on a turning machine tool with the indication on the machine tool process cooling.

Conclusion

The functional oriented energy evaluation represents an approach of a conceptual review of machine tools. It helps to understand the energetic behavior of a machine tool and establishes a common basis for comparison, energetic evaluations, and further optimizations. The assessment is made based on total energy consumption and data acquisition, which is attributed to defined machine tool functions. The functional oriented evaluation provides a clear depiction of value adding functions, as well as a sensible clustering of data acquired from a machine tool production system. The advantage is a simple, easy to understand picture of the energy consumption distributed on the general machine tool functions. Furthermore, it provides the obviousness of proportions which can indicate to the potential field for optimization. Another advantage is the possibility to compare different assemblies of components, either for one machine tool or the comparison of various machine tools for the decision-making on purchasing or production planning. Based on the relation of qualitative to quantitative elements, a disadvantage is given by the uncertainty in the component mapping. As it is related to known function-oriented methods in value analysis, target costing, product development and testing, the concept is easy to adapt and can be implemented in an industrial R&D environment and current SRI/SRM approaches as a complementary tool for energy assessments.

5.4.2 Retrofit Indication

A key optimization goal is the indication of inefficient components in order to define specifically and target-oriented optimization measures. An indication of inefficient components should lead to their replacement or retrofit. The potential for retrofit in industry is either unknown or underestimated as showed by an internal study among Swiss SMEs [266].

Retrofit is recognized by Ayres and Ayres [267] as a potential energy and waste saving activity. Kircher et al. [179] and own measurements [268] ascertain that machine tools are often not designed towards energy consumption requirements, mainly due to the peripheral design and the inter-peripheral adjustment. On given machine tool systems with defined machining processes retrofit can be applied in line with economic and ecologic requirements. As the use phase of machine tools is expected to be higher than ten years [18], retrofit and refurbishment must be considered not only for maintenance and service reasons but for continuous improvement during machine tool usage as well. For this reason an indication of inefficient components is developed. The following chapter was partly published in Gontarz et al. [262].

Measurements of the effective power of subcomponents revealed that process-relevant components follow a process-dependent or demand-driven fluctuation. It is assumed that supporting function, e.g. cooling or process conditioning, should be fluctuating and controlled as well to reach a load and demand-driven application. For this reason two technical aspects are considered for evaluation of the energy efficiency of a machine tool components:

• Share of energy consumption (A_E): Components with a high share of the energy consumption in comparison to other subcomponents of the machine tool are assumed to have a higher saving potential.

• Mode of operation (A_o): Open loop controlled components are assumed to have a higher potential for efficiency improvement than closed loop controlled components.

In combination, both indications represent an indicator (I_R) for the potential inefficiency of a subcomponent:

$$I_R = A_E \cdot A_O \tag{5.1}$$

In equation (5.1) A_E $[-]$ represents the share of the average power consumption $\emptyset P_i$ in relation to the total power of the machine tool system $\emptyset P_{tot}$ in each operational state. $A_O[-]$ represents a weighting factor for the mode of operation of each component, whereas $A_O \approx 1$ indicates a stationary energetic behavior and $A_O \approx 0$ indicates an alternating or variable energetic behavior as further explained below. This follows the assumption that variable component power behaviour indicates a need-driven and therefore more efficient application.

Methodological steps

Step 1 – Machine tool measurement

For the retrofit indication a detailed effective power measurement of all subcomponents within the system boundary is mandatory. The indication methodology depends on the individual energetic subcomponent behavior and its interrelation as well as environmental and infrastructural constraints. For this reason the measurement data based on the component measurement needs to be synchronized or done simultaneously by a multichannel measurement system as introduced in chapter 3. This is required to gain coherent data from all active machine tool components in all relevant machine tool modes. The machine tool measurement and assessment include several subtasks:

• Definition of appropriate system boundaries that includes all relevant and peripherals and all relevant energy forms as in- and outputs to and from the system boundaries simultaneously. A valid definition of a system boundary is defined in chapter 3.3 and clause 6.2 of the ISO 14955-1 [29].

• Definition of operation states and definition of shift regime, i.e. sequence of operating shifts, observation period and use scenario for the given machine tool manufacturing environment. Usually those machine tool operating states are manufacturer-specific.

• Definition of a reference process for the operation state *machining*, which exploits the capabilities of the machine tool and defines a basis for optimization. This reference is machine tool dependent and represents in the best case the target machining process for this machine tool and its configuration. The reference process can be also represented by a set of different machine tool modes.

The indication methodology further focuses mainly on the process-independent optimization of auxiliary devices. For a simplified evaluation, the function-oriented classification, as introduced in chapter 5.4.1, is recommended to classify the machine tool subcomponents.

To evaluate the needed parameters in (5.1) the following measurement values have to be identified:

- $\emptyset P_{tot}(t)$: This value represents the average effective power of the entire machine tool during the reference process.
- $\emptyset P_i(t)$: This value represents the effective power of each subcomponent i during the reference process in the sampling intervals of the length t_s.

Step 2 – Calculation of retrofit indicator I_R

For each machine tool component, the retrofit indicator I_R must be determined by an individual measurement during the observation period, where the period is subdivided by sampling intervals of length t_s. As the measurement consists of discrete effective power values, the energy share of each component i, $A_{E,i}$ is calculated as follows:

$$A_{E,i} = \frac{E_i}{E_{System}} = \frac{\sum_{j=0}^{n} P_{i,j}}{\sum_{j=0}^{n} P_{i,System,j}} \tag{5.2}$$

with

$$n = \frac{t_{total}}{t_{sample}} \tag{5.3}$$

$E_i[kWh]$: Energy supplied to component i during observation period.
$E_{sys}[kWh]$: Energy supplied to machine tool, accordingly to system border definition.
$P_{i,j}$ [W]: effective power of each component i at sampling point.
$P_{i,system,j}$ [W]: total effective power of machine tool, according to system border definition at sampling point.

n [-]: number of samples within observation period t_{total}.
t_{total} [s]: observation time variation of process parameters.
t_{sample} [s]: length of sampling interval.

The second parameter, the actual component power behavior requires a more detailed approach. As components, which are generally considered as constant, e.g. fans, represent a startup peak a variance analysis cannot be applied to evaluate the individual machine component power constancy. Thus, several mathematical methods were evaluated for an adequate representation of the subcomponent operational mode. A component is considered as process-independent if it has at all sampling points the same power values within the measurement accuracy. Components with a close loop controlled energetic behavior are represented by power values on different power levels. This fluctuation is considered to be either process-dependent or party needs-oriented towards the machining process. A mathematical description is required to indicate the fluctuation of a component's power supply. Methods such as rainflow [269], time at level counting [270], occurrence frequency evaluation [271], or Gini coefficient [272] were investigated and reviewed for this application. Special focus and a detailed validation is given on the following approaches for the calculation of the A_O factor:

- Time on level counting
- Occurrence frequency evaluation
- Gini coefficient

Time on level counting

The time on level counting classifies a statistical value, in the following the effective power measurement values, in equidistant classes. Thus, an appropriate definition of the class width $\Delta_{class}[W]$ is needed for the signal interpretation. In the following the procedure for the evaluation of A_O according the time on level counting is introduced.

An approach with an assumed class width of $\Delta_{class} \approx 0.005 \cdot (max\{P_i(t)\} - min\{P_i(t)\})$ is chosen. This value is chosen as a tradeoff between required calculation time and level of detail based on the measurement accuracy. The class definition and corresponding quantity are represented by:

Positive-oriented effective power leveling:

class $\quad n = \{x|(n-1) \cdot \Delta_{class} < x \leq n \cdot \Delta_{class}\}$ for $n \in N \cap 1 \leq n \leq \frac{max\{P_i(t)\}}{\Delta_{class}} + 1$ (5.4)

Negative-oriented effective power leveling:

class $\quad p = \{x|(p-1) \cdot \Delta_{class} < x \leq p \cdot \Delta_{class}\}$ for $p \in N \cap \frac{min\{P_i(t)\}}{\Delta_{class}} - 1 \leq p \leq 0$ (5.5)

N: natural number.

In the case of $min\{P_i(t)\} \geq 0$, no classes are needed in the negative-oriented effective power leveling. Furthermore, measurements showed that negative effective power values can be assumed as energetically irrelevant, thus their control behavior still must be considered. The applied class definition and the time at level counting is visualized in Figure 5.15.

$$n \in N \cap \frac{min\{P_i(t)\}}{\Delta_{class}} - 1 \leq n \leq \frac{max\{P_i(t)\}}{\Delta_{class}} + 1 \tag{5.6}$$

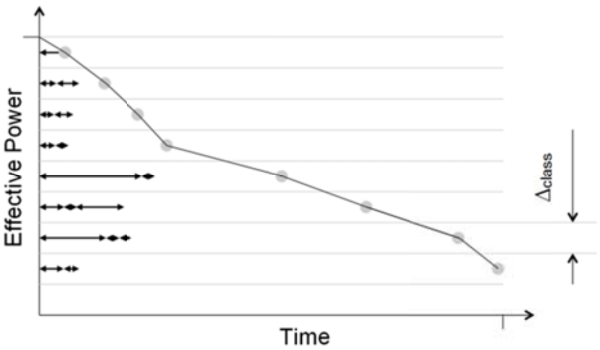


Figure 5.15: Example of the classification in equidistant classes of the effective power over time measurement and normalization.

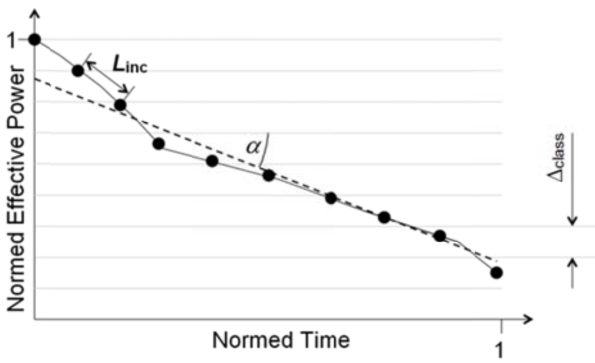


Figure 5.14: Resulting graph with regression line and gradient for the calculation of $\boldsymbol{A_{O,i}}$.

The discrete normalized effective power values are organized equidistantly in the ordinate direction with a constant width of $\Delta class$ (Figure 5.14). The data point allocation in abscissa direction is dependent on the sum-level-duration levelling plot and therefore not equidistant. A parameter sensitivity of the regression line gradients depending on $\Delta class$ is given as fewer points are given on the horizontal levelling whereas many points are given on the vertical levelling. This effect increases the more classes are passed by the measurement signal. This makes the evaluation complicated and requires further effort. For this reason an algorithm was applied to sample the sum-level-duration levelling plot equidistant along the data points. The horizontal and vertical sequence plots are weighted equally in the calculation of the regression line.

The regression line is finally described by total length of the sum-level-duration plot. It is calculated by connecting all discrete normed effective power values by lines. The sum of these intervals is $L_{tot}[-]$. The length is further revealed as the increment $L_{inc}[-]$ is calculated with:

$$L_{inc} = \frac{L_{tot}}{ceil\left\{\frac{P_{max} - P_{min}}{\Delta class}\right\} - 1} \tag{5.7}$$

with

$L_{tot}[-]$: Total length of sum-level-duration plot.

$ceil\{x\}$: Function to round the following element to the next integer.

$P_{max}[W]$: Highest effective power among all consumers.

$P_{min}[W]$: Lowest effective power among all consumers.

A linear interpolation between the discrete normed effective power values is made to find the corresponding points for the evaluation plot. Finally, the gradient of a regression line through the allocated points quantifies the dimension of the operational mode of each consumer i. The weighting factor $A_{O,i}$ is calculated according to:

$$A_{O,i} = \frac{90[°] - |a_i|}{90[°]} \tag{5.8}$$

The time at level counting complicates the interpretation by class-width-dependent convergence behavior in the analyzed data. The calculation of the A_O factor requires multiple calculation steps, high calculation effort, and depends on the signal quality and resulting $\Delta class$ definition. The appropriate definition of the class width $\Delta_{class}[W]$ is needed for the signal interpretation, but is also dependent on several aspects, e.g. signal noise and signal quality and the resulting calculation period. Wide class ranges ($\Delta_{class} > 0.005 \cdot (max\{P_i(t)\} - min\{P_i(t)\})$) could lead to false interpretations of the effective power signal, whereas narrow class ranges ($\Delta_{class} < 0.005 \cdot (max\{P_i(t)\} - min\{P_i(t)\})$) increase the calculations time without any improvement in the information content. For this reason further methods were determined to find a suitable description of the component constancy.

Occurrence frequency evaluation

In this given approach, a definition of classes is not needed as a consequence of a direct value counting procedure, as it is mandatory within the time at level counting. The calculation of $A_{O,i}$ can be described in four steps.

Step 1 - Value transformation

The measured discrete values P_i must be transformed with the lowest global value $P_{min,g}$ in order to provide $P_{i,tr} \geq 0$ values for further accumulation and comparability among the components. The transformation, given by an origin of coordinates shifting, is done by:

$$P_{i,tr} = P_i - P_{min,g} \tag{5.9}$$

with

$P_{i,tr}[W]$: Transformed effective power of each component i.
$P_i[W]$: Effective power of each component i during the observation period.
$P_{min,gl}[W]$: Lowest global value within the observation period.

Step 2 – Normalized values

To provide a comparison among all evaluated machine components, $P_{i,tr}$ must be normalized with the global maxima according to:

$$P_{i,norm} = \frac{P_{i,tr}}{P_{i,max,gl} - P_{i,min,gl}} \quad (5.10)$$

with

$P_{i,norm}[-]$: Normalized value of each machine tool component

$P_{i,max,gl}[W]$: Highest global value within the observation period

This calculation is done for each component.

Step 3 – Sort values

The measured values are normalized by the global limit values. In the second step the $P_{i,norm}$ values are sorted by their value. In the following approach a descending order is chosen. The sort-value distribution describes a cumulative frequency distribution as indicated in Figure 5.16.

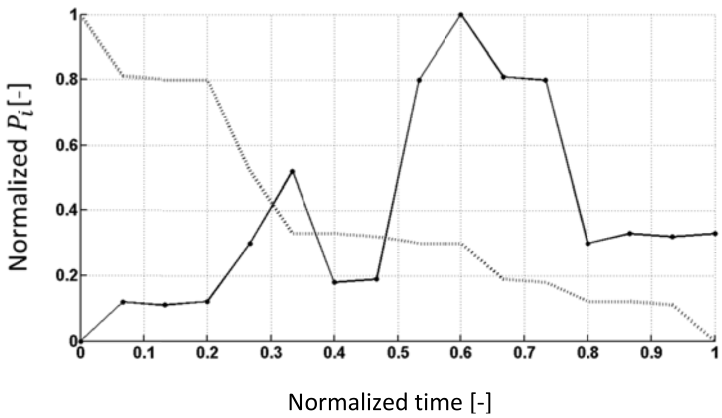


Figure 5.16: Normalized and sorted $\boldsymbol{P_i}$ values according to a test measurement on a turning machine tool. The solid line represents the unsorted normalized values $\boldsymbol{P_{i,norm}}$, the dotted line represents the sorted $\boldsymbol{P_{i,norm}}$ values in descending order.

Step 4 – Regression line

Similar to the time-on-level-counting approach a regression line is applied. The cumulative frequency distribution is dissolved equidistantly in abscissa direction but not in ordinate direction. To maintain an equal weighting of both axes, the cumulative frequency distribution is sampled along the path with a length increment $L_{inc}[-]$ represented in:

$$L_{inc} = \frac{L_{total}}{(n-1)} \tag{5.11}$$

with

$L_{inc}[-]$: Incremental length of supporting points.

$L_{total}[-]$: Total length of sum-level-duration plot.

$n\ [-]$: Number of samples within observation period t_{total}.

In the last step the gradient of a regression line through the allocated points quantifies the dimension of the operational mode of each consumer. The weighting factor $A_{O,i}$ is calculated according to:

$$A_{O,i} = \frac{45° - |\alpha_i|}{45°} \tag{5.12}$$

with $\alpha_i[°]$, inclination angle of the regression line, results in Figure 5.17:

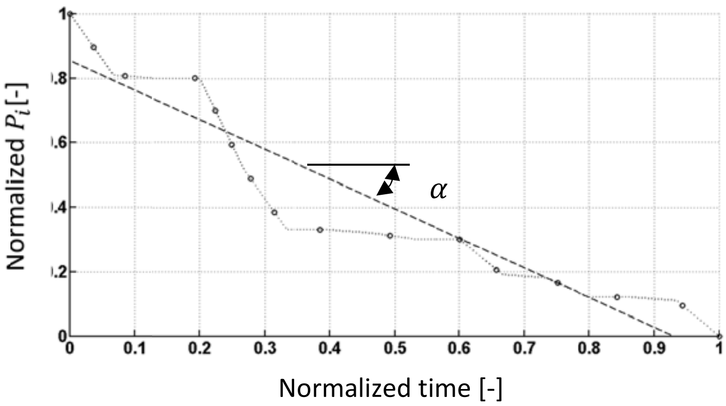


Figure 5.17: Sorted and normalized $\boldsymbol{P_i}$alues. Dashed line represents the resulting regression line with the inclination.

Gini coefficient

An alternative mathematical approach to the above mentioned time-on-level counting and occurrence frequency evaluation is given with the Gini coefficient based on the Lorenz Curve. As shown by Jovanovic [273] the Gini coefficient is a well-established statistical tool which is mainly used in economics and statistic analysis of dispersion in values, e.g. levels of income. Thus this coefficient is also assessed for the required analysis for dispersion of effective power values in order to detect and assess the constancy of machine tool components. Jovanovic [273] also provides a simple formula for the Gini coefficient that can be applied on discrete and continuous distributions (Equation 5.13). A resulting Gini value $A_{O,GINI} = 0$, represents a perfect quality or static machine component energetic behavior, whereas a Gini value of $A_{O,GINI} = 1$ expresses a maximal equality and therefore a variable or highly controlled machine tool component. The Gini coefficient is explained by a simplified three step methodology. Further reference on the calculation is given to Jovanovic [273]:

Step 1 – Arrange effective power data: In the first step the effective power values $P_i(t)$ according the performed measurement are arranged for the lowest value to the highest value.

Step 2 – Distribution of values: In the second step it is needed to divide the value in quintiles and define the highest value in each quintile and individual share within each quintile.

$$S_q = \frac{P_{eff,sorted}}{5} \rightarrow S = \frac{S_q}{\sum P_{eff,i}} \tag{5.13}$$

with

$S_q[kW]$: Sum of the sorted P_{eff} values per quintile.

$S[\%]$: Share of each quintile in comparison to the sum of P_{eff}.

Step 3 – Plot the Gini coefficient: Based on the $S_q$and S values the Gini Coefficient can be plotted. The resulting curve represents the Lorenz Curve.

The application of the time-on-level approach showed that a brief peak load within an ideally periodic controlled component ($A_O \approx 0$) leads to an increase of the A_O factor and results in an indication of an inefficient component. On the other hand a brief peak load within an uncontrolled component ($A_O \approx 1$) decreases the A_O value. In second case this is reasonable as a control application might occur whereas the first case is not reasonable. The observations based on the test values show that a duty-cycle of 20% results in a better $A_O(with\, A_O \rightarrow 0)$ that a duty-cycle of 10%. This would result that a consumer which is switched on for a short time is more efficient and better controlled than a consumer which is switched on for a longer time within the same observation period. Appendix A.5 shows the evaluation of the Gini coefficient based on a test signal.

Conclusion

The following analysis of the possible and available evaluation methods, to determine the constancy of values within measurements, and performed experiments reveals that the occurrence frequency evaluation fulfills the analysis requirements to the furthest extent through a clear peak- and constant value identification, interpretation, and weighting. Furthermore, it provides an easy-to-read statement and acknowledges the performed experiments. The time-on-level counting is reasonable for consumers which are either very constant or very variable, e.g. high duty cycle. It shows massive misinterpretations based on various measurement data. On the other hand the Gini coefficient approach is suitable for the exact interpretation of value distribution. Still a comparison of components with similar energetic behavior or short and frequent peaks is not possible. For this reason the occurrence frequency evaluation is used for the retrofit analysis.

5.5 Economic Analysis

Besides the given mathematical and statistical approaches as introduced above, several economic approaches can be pointed out to describe and assess a production system. The economic evaluation of machine tools based on the investment costs is not sufficient according to Lauven et al. [274]. It is obvious that energy efficiency considerations need to be combined with economic evaluation, especially in retrofit application, to achieve an industrially applicable optimization. Current methods such as Total Cost of Ownership (TCO) and Life cycle costing (LCC) based on VDI-2884 [275], Design for Manufacture and Assembly (DFMA) [276], Return on Investment (ROI) [277], Methods-Time-Measurement (MTM) [278] or REFA [279], are generally not applied in combination with the power measurements on machine tool components.

The economic performance evaluation of machine tool components in combination with the energetic machine tool behavior, depends on the segregation and identification of the machine tool states *off*, *on*, *standby*, *ready* and *in process* for the retrofit optimization. The detection of these modes is required to assess the active and inactive components and their energetic share in order to evaluate their individual improvement potential. The findings based on the technical and economic system evaluation provide a reasonable basis for decision-making for optimization measures and related investments. The following method was developed in order to quantify the economic performance of different machine tool configurations and to evaluate retrofit options on given machine tool systems.

Economic machine tool evaluation

The following method combines LCC and TCO elements with the detailed effective power measurement as introduced in chapter 3. The combination of a detailed multichannel measurement based on the machine tool component level enables the calculation of the actual costs for the machine tool use phase for the comparison of optimization options and possible machine tool configurations.

Step 1: Machine tool state definition

Multichannel measurement must contain all possible machine tool modes on all relevant machine tool components. In some cases individual machine tool modes of the machine tool standby must be defined. The measurement should be performed in the following machine tool states:

Table 5.2: Relevant machine tool states for economic evaluation.

Machine tool mode	Description
OFF	Machine tool main power supply is turned off
STBY	Machine tool in standby and remains in a constant or near constant energetic behavior, e.g. power fluctuation due to cooling compressor.
READY	Machine tool is heated up and pre-lubricated and all necessary setup is done and machine is ready for production.
PR	Processing. The machining process begins as soon as NC code is running. The process is either defined internally or is represented by a customer part, including all required preparation, setup, and handling activities.

Step 2: Machine tool measurement

The multichannel measurement system should be installed covering all necessary channels according to ISO14955 [29], incl. compressed air and external cooling units. For the comparison of retrofit options or the comparison of two machine tool configurations the measurement of the standard machine tool (machine A) and the optimized machine tool configuration (machine B) needs to be measured resulting in the following measurements:

Measurement set for machine tool A:

Table 5.3: Measurement set of machine tool A. Machine tool in standard configuration.

Measurement	Description
M01	Effective power measurement with a sampling rate of 5Hz for 5 min in machine tool mode *OFF* on all relevant machine tool components.
M02	Effective power measurement with 5Hz for 5min in *STBY* mode on all relevant machine tool components.
M03	Optional. If the machine tool mode *READY* is available the measurement of needs to be applied within this machine tool mode for 5min on all relevant machine tool components.
M04	Measurement of the machining process.

Same measurements are applied on the optimized machine tool configuration resulting into the measurements M05, M06, M07, and M08.

Step 3: Required parameters

For the detailed economic machine tool evaluation several input parameters are required in order to fulfil the requirements for a TCO evaluation based on the multichannel measurement. The following parameters are required:

Table 5.4: Required parameters for the economic evaluation.

Parameter	Description
K_E [CHF/kWh]	Price of Energy for specified region and supplier default is set to 0.14 CHF/kWh
F_{CO2}: [CO2/kWh]	Local emission rate for the calculation of CO_2 emissions
T_U [a]	Lifetime of machine tool, default is set to 15 years
N_S [-]	Number of shifts in production 1, 2, 3 shift
d_w [d]	Number of working days of production per week
d_f [d]	Number of non-working days in the year
C_{air} [kW/(Nm^3/h)]	Internal compressed air conversion factor in 6bar environments to power, default is set to 0.13 kW/(Nm^3/h).
E_m [kWh]	equivalent energy consumption
Δt [h]	Duration of machine tool mode
P_m [kW]	Average machine tool power consumption

Furthermore, all financial related parameters for the economic evaluation must be given. These parameters are split in variable and fix costs and are defined as follows (Table 5.5 and

Table *5.6*):

Table 5.5: Required parameters for fixed costs.

Parameter	Description
K_A [CHF]	Purchase price of the machine tool, default is set to 500 000 CHF
K_i [CHF]	Installation costs of the machine tool at customer site, default is set to 5000 CHF
K_R [CHF]	Define costs for machine tool handling and all related costs, e.g. customs, default is set to 5000 CHF.

Table 5.6: Required parameters for variable costs.

Parameter	Description
K_W [CHF]	Service and Maintenance costs per year, default is set to 5000 CHF
K_B [CHF]	Operating costs of machine tool system (will be calculated)
K_E [CHF]	Energy costs of machine tool system (will be calculated)

The machine tool use phase and related value add time is defined by the production type, days of production, and numbers of shifts. In the following the parameters for each production type are predefined in the evaluation tool according to [16] but can be changed by the user if required. The default values are represented by Table 5.7:

Table 5.7: Machine tool mode share according to production type according to Kuhrke [16]:

Production type	OFF (s_{OFF})	STBY (s_{STBY})	READY(s_{READY})	PR (s_{PR})
Single-part	30%	40%	10%	20%
Small series	20%	30%	10%	40%
Mid series	10%	20%	10%	60%
Full-production	0%	20%	10%	70%

The production type is further related to the number of shifts and resulting active production time.

Table 5.8: Relation of production type to number of shifts and related working hours per day.

Production type	Number of shifts	Hours per day
Single-part production	1 shift	8h per day
Small series production	1 shifts	8h per day
Mid series production	2 shifts	16h per day
Full-production run	3 shifts	24h per day

Step 4: Calculation

The measured or estimated time shares in combination with the actual power measurement in each machine tool mode result in the equivalent energy consumption and results in the actual machine tool usage profile. The individual usage profile of each machine tool and its components is represented by:

$$E_m = \begin{pmatrix} \Delta t_{OFF} \times P_{mOFF} \\ \Delta t_{STBY} \times P_{mSTBY} \\ \Delta t_{READY} \times P_{mREADY} \\ \Delta t_{PR} \times P_{mPR} \end{pmatrix} \tag{5.14}$$

with

$$P_{mOFF} = \frac{\sum_1^n P_{m\,off}}{n} \tag{5.15}$$

$$P_{mSTBY} = \frac{\sum_1^n P_{m\,stby}}{n} \tag{5.16}$$

$$P_{mREADY} = \frac{\sum_1^n P_{m\,ready}}{n} \tag{5.17}$$

$$P_{mPR} = \frac{\sum_1^n P_{m\,PR}}{n} \tag{5.18}$$

and

$$\Delta t_{OFF} = (52 \times d_w - d_f) \times n_s \times 8h \times s_{OFF} \tag{5.19}$$

$$\Delta t_{STBY} = (52 \times d_w - d_f) \times n_s \times 8h \times s_{STBY} \tag{5.20}$$

$$\Delta t_{READY} = (52 \times d_w - d_f) \times n_s \times 8h \times s_{READY} \tag{5.21}$$

$$\Delta t_{PR} = (52 \times d_w - d_f) \times n_s \times 8h \times s_{PR} \tag{5.22}$$

Step 5: TCO calculation

The TCO calculation evaluates the expected costs for the machine tool, based on the detailed knowledge on the machine tool use and energetic behavior. The total costs are represented by fixed costs and variable costs. While related fix costs are represented by the sum of purchase price K_A, installation costs K_I, and other related costs, the variable cost follow a linear function dependent on the equivalent energy consumption and machine tool life time T_U. This equals to:

Fixid costs:

$$K_f = K_A + K_i + K_R \tag{5.23}$$

Variable costs:

$$K_B = E_m \times K_E + K_W \times T_U \tag{5.24}$$

TCO (K_{TCO}) can be calculated to:

$$K_{TCO} = K_f + K_B \tag{5.25}$$

Step 6: ROI calculation

For the calculation of the amortization time both cost function, standard machine tool costs and optimized machine tool cost, have to be equalized to calculate the amortization time.

Cost function standard machine tool:

$K_{TCO\ ST}$ = Costs of standard machine tool:

$$K_{TCO\ ST} = K_f + \sum_{1}^{n} P_{m\ n} \times T_U \tag{5.26}$$

With

$$\sum_{1}^{n} P_{m\ n} = s_{OFF} \times P_{off\ M1} + s_{STBY} \times P_{STBY\ M2} + s_{READY} \times P_{READY\ M3} + s_{PR} \times P_{PR\ M4} \tag{5.27}$$

and the cost function of the optimized machine tool.

$K_{TCO\ OPT}$ = Costs of optimized machine tool

$$K_{TCO\ OPT} = K_f + K_{opt} + \sum_{1}^{n} P_{m\,n\,opt} \times T_U \tag{5.28}$$

with

$$\sum_{1}^{n} P_{m\,n\,opt} = s_{OFF} \times P_{off\ M5} + s_{STBY} \times P_{STBY\ M6} + s_{READY} \times P_{READY\ M7} + s_{PR} \times P_{PR\ M8} \tag{5.29}$$

This should be calculated and plotted to:

$$T_U = \frac{K_{OPT}}{(\sum_1^n P_{m\,n} - \sum_1^n P_{m\,n\,opt})} \tag{5.30}$$

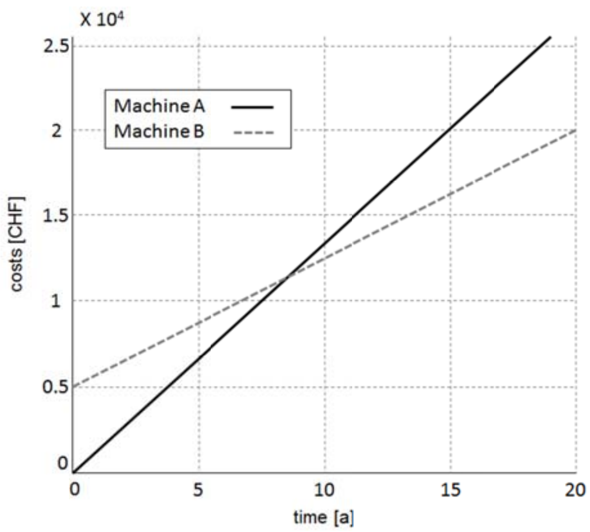


Figure 5.18: Example of linear cost functions based on given Studer use case and related amortization time.

Step 7: NPV calculation

The ROI for energy related optimization measures, e.g. retrofit, are often exceed two years. Based on this evaluation measures are seem to be unprofitable. Therefore, a second decision criterion is chosen to evaluate the economic benefit of the given measure. The net present value (NPV) calculation according to Lauven et al. [274] determine the value of an investment within an optimized system. This approach guarantees a better comparison of resulting costs. The premise to apply NPV for the comparison of machine tool investments, requires a modification and an equal investment for optimization measures according to Seiler [280], Warnecke [281], and Volkhart [282]. As individual optimization measures are given, an equal investment is not the case for retrofit applications. For this reason the NPV represents a qualitative indication if an investment is worthwhile and should be not used to compare several investments on different machine tool systems. A positive NPV indicates a worthwhile investment into the new technology as the following method evaluates alternative investments based on their present value. This value is represents by the imputed interests on the initial investment during the amortisation time. If the NPV is negative the investment is financially not worthwhile and should be denied. An alternative for the NPV is given by the internal rate of return (IRR). In the following the focus is given on the NPV as this method is used of the calculation of life cycle costs according to Herrmann [283]. The NPV value is calculated by:

$$NPV = -I_0 + \sum_{t=1}^{T_U} \frac{C_t}{(1+i)^t} = -(I_{IB} - I_{IA}) + \sum_{t=1}^{T_U} \frac{D_t}{(1+i)^t} \quad (5.31)$$

with

$$D_t = -(E_{mB} \times K_E + K_{WB} \times T_U) + (E_{mA} \times K_E + K_{WA} \times T_U) \quad (5.32)$$

I_O: Initial investment

C_t: Cash-flow per year

t: observation period

I_{IB}: Investment in machine B

I_{IA}: Investment in machine A

D_t: Difference between variable costs of component A and B

i: Required rate of return in %

A similar approach to the NPV approach is represented by the IRR-method. The internal rate of return (IRR) is calculated accordingly to the NPV, whereas the NPV is set to zero. The requested value results in the effective interest rate *i* and is called IRR: The IRR represents the rate of return which is required to be used for interest of the investment. The IRR is calculated as follows:

$$0 = -I_0 + \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} \quad (5.33)$$

with

IRR: Internal rate of return

t_0: Initial investment

C_t: Net flow of funds

T: Observation time

Step 8: Additional KPIs

The used parameters in combination with the measures effective power values can be used for further KPI calculation. For instance, the CO_2 value for the entire machine tool configuration A and B can be compared down to the component level. The CO_2 depends on the regional gCO_2/kWh value. The regional carbon dioxide equivalent $F_{CO2}$for the metropolitan area of Zurich Switzerland is given with 124g CO2/kWh and can be calculated as follows:

$$g_{CO2} = E_m \times F_{CO2} = \begin{pmatrix} \Delta t_{OFF} \times P_{mOFF} \\ \Delta t_{STBY} \times P_{mSTBY} \\ \Delta t_{READY} \times P_{mREADY} \\ \Delta t_{PR} \times P_{mPR} \end{pmatrix} \times F_{CO2} \tag{5.34}$$

The presented method represents an economic evaluation of machine tools and its configuration based on the multichannel measurement. This approach is based on the TCO calculation with additional information on the component level by detailed effective power measurements. This leads to a detailed analysis down to the component level and helps to not only compare different machine tool configurations but also to indicate retrofit options. As amortization times of energetic optimization and retrofitting exceed two years in most cases, a dynamic evaluation method is required. The NPV shows if a given investment, e.g. retrofit solution, is economically reasonable based on the entire machine tool use phase. This helps to detect worthwhile investments. In combination with the technical analysis approach the economic approach fulfills the industrial requirements and represents the approach as indicated in Figure 5.1.

5.6 Conclusion

The given chapter introduced micro and macro optimization approaches in line with the findings from the multichannel measurement. Based on the presented energy evaluation levels from literature, this analysis and evaluation is applied on the subcomponents of a machine tool. Main focus was given on micro optimization. It implies all optimization activities that are given within the machine tool system boundary as defined by ISO 14955 and can be further aggregated towards macro optimization, e.g. production scheduling or production-dependent machine tool selection.

The evaluation of the machine tool component efficiency with the indication of individual optimization measures have influence on both, the energy consumption and investment, and is an important aspect of competitiveness and improvement of SMEs. In the future this might also become mandatory in EU legislation [23]. Indefinite information or the application of rule based optimization could lead to false or ineffective investment strategies. For instance, a machine tool that is used in a three shift work pattern requires different optimization actions and retrofit solutions as machine tools for occasional use on the shop-floor level. One main reason for those differing optimization activities is the effectiveness and the value-add and nonvalue-add usage ratio of the machine tool components in various machining processes.

Retrofit in combination with service and repair, longevity of the product and replacement is seen as a potential technical and economic field of action. In retrofitting, the challenge remains the selection of appropriate, economic, and ecologic solutions. The detection and evaluation of potential retrofit activities is particularly given on peripheral equipment whereas process-related components are analyzed in a second optimization step. This focus is preferred according to [11,2] and since measurements show that there is less potential for optimization for process-related components, e.g. controls.

Multichannel measurements indicate the individual energetic behavior of each component, its control and dependency towards other machine tool components and the machining processes. The use of the multichannel measurement system based on machine tool subcomponents is therefore a key element for the analysis towards the energy efficiency on the subcomponent level. In combination with analysis algorithms to for the indication of system inefficiencies and the economic assessment of these measures, retrofit and other optimization can be applied where necessary and worthwhile.

6 Monitoring

6.1 Introduction

The following chapter introduces a monitoring strategy which is based on the multichannel measurement, data acquisition, simulation and analysis. This approach is further suitable for the continuous evaluation and optimization within industrial environments.

Monitoring is understood as continuous measurement on a given system to validate and assess defined system parameters. The continuous measurement can be performed within a defined or undefined observation period. *Figure 6.1* shows the relation between measurement and monitoring, whereas measurement represents the selective and individual application of measurement equipment, and monitoring with defined, continuous measurement application and structured system architecture. Figure 6.1 shows further that selective measurements are application dependent and need to be individually defined, whereas monitoring application refer to standardized data points.

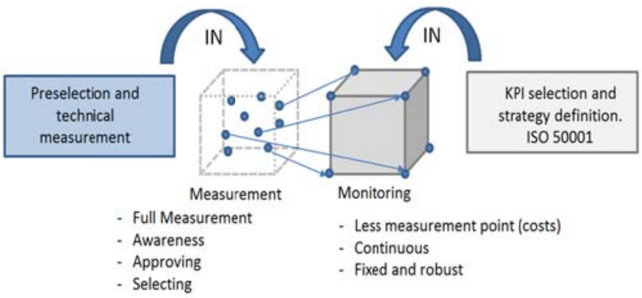


Figure 6.1: Relation between measurement on monitoring applications towards measurement point selection and required input information.

A monitoring system is therefore seen as the "check" - element within the Deming cycle and is considered as an element of the continuous improvement process (CIP). The application of monitoring systems is therefore seen reasonable if the monitoring strategy is embedded within a control loop leading to any optimization measures. Energy and resource based monitoring is addressed by current standardization approaches such as ISO 50001 [27]. This standard introduces an energy management system with the purpose to provide guidance for industrial facilities to integrate energy efficiency for industrial systems, as shown by McKane [284]. The essential elements within an energy management system are data acquisition and energy monitoring. Monitoring is further commonly defined as continues data acquisition for supervising activities in order to ensure the required performance targets. Sextl [285] showed that the application of monitoring systems for machine tools without the application of hardware optimization measures can lead to an efficiency increase of up to 30% through awareness raising and adequate code of practice, e.g. the machine tool switch of in non-productive machine tool modes or reduction of compressed air leakage.

Data capturing for monitoring applications can either be done by the use of sensors or precise simulation. Simulation can provide different kind of necessary information. For monitoring purposes, system supervision and dynamic optimization, simulations are only partially applicable as shown in chapter 4. Limitations for the industrial application of simulations are given by unproven or imprecise parameters, the amount of required parameters and the resulting accuracy of the calculated effective power. Elements for the power and flow measurement are provided by the multichannel measurement approach as introduced in chapter 3 and in [216]. The following development is based on the process unit level and is intended to provide adequate data and optimization indication to apply macro optimization, e.g. production scheduling or automated machine tool switch off, and micro-optimization, e.g. machine component control as shown in chapter 5.

A major requirement of an industrially useful approach and applicable method is the modularity of the given approach as confirmed by Verl et al. [188]. This is required to serve the variety of machining procedures as well as the individual machine tool and production system configuration and use. As the optimization potentials can vary from 10% to 50% an accuracy of at least $\pm 5\%$ is mandatory for monitoring applications.

Substantial improvement potential in energy efficiency is seen in the energetically dynamic component compensation and control according to the current machining process. For this reason monitoring systems are required to provide all relevant information based on a real-time or near-real-time system with a direct or indirect interface to the machine tool control, e.g. NC kernel, and external systems such as MES.

The application of energy and resource monitoring to enable energy efficiency methods must be given without compromising the flexibility, quality, and output of the manufacturing system. Therefore, main attention is given to auxiliaries and non-value adding machine tool states with limited influence and dependency on the machining process, e.g. external cooling, chip conveyor, exhausters. Still, relevant data from the component and subcomponent level need to be aggregated to higher shop floor data collection, e.g. MES or ERP, to be able to evaluate the overall energy and resource-related performance of the machine tool or production system. The environmental performance in manufacturing, which is assessed from a bottom-up approach, can be attained by technical measurements on the shop floor, machine tool and component level. A top-down approach represents strategic goals based on aggregated predefined measurement points in manufacturing or at the enterprise level. A combination of both approaches as depicted by Bunse et al. [62]. Westkämper et al. [51] have proven its industrial applicability in the operationalization of stakeholder requirements to shop floor level, which serves as a basis for eco-efficiency improvements in production, planning and control (PPC) and as a first step to prioritize further improvements at the machine design level.

As stated by Hu et al. [157] an energy efficiency monitoring system is a base to improve the energy efficiency. Therefore, a high precision as well cost efficient energy efficiency monitoring system is necessary. Assessing the power consumption and the energetic behavior of machine tool components, based on direct measurements with a high time resolution, is considered as expensive due to complex system architecture and required sensor implementation. Resulting benefits of this detailed evaluation is the quantification of the improvement potential and the indication for possible analysis applications. Furthermore, the combination with different resources and energy forms can cause complex, expensive sensor architectures. For this reason most monitoring applications of today focus on the tool wear or on the machine tool condition monitoring [127]. It is therefore obvious, that energy and resource monitoring systems are confronted with the tradeoff between reliability, accuracy, and costs. The developed monitoring strategy within this study, as a new patented approach, is paving the road for smart monitoring devices by keeping implementation costs low, whilst ensuring a high level of detail in the revealed information. To do so, an implementation method leading to a customized monitoring architecture, based on different information sources, is created. The developed system architecture selection was applied on two different machine tools to ensure the interoperability for different machine tool controls, configurations and machining processes.

The following section was party published in [286] and [287] and introduces a condign monitoring strategy and architecture that fills this gap and fulfils the requirements of accuracy within an acceptable cost-to-information ratio.

6.2 Requirements

Today's data acquisition for electrical power measurement in research and industry is mainly based on external sensors. In industry, data acquisition can be divided into two principle approaches: Either sequential measurement in order to obtain punctual and detailed information with high resolution, or the continuous monitoring of machine tools over a longer observation period. Measurement systems of today are restricted to a few measuring points, especially for monitoring systems and continuous measurement. Furthermore, most monitoring systems provide a low data resolution. Apart from this, external sensors represent the main cost factor and require complex implementation procedures. Therefore, there is a strong interest in finding alternative ways for the necessary data acquisition.

The following requirements for energy efficiency monitoring on machine tools and production systems can be revealed:

- **Accuracy:** The monitoring system must guarantee an accuracy for the indication of improvements of $\pm 5\%$.
- **Resolution:** For an appropriate machine tool or production system evaluation in-depth power level data is needed with a sampling rate of 5 Hz or better for an appropriate analysis of dynamic machine tool features.
- **Completeness:** The energetic behavior is mostly dominated by auxiliary components of the machine tool. Therefore, it is required that all energetic relevant components need to be assessed. The predominant energy forms are electrical energy and compressed air. Components are electronically controlled either by the CNC kernel or the PLC. Some components may comprise dedicated sensors for control reasons or safety purposes. As there is no standardized interface or data format for energy relevant data, the data acquisition system must support interfacing with various data sources.
- **Costs:** For the industrial application of energy monitoring systems direct monetary benefits can hardly be quantified. Monitoring systems for process and tool condition monitoring are situated between 1-10% of the machine tool costs. It is therefore required to minimize the costs for an energy monitoring system.

Solutions for energy consumption measurement and monitoring in manufacturing are known but rarely implemented due to several reasons such as lack of awareness, high costs, implementation complexity, unknown indication possibilities and optimization measures definition. Despite the availability of several standards and guidelines towards environmental performance evaluation and optimization as well as punctual energy measurements for production systems, a user-oriented monitoring system to gather the relevant data in an efficient way has not been formulated yet.

6.3 Implementation methodology

The implementation methodology consists out five steps and considerations which are explained in detail below: (1) machine tool selection, (2) component classification, (3) architecture definition and (4) implementation. The monitoring approach consists of developed elements from the previous chapters in order to measure machine tools, perform analysis on the given data, and for the information source selection including internal, external, and simulated data. This section is partly published in the patent PCT/IB2013/001677.

Machine tool selection

Monitoring strategies have to be applied reasonably were systems can be changed, different parameters can be set or the selected system represents a key process in relation to importance and energetic relevance. Therefore, an overview on the production systems within a given production site is recommended. The deployment of the following monitoring strategy is appropriate on production systems with a relevant energy share and process dependency with multiple active components. The relevant energy share and expected potential optimization of up to 30% must therefore cover the implementation costs of this system. Furthermore, machine tools and production systems are reasonable for monitoring activities if they represent a high energy demand, e.g. milling or grinding operations, within the given manufacturing. Thus, the selection of the machine tool for the monitoring application is mostly done based on qualitative information from the manufacturing environment. The selection of the appropriate machine tool for monitoring purposes can be chosen based on quantitative information, e.g. the Environmental Values Stream Map (EVSM), as proposed by Sproedt and Plehn [288] and shown in Figure 6.2. The EVSM is an adaption of value stream mapping and a well-known method from lean production. Its aim is to represent all activities in production, e.g. production processes, transportation, and storage, and in all relevant data, e.g. cycle times, setup times, scrap rates and lot sizes, to measure the corresponding economic performance. In contrast to traditional value stream mapping, EVSM represents environmentally relevant input and output flows such as energy materials, water, waste and emissions. The selection based on the EVSM can be done by a pre-measurement on the aggregated machine tool level as shown in Figure 6.3 by the multichannel measurement system. After the machine tool or production system is chosen the components must be classified (1), the individual architecture can be defined (2) and the system can be implemented (3).

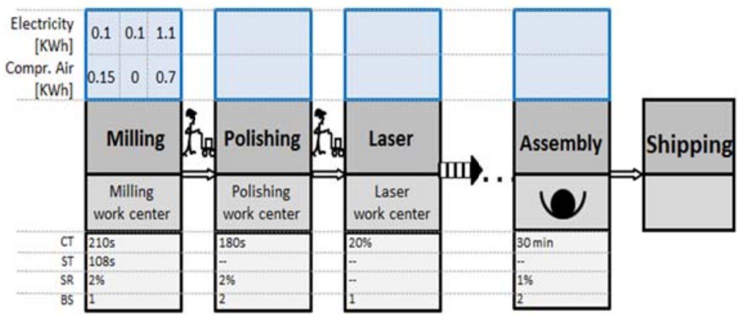


Figure 6.2: Example of an EVSM based on an example manufacturing infrastructure.

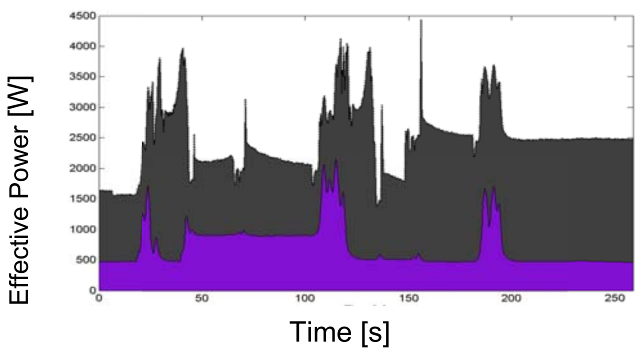


Figure 6.3: Premeasurement of milling process based on aggregated measurement points.

1. Component classification

For the machine tool component classification in constant, controlled-constant and variable energetic behavior, each component need to be measured in its possible energetic states and evaluated based on the occurrence frequency evaluation as shown in sub-section 5.4.2. The evaluation of the energetic behavior of the machine tool components is required for the definition of the monitoring system architecture. Based on the multichannel measurement on revealed energetic machine tool component behavior, the components are assigned to the specific data source within the monitoring architecture.

The relevance of energy consumers is dependent on the individual machine tool configuration and use. For this reason the monitoring architecture is individual but based on a structured modular system approach. One of the main problems encountered by commercially available effective power sensors and power analyzers besides the accuracy and resolution is the amount of available measurement points. A five axis milling machine tool requires 12 to 15 measurement points (see Figure 5.8) for the measurement of all relevant machine tool components. This leads to a high implementation errors and high costs. The monitoring architecture is individually defined, based on the given machine tool system configuration and related energetic behavior of the machine tool components.

In line with the commonly accepted energy evaluation by Dahmus and Gutowski [112]; idle, run-time, and production mode, the given approach classifies the energetic behavior of machine tool components in three different consumption behavior modes as described in the analysis chapter 5, Figure 5.5.

Constant: Constant machine tool components in discrete part manufacturing are represented by a process independent stationary energetic behavior and are mostly used to maintain a certain machine tool state, e.g. thermal stability. Those components are either *on* or *off* and show a fixed power level within the measurement accuracy of $\pm 5\%$. In the given methodology, constant components are classified by their time on level calculation and A_O value according to Gontarz et al. [24]. A_O is a weighting factor which indicates the mode of operation of the component as shown in chapter 5.2. $A_o \geq 0.9$ indicates a stationary energetic behavior..

Controlled-constant: Controlled-constant components, e.g. pumps or chip conveyor are represented by a periodic switch on and switch off mode which is controlled by the PLC or external devices. In most cases the PLC status indicates the current *ON/OFF* status of this component. The energetic behavior during operation mode can be separated into three phases that have to be either measured or simulated. Those phases imply the startup and switch-off peak which need to be recorded with a minimum resolution of $5\ Hz$, to ensure the evaluation of the peak amplitude and length and the constant phase as defined above. Components in this category are represented by $A_O[-] = 0.5$.

Variable: Variable components, e.g. spindle or axis, are represented by a process dependent and heterogeneous energetic behavior. In monitoring applications those components need to be measured with a minimum resolution of $5\ Hz$ or are required to be simulated with a precise model. This can either be done by the evaluation of given forces at the TCP or parameter readout to achieve an accuracy of at least $\pm 5\%$. The behavior of these components is characterized by the weighting factor $A_O \leq 0.5$.

Other energy flows, such as compressed air, are classified according to the component characterization as introduced above. The presented monitoring approach includes the measurement or simulation of media flows and calculates the measured values into electrical equivalent, e.g. standard cubic meter per hour (m^3/h (ANR)) into kilowatt (kW). This can be done by either using a general benchmark factor, e.g. 0.13 kWh/m^3 for compressed air according to [289] or individually measured with the following equation (6.1) as shown in [228].

$$C_{cair} = \frac{\sum_J W_{el,j} + \sum_i C_{th,i}\left(Q_{th,i}\right)}{V_n} \tag{6.1}$$

This equation reveals the individual transformation factor C_{cair} and combines the electrical energy used by the components $W_{el,j}$ with the required energy for additional compressor functions $C_{th,i}(Q_{th,i})$, for example fluid cooling, as a function of the consumed compressed air V_n at normal conditions. Therefore, this approach includes a defined conversion rate into an electrical equivalent from flow (m^3/h (ANR)) to power (kW) in two ways.

2. Architecture definition

The system architecture defines the type of the data source for each component effective power value $P_{eff,n}$. The possible data sources are internal sensors, external sensor or simulations. The monitoring system comprises a hardware and software part. The software part contains the readout of internal sensors and simulations. The step represents the selection of data sources, based on a case wise observation to reach the full improvement potential with a reasonable cost-benefit ratio.

Internal sensors

According to the requirements related to cost saving, accuracy, and reliability all available internal energy-dependent sensors within the machine tool control are used. Open Computer Numerical Controls (open CNCs) facilitate for users the use of various programming languages, operating systems, control strategies, system dynamic models and sensor signal processing. CNCs provide multiple internal sensors necessary for regular operation which can additionally be used to decrease the number of external sensors for energy consumption monitoring. These functionalities are rarely used or in most cases unknown. As external sensors represent a primary cost driver in energy monitoring, their reduction and / or replacement is an integral part to create customer acceptance for energy efficiency monitoring systems. CNCs data from internal sensors and controllers is occasionally used for process tracing, tool failure monitoring, thermal compensation or other process related purposes by dedicated supplementary systems. The required power information is available from the drive controller as part of the drive control loop and internal reference parameter on a system variable. For instance the system variable AA_Power on SIEMENS 840D controls [126] represents the a system variable defining the set value of a specific machine tool axes. Altintas and Erol [290] have used a similar procedure in order to access the motion and machining process control. CNCs without integrated PCs offer specific communication protocols. In case of FANUC for instance Focas2 (FanucOpen CNC API specification version 2) for bidirectional communication of the CNC kernel with an external PC [291] is used. This allows accessing the power consumption information on control-dependent and highly variable machine tool components, such as spindles, axes, or lasers, without using external sensors. Despite of the multitude of available data and controllers on the machine tool controls this information is rarely used in order to achieve a cost-efficient and effective measuring and monitoring of the machine tool or machining process. One reason is the missing standardization of protocols and interfaces, and manufacturer-specific solution for data acquisition opportunities on machine tool controls. The required elements for data acquisition from CNCs are described below.

Data link layer

In the automation technology process field bus is standardized and a commonly used communication protocol within industrial applications. The standard is not openly published and governed by the PROFIBUS and PROFINET international consortium. The protocol is physically build on EIA-485 twisted pair cable. Alternatively Profibus DP can be used with a fiber optics bit transmission layer. Other physical transmission layers are given with Ethernet and TCP sending data on three media; optical fibre, shielded twisted pair and coaxial Ethernet. In industrial equipment, coaxial Ethernet is commonly used. It represents a low cost, compact, and low-noise solution according to Gosbell et al. [292]. For this reason Ethernet is preferred for the physical data transmission layer for internal sensor communication.

The access to available data and available real-time variables, e.g. AA_Power, the system specific solutions as modular software packages are briefly introduced. In relation to the data link layer several options based on a SIEMENS 840D Solutionline control for the data acquisition from the machine tool control are possible as represented in Figure 6.4. Different data read-out options and their required elements are explained.

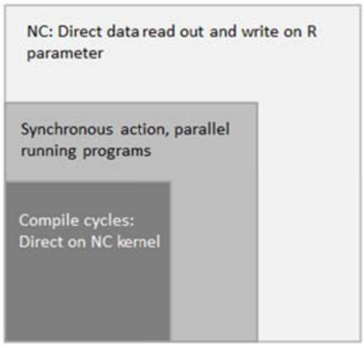


Figure 6.4: Possible ways to access system variable from the machine tool control.

Depending on each possible approach the pros and cons are investigated. Furthermore, a brief overview on current available systems is made.

OPC: OLE for Process Control represents a software interface for the data exchange between various hardware ports Even though OPC is not a Siemens technology, the combination of OPC and SIEMENS NC is assessed. Data transfer methodologies like OPC and data acquisition methodologies, e.g. synchronous actions, have to be distinguished as they represent different data transfer applications.

> **PRO:** Easy configuration, no intervention into the machine tool system, values can be read out directly.
>
> **CONTRA:** No real time functionality, data must be summarized with the help of synchronous actions or compile cycles. Furthermore a COM interface and an IP network are needed.

DDE: Dynamic Data Exchange is considered as a possible way to withdraw machine data from the Siemens control based on the Microsoft Windows operating system on the machine tool HMI.

> **PRO:** Similar scope as OPC but easier to access, as code can be directly written in Excel sheets.
>
> **CONTRA:** Old standard, not supported by windows vista +, some limited functionalities as OPC.

Synchronous actions: Despite that this function is also available in a similar form on other systems, it can be considered as a Siemens technology and can be used mainly for manipulating machine tool data.

> **PRO:** Real time, easy to implement and to develop. Synchronous actions are applicable on the Siemens control types Powerline and Solutionline and represent therefore a universal data read-out option..
>
> **CONTRA:** Must be activated before every machining operation as a separate NC program. Static synchronous actions require a license from Siemens.

Compile Cycles (CC): This function represents a core Siemens technology. This function is designed to withdraw, manipulate, or alter machine tool data.

> **PRO:** Control is fully accessible, all features of the control are available. All data is accessible including NC, PLC, and system variables. Furthermore, external sensors can be read and written if those are connected to PLC or through Profibus.
>
> **CONTRA:** As all features are accessible fatal error are possible, e.g. machine damage, axis movement, and security features. CC are considered as very complex and are generally used for machine tool adaptive control or thermal compensation. A development environment is required and has to be done under the supervision of Siemens if they are commercially used. Licensing from Siemens is required. The CC-functions are not available on export versions of SIEMENS machine tool controls.

Direct Read Out: This function is also available on other controls. Herewith it is assessed based on the SIEMENS technology.

> **PRO:** Easy to implement but with limited possibilities which is considered as a secure approach for data acquisition.
>
> **CONTRA:** Limited possibilities, such as missing real time functionalities. The readout code must be written in the NC program. The available data is limited, no PLC readout.

Based on possible ways to access data and information of the machine tool control different machine tool control providers are investigated and compared.

Siemens

Siemens CNCs give users a wide variety to access information on the NC control. The highest flexibility in the data availability and processing is achieved through a system level implementation by Compile Cycles (CC) and direct access to the Profibus as described above. This is required as the access to the NC through Compile Cycles can lead to a serious damage of the CNC system and related machine tool components. An alternative is given through synchronous actions to prepare data for the transmission over the network protocols. Real-time variables representing the set value of a component state, e.g. AA_Power for the set value of the axis power, can be read, aggregated and stored in so-called R-parameters. Those parameters have defined readout gateways for the external data readout. This requires an access to the PLC program of the machine tool. Direct reading of parameters is provided through an OPC and DDE Server to access R-parameters, as well as machine, channel and drive data. OPC DA (data access) is being currently defined in IEC62541 [293] and represents a potential standardized data access approach.

For the developed monitoring system an OPC connection over PROFIBUS was chosen. This facilitates the data access, reduces the overall system complexity, ease the integration process with the PROFIBUS configuration. The data, e.g. power consumption of the axes, is provided in IPO cycle frequency which is set to $250\ Hz$. For the synchronization procedure and for a comparable sampling rate to the used external sensors the control data was averaged over 50 IPO cycles within a synchronous action and further stored in a defined R parameter. These R parameters where read periodically at $5Hz$ over OPC and stored in a database as raw data from the axis and main drives. Figure 6.5 shows the comparison of the power measurement of the CNC system including the kernel, amplifier and drives, and the sum of the effective power of all axes from the set value parameters. Whereas the sum of all axes is measured by an external power meter and represents therefore the external measurement data.

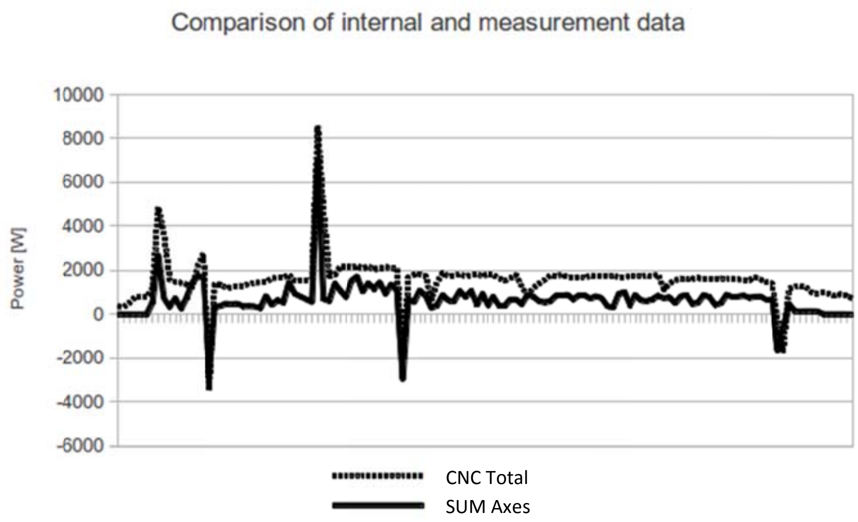


Figure 6.5: Comparison of measured CNC system power with the power sum of all axis X,Y,Z, B and the spindle in a 5-axis-milling operation.

For the validation measurement, the power sum of the internal data through set values, was compared to the power supply measurement values of the entire CNC. The CNC was measured with an external measurement sensor. It is expected that the sum of the effective power of each component $P_{n,int}$ together with the power loss of the CNC P_{loss}, which is given from the CNC data sheet equals the CNC supply P_{CNC} as indicated by the external sensor:

$$\sum_{i}^{n} P_{n,int} + P_{loss} \approx P_{cnc} \tag{6.2}$$

The measurement has an offset of roughly 800W, which is attributed to the base consumption of the CNC and not the drives. Additionally, the CNC system including the amplifier recovers and stores at short term energy from the drives internally. Therefore, the CNC's total power is less fluctuating than the sum of the drives' power.

The above mentioned data access is based on Siemens controls only. The data access path for common machine tool controls of other manufactures is introduced below in brief.

Fanuc

For Fanuc controls the consumption data is available through diagnosis data and can be read directly from the CNC kernel or the Programmable Motion Control (PMC) through the FOCAS2 library. Both machine and drive data can be read. For the newer generations of the CNC, such as 30i, 31i, 32i version 15 or later, the axes power consumption can be read directly through the *SV_meter* variable. As an alternative, the power consumption of servo axes can be read through the diagnosis variable 4901 or 4902 for spindle axes respectively. Older versions such as 16i, 18i or 21i need to calculate the power consumption of each axis $P_{eff,n}$ from the axis load c and the axis' nominal power $P_{nom,n}$:

$$P_{eff,n} = c \cdot P_{nom,n} \tag{6.3}$$

Direct access through Ethernet connection is available and allows for network based diagnostics.

Heidenhain

The software interface Heidenhain Direct Numeric Control (DNC) provides a multitude of possibilities to access data from the TNC based on the proprietary LSV2 protocol. The DNC provides Microsoft common object model components. It is based on Ethernet TCP/IP communication and provides direct access to PLC input, output and memory.

Fidia

Fidia controls do not provide absolute power values of the machine tool components. Similar to the Fanuc approach the power consumption of each axis is calculated on the given load and relation to the nominal power $P_{nom,n}$:. This information is available through servodrive parameters which can be accessed directly through the Common Object Request Broker Architecture (CORBA) protocol over Ethernet.

External sensors

External sensors are required for variable machine tool components ($A_O[-] < 0.5$) and where simulation results fail to reach the required output data accuracy of $\pm 5\%$ and when no internal sensor covers the information needed. External sensors are further needed for internal calibration and verification in combination with the PLC controlled simulation and internal sensors. In the given monitoring strategy external sensors guarantee the accuracy of the entire system by plausibility checks in relation of the measurement value at the main supply $P_{eff,tot}$ and the sum of all internal measurement points $P_{eff,n}$:

$$P_{eff,tot} \geq \sum_{i=1}^{n} P_{eff,n} \tag{6.4}$$

This condition is true for all machine tool states, also in case of energy recovery. For this reason at least one external sensor has to be installed on the main power supply of the machine tool. The amount of needed sensors can be further minimized by several machine tool specific preconditions:

Relevance: If the machine tool component represents a share below 10% of the entire machine tool effective power $P_{eff,tot}$ in all possible machine tool modes, the measurement point is not relevant for further monitoring purposes. The relevance threshold is defined in ISO 14955 [4].

Dependency: In some cases it is possible to reduce required measurement points if same or similar energetic behavior is given by a component which is already measured. For instance the cooling compressor of a cabinet cooling can consist of two connected devices in master and slave configuration. Therefore the master signal can be copied and no additional measurements of slave components are required.

Energetic behavior: Depending on the energetic behavior as indicated above, an external sensor might not be not needed and can be replaced by suitable simulations. This can either be done with the sensor analysis according to its energetic behavior or through individual accuracy restrictions.

Energy forms: Depending on the energy form, various sensors can be used. As flow measurements, e.g. compressed air, can be cumbersome and costly, alternative indirect measurement points can be chosen. The fluid flow of a pump, for instance, can be measured through the combination of the pump power supply and the individual efficiency map provided by the component data sheet. This leads to the application of an effective power sensor instead of a fluid measurement sensor and results in cost reduction. In the case of the use of indirect measurement it is required to calibrate the sensor for the assurance of the measurement accuracy.

When the measurement points based on the above mentioned reduction and selection options are done, suitable sensors can be chosen. Table 6.1 shows tested external sensor for the applied energy and resource monitoring system architecture.

Table 6.1: Possible application of sensors.

Sensor type	Energy form	Communication
Christ CLT 310	Electric	RS232 / analog
Accuvim II	Electric	RS485/Modbus
Sentron PAC4200	Electric	Modbus / Profibus
Postberg&Co BS	Air flow	RS232 / analog
VP FlowMate	Air flow	RS485 / Modbus
EndressHauser	Fluids	RS485 / Modbus

Simulation

As shown in chapter 4, two possible ways for the adaptation of simulations for monitoring purposes are introduced. In the following the *Teach-in* approach is chosen. The simulation s applied on machine tool components with a constant or controlled-constant energetic behavior. For those components a virtual measurement channel, as a PLC-controlled I/O model can be defined. In order to achieve the highest accuracy in the power and energy monitoring, the energetic machine tool components behavior can be distinguished in three different component states; startup phase, constant phase, and switch off phase, leading to the exact energetic behavior and power level. The model inputs are received by the PLC status through a DDE gateway or PLC listener and indicate the machine component state, such as on, off or standby. This component model is based on recorded component power measurement and reveals the detailed energetic behavior of the machine component without the use of any external sensor. To ensure the accuracy of the monitoring system and for the internal calibration, the sum of all simulated components $\sum P_{sim,n}$ and all additional power measurements $\sum P_{eff,n}$ is compared continuously with the external sensor data at the overall machine tool supply $P_{eff,tot}$ (equation (6.5)). In the case of a deviation of $\pm 10\%$ (equation 6.6) the virtual measurement channel must be recalibrated. This can be the case when the energetic behavior of the simulated component changed, e.g. component breakdown or component change.

$$\sum_{I=1}^{n} P_{sim,n} + \sum_{i=1}^{n} P_{eff,n} \leq P_{eff,tot} \tag{6.5}$$

and

$$0.9 \cdot \Delta P_{test,1} \leq \Delta P_{test,n} \leq 1.1 \cdot \Delta P_{test,1} \tag{6.6}$$

Implementation

For the implementation of the energy and resource monitoring on the selected machine tool system a detailed multichannel measurement is required to evaluate the energetic behavior and interdependencies of all active machine tool components based on individual machining processes and various machine tool states. Based on those measurements the type and quantity of required data sources can be evaluated and the parametrization of the simulation models and virtual channel can be done. The energy and resource monitoring architecture is shown in Figure 6.6.

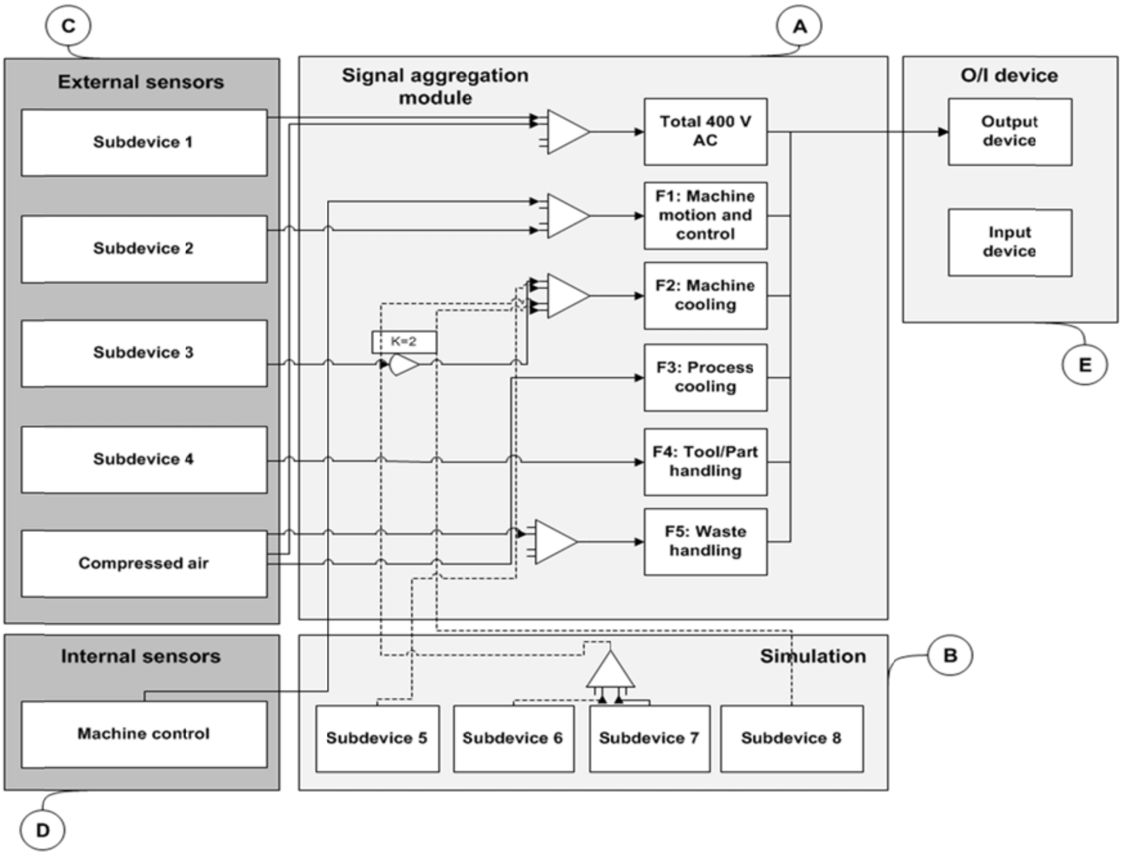


Figure 6.6: Overall architecture of the energy and resource monitoring system (EMon).

A: Module A represents the signal aggregation module. Consumer signals are synchronized to a time equidistant format with a resolution of $5Hz$ with a polynomial interpolation algorithm.

B: Module B represents the simulation block which contains all consumers that can be simulated. This module is part of the signal aggregation module with a communication interface to the PLC.

C: Module C represents external sensors for the effective power measurement, e.g. smart meter and compressed air flow measurement equipment as shown in Table 6.1.

D: Module D represents the machine tool numeric control (NC) and all related energy flows for the function F1, machine motion and control.

E: Module E represents the human machine interface (HMI) for information input and output.

6.4 Conclusion

A combination of internal sensors, external sensors and simulation provides comprehensive information of the monitored manufacturing system in line with the requirements of the ISO 14955 and ISO 50001 standards. Moreover, it represents an integrative element of the environmental EnMS described in DIN EN ISO 14001 and the DIN EN ISO 9001 organization principle. The given system can be used for the continuous machine tool monitoring and the application of micro and macro optimization. The system enables to calculate energy performance indicators (EnPIs) or Key Performance Indicators (KPI) for efficiency improvement. Relevant EnPIs are elaborated by the ISO 22400-2 [16]. EnMSs depend on reliable, robust data for control purposes. In contrast to punctual effective power measurements, energy monitoring comprises the continuous or repetitive measurements of a set of linked data for control, feedback and tracing purposes. The implementation is verified within an industrial case study based on industrial requirements. As this application is in line with the industrial requirement and at the same time aims at indicating measures of energy efficiency optimization, further links towards legislation are possible.

The given monitoring architecture represents a modular approach which is suitable for various machine tool configurations and requested levels of detail. The necessary elements for the application of a monitoring system are given by the multichannel measurement and the selection method for the individual definition of the system architecture. The developed monitoring approach is further compared to the industrial requirements:

- **Accuracy and resolution:** Based on the component behavior the appropriate information source is used. Furthermore, the correctness of the simulated values is monitored by a continuous checksum calculation as indicated in equation (6.4). The simulated values correspond to the measurement values including all transient energetic behaviors. This guarantees an overall accuracy of $\pm 5\%$ which is defined by the multichannel measurement system accuracy. The multichannel measurement as well as monitoring approach, including the modeling elements, provide a data output rate of $5\ Hz$. Based on the internal sensors and for further dynamic analysis, process-related components, e.g. spindle and axes, can be monitored and measured with higher frequencies.
- **Completeness:** All active components with a share of more than 10% within all possible machine tool modes and at least 80% of all system components are either measured by internal or external sensors or simulated. The given approach includes all auxiliary components and enables therefore complete analysis possibilities as indicated in chapter 5.
- **Costs:** The tradeoff between completeness of required data for the analysis features and cost can be solved by the modular monitoring implementation approach. This approach focusses on the reduction of external sensors by maintaining a high level of detail and accuracy. Based on the component classification the appropriate data source, observer or sensor can be chosen. The

accuracy of the developed simulation relies on the available PLC signal and related component behavior. If the component behavior information is available, externals sensors are not needed and models can be used.

The developed multichannel monitoring strategy proofs that detailed and required information on the energetic behavior of machine tools can be revealed and used to indicate optimization potential on the component level and through component control. The approach further shows an universal monitoring system with a reasonable cost to benefit ratio as the amount of external sensors, representing the main cost driver of the system, is reduced. Thus, detailed information on the component level can be aggregated for higher assessment level and various top down evaluation approaches as shown in chapter 2.1.3.

6.5 Case study

In the following implementation the EDM machine CUT 200 of AgieCharmilles was chosen in order to validate the concept and to support the interconnection with the parametrization software by AgieCharmilles. The given machine tool consists of 7 subcomponents which are shown in table 6.7.

Table 6.2: Components of the AgieCharmilles CUT 200 for energy monitoring.

Subcomponent	Description	Source
24 V AC	Supply of all 24V components including PLC	Simulation
Cooling/Deion. pump	Cooling pump of the deionizing fluid, incl. Part cooling	Simulation
Filter / filling pump	Pump for tank filling and deionizing fluid filtering	Simulation
Drives	X, Y, Z Axis incl. motors for EDM wire	FOCAS 2
Flushing pump	Fluid pump for tank flushing and filtering	Accuvim II
Generator	EDM generator, externally controlled device	FOCAS 2

Accordingly to performed pre-measurements (Figure 6.7), the energetic behavior of the given EDM machine is dominated by the generator power and auxiliary pumps. The generator power can be revealed by the machine tool control, whereas the auxiliary pumps represent components with a stationary energetic behavior. Therefore, the monitoring architecture requires only two external sensors. One sensor is required for the flushing pump and one for the value supervision of simulated and measured values.

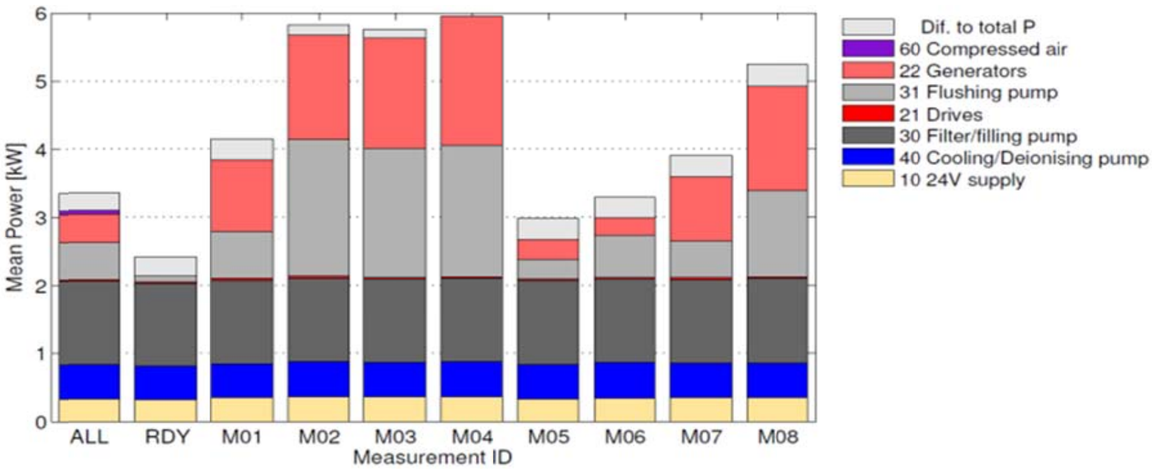


Figure 6.7: Measurement of the AgieCharmilles EDM Cut 200 in all different machine tool modes. ALL = average over all measurement, RDY = Ready, M01 = Machine tool standby, M02 – M04 and M08 = machining processes with different parameterization. M05 = emergency stop, M06 – M07 = machine tool setup.

Figure 6.7 shows the average power consumption of the machine tool components in different machine tool modes. The measurements M01 to M08 represent different machining processes of the CUT 200 with different process parameters such as wire thickness and generator power. Based on this analysis and the A_O value calculation, the variance of the machine tool component can be quantified. This results in a process-independent and predictable energetic behavior of the cooling and deionizing pump, the 24V power supply, and the filter/filling pump. Those components are therefore selected for simulation. The input parameters for those components are given by the individual PLC status from each machine tool mode. Further the measurements show that the drives and the compressed air have minor influence on the power consumption, whereas the generator and the flushing pump are strongly variable and highly process dependent. For this reason the flushing pump must be measured in order to provide a suitable and adequate monitoring functionality. The values of the generator can be read from the machine tool control over the FOCAS2 library. The application of the resource and monitoring approach for this machine tool requires therefore the application of only two external sensors to provide the entire energetic behavior of the machine tool components as shown in the system architecture in Figure 6.8. The second sensor serves for the approval and data supervision of the entire system in order to compare the sum of measured and simulated values with the total energy input. The revealed synchronized machine tool component information can now be further used for any other macro and micro optimization features.

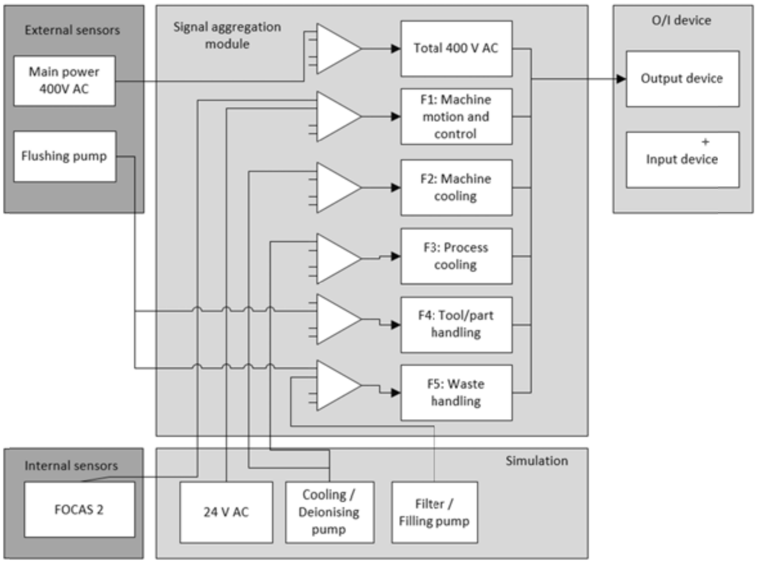


Figure 6.8: Final monitoring system architecture of the AgieCharmilles CUT 200.

The introduced case study with the implementation of a monitoring strategy proofs that detailed and required information and the energetic behavior of this machine tool can be revealed. Furthermore this information can be used with the analysis as shown in chapter 5.4 and further lead to optimization on the component level. The approach further shows a universal monitoring system with a reasonable cost to benefit ratio. Based on the data collection on the component level, the revealed data can be further used on the production, factory or enterprise level, e.g. the calculation of performance indicators.

7 Conclusion and Outlook

In this thesis, the energetic behavior of machine tools and related optimization analysis is characterized based on a multichannel measurement procedure. Power and energy measurements of machine tools during different operational states show that significant inefficiencies are given in manufacturing operations. These inefficiencies represent not only economic or environmental factors, but might have also negative effects on the machining process and manufacturing environment. While the European Union set machine tools under environmental supervision, a comprehensive machine tool evaluation on the component level for industrial use does not exist yet. Results in this thesis clarify that this needs to be changed, and a proposal for a comprehensive machine tool measurement and monitoring procedure for the determination of energetic inefficiencies is given.

Measurements on various machine tools during different machining processes show that inefficiencies of up to 40 % are present. As most of these inefficiencies depend on individual parameters, e.g. configuration or use, rule based optimization measures are not sufficient. While direct process-related machine tool components, e.g. spindles and control, are often adjusted to the required machining operation, main focus must be given on uncontrolled auxiliary components. Therefore, the machining process optimization is neglected in this thesis. As machine tools represent an assemblage of different components with various energy forms and behavior, conventional single-channel measurement systems are not expedient. The developed multichannel measurement system in this thesis covers relevant resources, electrical energy and compressed air that are required to perform a specific machining operation. This system is marvelously suited to identify inefficiencies on the component and subcomponent level. Thereby, it is shown that in addition to the machine tool energy evaluation in ISO 14955 besides the analysis of machine tool functions, control-dependencies and operational modes of subcomponents have to be considered. When comparing the energetic behavior of machine tools during different measurements, differences in the consumption and component controls carried out that the machine tool configuration and individual use strongly influences the type and location of optimization measures. These indications are strongly dependent on the measurement procedure. Therefore, it is fundamental to specify the way measurements have to be carried out when optimization measures have to be identified.

The measurement and monitoring methodology developed in this thesis follow and assist the ISO 14955 and ISO 50001. In addition to measurements procedures for the machine tool retrofit indication, some indications for the machine tool design improvement are given. This indications show that the machine tool development and pre-configuration has a significant or dominant influence on the energetic machine tool consumption behavior and further studies are of essential importance.

In order to improve the efficiency of machine tools and production systems it is necessary to evaluate the actual share of process-independent and constant machine tool subcomponents, and to apply a needs-based control. A lot of approaches to measure and indicate inefficiencies can be found in literature: Besides top down evaluation, e.g. performance indication of the manufacturing processes and machine tools, many different bottom up approaches, represented by measurement, monitoring and modelling approaches on the machine tool and process level, have been developed.

In this thesis, two evaluation approaches are presented that are suitable for industrial use: The multichannel machine tool measurement (1) and the monitoring approach (2). Whereas the measurement approach provides a static and selective analysis tool, based on multichannel sensors, the monitoring approach uses a combination of sensors, internal signals of the numerical control, such as the power supplied to the axis and PLC states, and simulations for the continuous system evaluation and indication of individual energy efficiency optimization measures.

The measurement hardware can be extended modularly and consists of sensors which are suitable for multichannel measurements of electrical power and fluid flow. The elementary components of this system are the time synchronization of the sensor information and the system-independent coverage of the required energy forms and active components within the system boundary. The system is designed in line with industrial requirements, such as costs, completeness, accuracy, and available communication protocols. The idea beyond the approach is to simplify the application of a multichannel measurement and to assure all required information with a minimal implementation effort. This enables the comprehensive measurement of all active machine tool components in order to specify and indicate the individual, technically and economically reasonable, efficiency optimization measures.

The monitoring approach developed in this thesis, combines suitable data sources from sensor hardware, numerical control, and simulations. The information source architecture is based on the individual energetic machine tool component behavior and its selection is defined by a methodological approach. Thereby, the architecture solves the tradeoff between hardware costs and the required accuracy on an industrial monitoring system for the system evaluation. The chosen model approach is based on a teach-in application and applied to replace sensor hardware. The continuous multichannel data acquisition, in combination with developed analysis algorithms, enables realtime optimization capabilities, e.g. adaptive component control. The monitoring system can be applied machine tool independent and can be used, in combination of process monitoring systems, for optimization and prediction of energy consumption and expected costs.

For both approaches, analysis algorithms are developed which are suitable for the evaluation of multichannel data to indicate individual inefficiencies within the machine tool system. Currently this monitoring approach is tested on two prototype systems and will be further developed for the industrial application.

Due to the modularity and applicability on different machine tool systems the development shows the great potential for a successful, industrial transfer and market readiness. With both approaches, a significant increase of energy efficiency of up to 40 % can be reached. More significant is the fact that machine tool and system independent and individual inefficiencies can be addressed.

Measurements and resulting optimization measures revealed that the predefined machine tool configuration has a significant effect on the machine tool efficiency. Technically identified optimization measures might be economically non reasonable or the pre-configuration cannot be changed on a given system. Further optimization potential is seen in the adaption of production system within the production infrastructure, for instance through HVAC management. In order to consider these effects more detailed, the machine tool design, configuration, and infrastructural amendment need to be analyzed. A promising approach to tackle the pre-configuration is to apply suitable energy models of machine tools on the basis of actual machining processes and future machine tool use.

Both evaluation methods presented in this work, represent bottom up approaches for the measurement, monitoring, and analysis of machine tool to increase the efficiency and to predict the machine tool performance. The monitoring system with modular information source architecture, guarantees a cost-effective and detailed monitoring approach. A disadvantage of this approach is the requirement of detailed multichannel measurements on an available machine tool system and the recalibration of the component models after a conventional service and maintenance time to guarantee the accuracy of +/- 5%. For an industrial application on ex-work level this seems to be technically and economically reasonable. The multichannel machine tool measurement duration with the developed system takes four hours on average today, which lead to the founding of SIGMAtools LLC in order to provide this solution as an industrial service. Further investigations need to be done in order to minimize the measurement effort and duration. A promising approach is to define standardized measurement points and voltage tapping. For the monitoring approach predefined machine tool models and control relation can be used in order to minimize the number of external sensors. Up to now and based on more than 50 measurements more than 3 GWh could be saved with this system.

A Appendix

A.1 Overview of standards and technical guidelines

Those standards and guidelines are related to energy efficiency in manufacturing.

Standard / Guideline	Name	Objective	Related life cycle phases	Basis of evaluation	Assessment criterion and cost elements (example)
VDI 2884	Purchase, operating and maintenance of production equipment using Life Cycle Costing (LCC)	Support of machine tool user in equipment selection Assessment framework for the machine tool builder for innovative configurations	Procurement Use / Ownership Recycling	Qualitative Quantitative	Machine tool procurement Auxiliary materials Maintenance costs Performance and quality values Recycling
VDI 2885	Standardized data for maintenance planning and determination of maintenance costs Data and data determination	Precise description of maintenance processes as a basis between OEM and supplier.	Use / Ownership	Qualitative Quantitative	productive capacity, machine capability, availability, etc.
VDI 2891	Maintenance relevant criteria for purchase of machines	Transparency of the relevant maintenance events	Use / Ownership	Qualitative Quantitative	Cost drivers of maintenance, e.g. reliability, effort for maintenance
VDMA 34160	Forecasting model for lifecycle costs of machines and plants	Definition of cost elements and formulas for calculation	Procurement Use / Ownership Recycling	Quantitative	Purchase price, installation, customs, maintenance, repair and services, energy, tools, dissembling, recycling
VDI 2893	Selection and formation of indicators for maintenance	Definition of key indicators for goal-oriented adjustment of maintenance	Use / Ownership	Qualitative Quantitative	Operating figures for the maintenance
VDI 4004 Page 3	Attributes of maintainability	Definition of criteria for the evaluation of the maintainability	Use / Ownership	Qualitative Quantitative	Maintenance operating figures, e.g. MTBF and qualitative evaluation criteria, e.g. accessibility.
VDI 4004 Page 4	Reliability attributes; availability figures	Definition of availability indicators	Use / Ownership	Qualitative Quantitative	Maintenance
VDI 3423	Technical availability of machines and production lines - Terms, definitions, determination of time periods and calculation	Definition of terms, time recording and calculation of the availability	Use / Ownership	Quantitative	Maintenance
DIN 31051	Fundamentals of maintenance	Definition of terms of maintenance	Use / Ownership	Qualitative	Maintenance
DIN EN 60300-3-3	Dependability management - Part 3-3: Application guide - Life cycle costing (IEC 60300-3-3:2004); German version EN 60300-3-3:2004	Description, purpose, approach and elements of LCC analysis	Use / Ownership	Quantitative	Formula and cost elements Investment and costing Example calculation
DIN EN 61703	Mathematical expressions for reliability, availability, maintainability and maintenance support terms (IEC 56/1506/CD:2013)	Mathematical expressions and formulas	Use / Ownership	Quantitative	functioning availability maintainability readiness of maintainability

A.2 Pipe equivalents

Table of equivalent length of straight pipe for various piping forms.

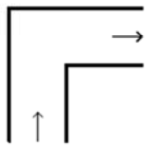
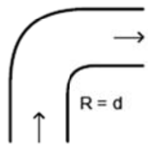
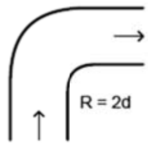
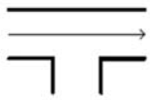
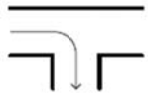
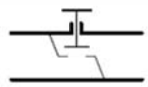
Fitting		Inner pipe diameter [mm] 25	40	50	80	100	200
Angle		1.5	2.4	3.0	4.5	6.0	9.0
Bend		0.4	0.6	0.8	1.3	1.6	2.4
Bend		0.3	0.5	0.6	1.0	1.2	1.8
Tee through-flow		0.3	0.4	1.0	1.6	2.0	3.0
Tee side-flow		1.5	2.4	3.0	4.8	6.0	9.0
Poppet valve		7.5	12	15	24	30	45
Flap check valve		2.0	3.2	4.0	6.4	8.0	12

Figure A.1: Examples of bends and fittings and their equivalent length of straight pipe L+ in m. The losses depend on the inner pipe diameter. These values have to be obtained by the manufacturer [251].

A.3 Overview of power sensors

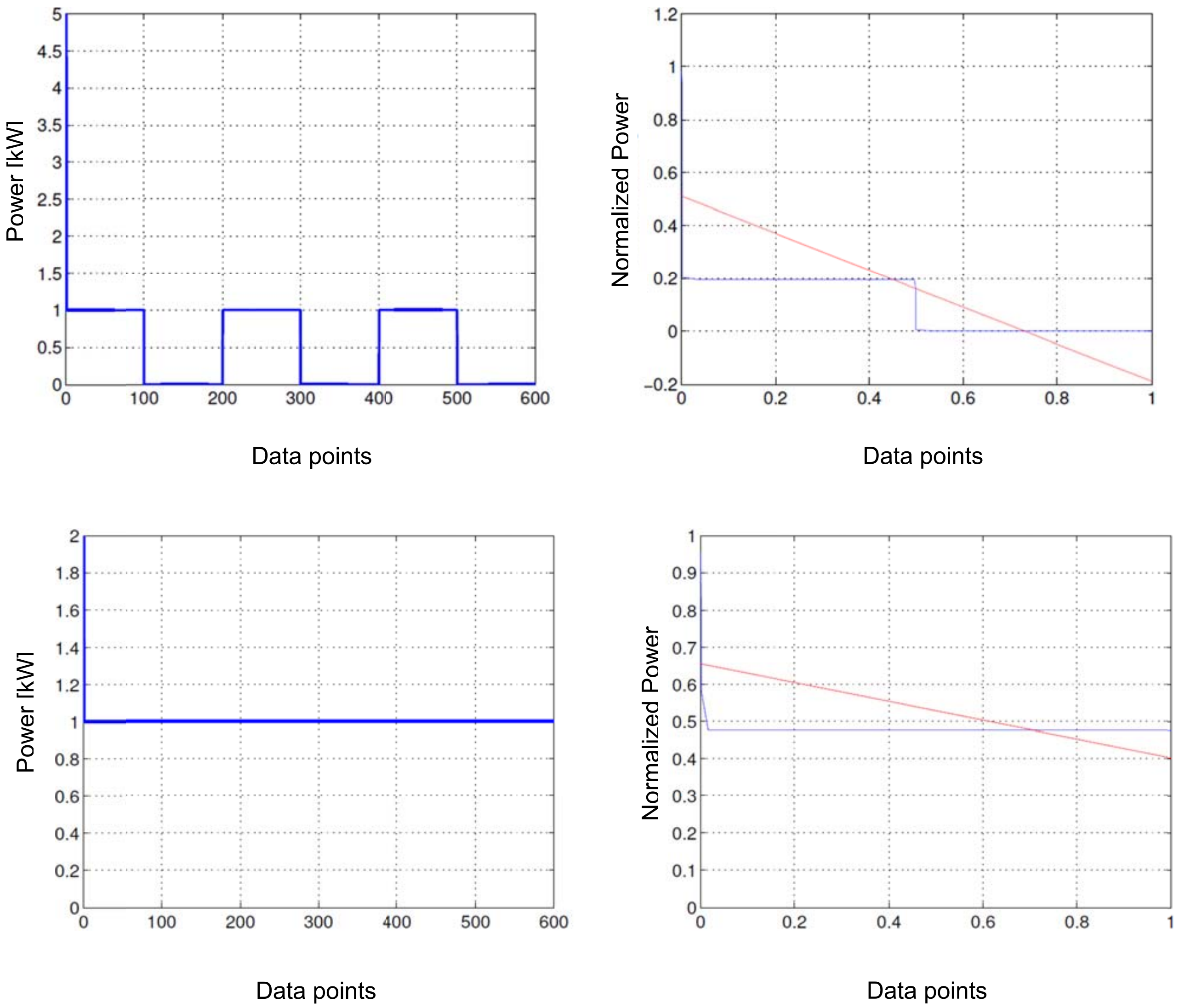
The following sensor were used and analyzed in the given research.

Device	Samping / refreshing rate	Input signals	Output signals	Communication	Dimensions (LxWxH)	Accuracy	Price
Pilot PMAC903	2800 Hz/ 1Hz	230V /400V; 100A / 5A directly	P1, P2, P3, U1, U2, U3, Peff, E, cos phi, additionally more than 50 other parameters	RS485, MODBUS RTU is supported	125,5 x 102 x 65mm	U, I: ≤ ± 0,2 %	~CHF 60
Acuvim II	4000Hz/ 5Hz - 20Hz	230V /400V; 100A / 5A directly	P1, P2, P3, U1, U2, U3, Peff, E, cos phi, additionally more than 60 other parameters	RS485, MODBUS RTU is supported, Profibus (optional)	96 x 96 x 56mm	U, I: ≤ ± 0,2 %	~CHF 150
CLT 310	4000 Hz/ 5Hz	230V /400V; 16A directly	P1, P2, P3, U1, U2, U3, Peff, E, cos phi, additionally more than 60 other parameters	RS232 / RS422 and RS485 (optional)	100 x 110 x 75mm	U, I: ≤ ± 1,0 % ≤ ± 1,5 % on Display	~CHF 250
Siemens Sentron PAC 3200	4000Hz / 17 Hz	230V /690V; 16A directly	P1, P2, P3, U1, U2, U3, Peff, E, cos phi, additionally more than 80 other parameters	Profibus DP / Ethernet	96 x 96 x 51mm	U, I: ≤ ± 0,5 %	~CHF 400

A.4 Example Raw data of the multichannel measurement

```
# =========================================
# ===          ENERGY MEASUREMENT        ===
# =========================================
#
# Measurement Information
# -----------------------
# Company        : Company XY
# Location       : Zurich
# Machine        : MT 001 Test
# Part           : Reference part 1
# Operation Mode : PR
# Config Number  : K1
# Measurement Nr : M08
# Date           : 18.06.2015
# Additional comments :
#
#
# Config of Acuvim
# ---------------
# CLT Number : 1
# Name : Acuvim1
# Serial Port : COM1
# Enabled : True
# ifac : 1
#
# Time (UTC)    P1       P2       P3       P        Q1       Q2       Q3       Q
11:08:09.822    114.032104492188          118.768272399902          92.3390731811523
11:08:10.446    117.850059509277          115.671981811523          88.6537780761719
11:08:10.992    112.957313537598          115.443321228027          92.5202789306641
11:08:11.647    109.086410522461          115.677345275879          94.2711486816406
11:08:12.302    115.619934082031          115.755821228027          103.112442016602
11:08:13.098    118.744651794434          118.519203186035          95.1803131103516
11:08:13.722    110.304054260254          114.956932067871          94.1895599365234
11:08:14.330    108.790237426758          120.274719238281          96.5549087524414
11:08:14.923    104.351806640625          117.229507446289          90.0664825439453
11:08:15.578    116.308471679688          113.709274291992          96.3041458129883
11:08:16.171    113.301635742188          117.921058654785          93.8482055664063
11:08:16.810    113.654197692871          120.336036682129          86.6339874267578
11:08:17.388    112.995315551758          119.499588012695          92.1647796630859
11:08:17.996    114.178466796875          116.211181640625          89.5544052124023
11:08:18.589    114.165733337402          115.011619567871          92.8965301513672
```

A.5 Gini Measurement point classification



Bibliography

[1] Züst, R., Weiss, L., Gontarz, A.Hauenstein, J., *Eco-effiziente Produktionsmaschinen in moderner Haustechnik bei METTLER TOLEDO - Hohe Energieeffizienz durch Optimierung des Gesamtsystems*, 2013. p. 2-3.

[2] Brinksmeier, E., Eckebrecht, J.Buhr, H., *Improving ecological aspects of the grinding process by effective waste management.* Journal of Materials Processing Technology, 1994. **44**(3–4): p. 171-178.

[3] Agency, I. E. Tracking Industrial, Energy Efficiency and CO2 Emissions, 2007.

[4] Bundesamt für Energie, B., *Ex-Post-Analyse des schweizerischen Energieverbrauchs 2000 bis 2011 nach Bestimmungsfaktoren* 2012, Bundesamt für Energie BFE.

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

[6] Paolino, M., Buchenel, B.Boesch, R., *Messung der Strompreisentwicklung in der Schweiz - Technik, Berechnung und Verlauf*, 2008, Bundesamt für Statistik BFS.

[7] Bundesamt für Energie, B., *Schweizerische Gesamtenergiestatistik 2011*, 2011, BFE.

[8] Klocke, F., Lung, D., Schlosser, R., Gerschwiler, K., Werner, A., Jahns, P., Lingg, G.Zeller, R., *Ressourcenschonende Produktion*, ed. A. Verlag2008, Aachen.

[9] Agency, I. E., *Towards a more energy efficient future*, 2009, OECD/IEA p. 15.

[10] Commission, E., *Action Plan for Energy Efficiency: Realising the Potential.* 2006.

[11] Zentralverband Elektrotechnik- und Elektronikindustrie e.V., Z., *Energieeffizienz rechnet sich*, 2013, Fachverband Automation Fachbereich Messtechnik und Prozessautomatisierung.

[12] Administration, E.-U. E. I. *World industrial sector and all other delivered end-use energy consumption, 2005-2040*. 2015; Available from: http://www.eia.gov/.

[13] Schleich, J.Gruber, E., *Beyond case studies: Barriers to energy efficiency in commerce and the services sector.* Energy Economics, 2008. **30**(2): p. 449-464.

[14] Schischke, K., Hohwieler, E., Feitscher, R., König, J., Kreuschner, S., Wilpert, P.Nissen, N., *Machine tools and related machinery: Task 4 report – assessment of base case: Energy-using product group analysis - lot 5* 2012.

[15] Zein, A., *Transition Towards Energy Efficient Machine Tools*2012: Springer.

[16] Kuhrke, B., *Methode zur Energie- und Medienbedarfsbewertung spanender Werkzeugmaschinen*. Schritreihe des PTW: "Innovation Fertigungstechnik"2011, Darmstadt, Germany

[17] Denkena, B., *LoeWe - Lebenszyklusorientierte Werkzeugmaschine Abschlussbericht* 2008, Garbsen: PZH Produktionstechnisches Zentrum GmbH. 95 S.

[18] Abele, E., Dervisopoulos, M.Kuhrke, B., *Bedeutung und Anwendung von Lebenszyklusanalysen bei Werkzeugmaschinen*, in *Lebenszykluskosten optimieren*2009, Springer. p. 51-80.

[19] Meadows, D. H., Meadows, D. L.Randers, J. r., *Beyond the limits global collapse or a sustainable future*1992, London: Earthscan Publications. XIX, 300 S.

[20] Pirlogea, C.Cicea, C., *Econometric perspective of the energy consumption and economic growth relation in European Union.* Renewable and Sustainable Energy Reviews, 2012. **16**(8): p. 5718-5726.

[21] Berndt, E. R., *Energy price increases and the productivity slowdown in United States manufacturing*, in *Federal Reserve Bank of Boston Conference Series*1980: Federal Reserve Bank, Boston, MA.

[22] European Commission, E., *Communication from the commission to the European Parliament, the Council, the European economic and social Commitee and the Commitee of the Regions. Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage* 2010.

[23] European Commission, E., *Directive 2009/125/EC of the European Parliament and the council of 21st October 2009, establishing a framework for the setting of ecodesign requirements for energy-related products. .* 2009.

[24] Industries, C.-E. A. o. t. M. T., *Self-Regulation Measure for Metalworking Machine Tools - Methodology Draft 4*, 2014.
[25] CECIMO, E. A. o. t. M. T. I., *Concept Description for CECIMO's SelfRegulatory Initiative (SRI) for the Sector Specific Implementation of the Directive 2005/32/EC*, 2009.
[26] Materials, I. A.-I. S. O. A. S. f. T. a., *ISO 14001 - Environmental management systems - Requirements with guidance for use*, 2004.
[27] *ISO 50001 – Energy Management Standard*, 2011, ISO-International Organization for Standardization.
[28] Muller, E., Buschmann, M.Wonneberger, K. U. *Cost-effective planning of energy-measurement-systems*. in *Industrial Engineering and Engineering Management (IEEM), 2011 IEEE International Conference on*. 2011.
[29] *ISO14955 Environmental Evaluation of Machine Tools*, 2012, ISO-International Organization for Standardization - ISO/TC 39/WG 12
[30] Development, U. W. C. o. E. a., *Our Common Future*1987: Oxford Press.
[31] Ferstel, O. K.Sinz, E. J., *Software-Konzepte der Wirtschaftsinformatik*1984, Berlin New York. IX, 286 S.
[32] Teichert, V., *Indikatoren zur Lokalen Agenda 21: ein Modellprojekt in sechzehn Kommunen*. Vol. 1. 2002: Leske + Budrich.
[33] Fritz, P., Huber, J., Levi, H. W.Busch-Lèuty, C., *Nachhaltigkeit in naturwissenschaftlicher und sozialwissenschaftlicher Perspektive eine Publikation der Karl Heinz Beckurts-Stiftung*. Edition Universitas1995, Stuttgart: Hirzel. 137 S.
[34] United NationsAgenda 21: Programme of Action for Sustainable Development, *Agenda 21: programme of action for sustainable development the final text of agreements negotiated by governments at the United Nations Conference on Environment and Development (UNCED), 3-14 June 1992, Rio de Janeiro, Brazil*1993, New York: United Nations. 294 S.
[35] Elkington, J., *Cannibals with forks the triple bottom line of 21st century business*1999, Oxford: Capstone. 410 S.
[36] Jayal, A. D., Badurdeen, F., Dillon Jr, O. W.Jawahir, I. S., *Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels.* CIRP Journal of Manufacturing Science and Technology, 2010. **2**(3): p. 144-152.
[37] Duflou, J., Sutherland, J., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M.Kellens, K., *Towards energy and resource efficient manufacturing: A processes and systems approach.* CIRP Annals - Manufacturing Technology, 2012. **61**(2): p. 587-609.
[38] *ISO 9000 - Quality management*, 2008, ISO-International Organization for Standardization.
[39] Pehnt, M., *Energieeffizienz ein Lehr- und Handbuch*2010, Heidelberg: Springer. 356 S.
[40] Newman, S. T., Nassehi, A., Imani-Asrai, R.Dhokia, V., *Energy efficient process planning for CNC machining.* CIRP Journal of Manufacturing Science and Technology, 2012. **5**(2): p. 127-136.
[41] Ostrom, E., *The drama of the commons*2002, Washington, DC: National Academy Press. 521 S.
[42] Beltratti, A., *Growth with Natural and Environmental Resource*. New Directions in the Economic Theory of the Environment, ed. e. Carlo Carraro and Diminico Siniscalco1997, Cambridge: Cambridge University Press.
[43] Vijayaraghavan, A.Dornfeld, D., *Automated energy monitoring of machine tools.* CIRP Annals - Manufacturing Technology, 2010. **59**(1): p. 21-24.
[44] Neugebauer, R., Wabner, M., Rentzsch, H., Scheffler, C.Kolesnikov, A., *Development approaches for energy efficient machine tool structures*, in *Towards sustainable manufacturing*, A. R. Astrid Vigtil, and Bjørn Moseng, editors, Editor 2010, IMS and Tapir Academic Press: ETH Zurich, Switzerland.
[45] Brecher, C., Triebs, J., Heyers, C., Jasper, D. , *Effizienzsteigerung von Werkzeugmaschinen durch Optiierung der Technologien zum Komponentenbetrieb - EWOTeK*. Forschung für die Produktion von morgen2012: Brecher, Christian. 121ff.
[46] Zein, A., *Energy Demand of Machine Tools and Performance Management*, in *Transition Towards Energy Efficient Machine Tools*2012, Springer. p. 5-36.
[47] Bellgran, M.Sèafsten, K., *Production development: design and operation of production systems*2010: Springer.
[48] Schieferdecker, B., *Technische Tools im Industriellen Energiemanagement*, in *Energiemanagement-Tools*2006, Springer. p. 7-97.

[49] Duflou, J. R., Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M.Kellens, K., *Towards energy and resource efficient manufacturing: A processes and systems approach.* CIRP Annals - Manufacturing Technology, 2012(0).
[50] Thiede, S., Herrmann, C., Seliger, G., Khraisheh, M. M. K.Jawahir, I. S., *Energy Flow Simulation for Manufacturing Systems Advances in Sustainable Manufacturing*, 2011, Springer Berlin Heidelberg. p. 275-280.
[51] Westkämper, E., AltingArndt, *Life Cycle Management and Assessment: Approaches and Visions Towards Sustainable Manufacturing (keynote paper).* CIRP Annals - Manufacturing Technology, 2000. **49**(2): p. 501-526.
[52] Hauschild, M., Jeswiet, J.Alting, L., *From Life Cycle Assessment to Sustainable Production: Status and Perspectives.* CIRP Annals - Manufacturing Technology, 2005. **54**(2): p. 1-21.
[53] Xirouchakis, O. I. A. a. P., *Evaluating the use phase energy requirements of a machine tool system.* Journal of Cleaner Production, 2011. **19**(6-7): p. 699-711.
[54] Jayal, A. D., Badurdeen, F., Dillon Jr., O. W.Jawahir, I. S., *Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels.* CIRP Journal of Manufacturing Science and Technology, 2010(2(2010)): p. 144-152.
[55] Kaebemick, H., Sun, M.Kara, S., *Simplified Lifecycle Assessment for the Early Design Stages of Industrial Products.* CIRP Annals - Manufacturing Technology, 2003. **52**(1): p. 25-28.
[56] Reap, J., Roman, F., Duncan, S.Bras, B., *A survey of unresolved problems in life cycle assessment.* The International Journal of Life Cycle Assessment, 2008. **13**(5): p. 374-388.
[57] Hendrickson, C., Horvath, A., Joshi, S.Lave, L., *Peer Reviewed: Economic Input–Output Models for Environmental Life-Cycle Assessment.* Environmental Science & Technology, 1998. **32**(7): p. 184A-191A.
[58] Gutowski, T., Dahmus, J.Thiriez, A., *Electrical Energy Requirements for Manufacturing Processes*2006.
[59] Thiede, S., Herrmann, C.Kara, S., *State of Research and an innovative Approach for simulating Energy Flows of Manufacturing Systems*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach and C. Herrmann, Editors. 2011, Springer Berlin Heidelberg. p. 335-340.
[60] Kolk, A., *Trends in sustainability reporting by the Fortune Global 250.* Business Strategy and the Environment, 2003. **12**(5): p. 279-291.
[61] Chen, D., Schudeleit, T., Posselt, G.Thiede, S., *A State-of-the-art Review and Evaluation of Tools for Factory Sustainability Assessment.* Procedia CIRP, 2013. **9**(0): p. 85-90.
[62] Bunse, K., Vodicka, M., Schönsleben, P., Brülhart, M.Ernst, F., *Integrating energy efficiency performance in production management – gap analysis between industrial needs and scientific literature.* Journal of Cleaner Production, 2011. **19**(6–7): p. 667-679.
[63] Adams, M. A.Ghaly, A. E., *The foundations of a multi-criteria evaluation methodology for assessing sustainability.* International Journal of Sustainable Development & World Ecology, 2007. **14**(5): p. 437-449.
[64] Erlach, K.Westkämper, E., *Energiewertstrom: Der Weg zur energieeffizienten Fabrik*2009, Stuttgart: Fraunhofer Verlag.
[65] Sproedt, A.Plehn, J., *Environmental Value Stream Map as a Communicative Model for Discrete-Event Material Flow Simulation*, in *In press - International Annual EurOMA Conference*2012: Amsterdam.
[66] Sarkis, J., *A strategic decision framework for green supply chain management.* Journal of Cleaner Production, 2003. **11**(4): p. 397-409.
[67] Schönsleben, P., *Integral logistics management: Operations and supply chain management in comprehensive value-added networks*2010: CRC Press.
[68] Hussey, D., Kirsop, P.Meissen, R., *Global Reporting Initiative Guidelines: An Evaluation of Sustainable Development Metrics for Industry.* Environmental Quality Management, 2001. **11**(1): p. 1-20.
[69] Aiginger, K., *Speed of change and growth of manufacturing.* M. Peneder et al., Structural Change and Economic Growth, WIFO, Vienna, 2001: p. Section 4, pages 14--17.
[70] *ISO 14040:2006* in *Environmental management -- Life cycle assessment -- Principles and framework*2006, ISO-International Organization for Standardization.
[71] *ISO 14040:2006b Environmental Management – Life Cycle Assessment – Principles and Framework*, 2006, ISO-International Organization for Standardization: Geneva.

[72] Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K.Klüppel, H.-J., *The new international standards for life cycle assessment: ISO 14040 and ISO 14044.* The International Journal of Life Cycle Assessment, 2006. **11**(2): p. 80-85.
[73] *ISO 14031:2013*, in *Environmental management -- Environmental performance evaluation -- Guidelines*2013, ISO-International Organization for Standardization.
[74] Schulz, H. E. S., *Prozessführung und Energiebedarf bei spanenden Fertigungsverfahren*, in *Zeitschrift für wirtschaftlichen Fabrikbetrieb*1998.
[75] Kuhrke, B., Schrems, S., Eisele, C.Abele, E. *Methodology to access the energy consumption of cutting machine tools*. in *Conference Proceedings LCE*. 2010.
[76] Nelles, J., Wurm, A.Augenstein, E., *Effiziente Werkzeugmaschine–Mehr Effizienz und weniger Abwärme in der Maschinenhalle.* KKA Kälte Klima Aktuell, Sonderausgabe Großkältetechnik, 2011.
[77] Newman S.T., N. A., Imani-Asrai R., Dhokia V., *Energy efficient process planning for CNC machining.* CIRP Journal of manufacturing Science and Technology, 2012: p. 10.
[78] Dahmus, J.Gutowski, T. *An environmental analysis of machining*. in *ASME International Mechanical Engineering Congress and RD&D Exposition, Anaheim, California, USA*. 2004.
[79] Behrendt, T., Zein, A.Min, S., *Development of an energy consumption monitoring procedure for machine tools.* CIRP Annals - Manufacturing Technology, 2012: p. 4.
[80] Diaz-Elsayed, N., Dornfeld, D.Horvath, A., *A comparative analysis of the environmental impacts of machine tool manufacturing facilities.* Journal of Cleaner Production, 2015. **95**: p. 223-231.
[81] Lv, J. X., Tang, R.-Z.Jia, S., *Methodology for Calculating Energy Consumption of a Machining Process.* Advanced Materials Research, 2012. **472**: p. 2736-2743.
[82] S. Hu, F. L., Y. He, T. Hu, *An on-line approach for energy efficiency monitoring of machine tools.* Journal of Cleaner Production, 2012: p. 8.
[83] He Y., L. F., Wu T., Zhong F.-P., Peng B., *Analysis and estimation of energy consumption for nu merical control machining.* Journal of Engineering manufacture, 2011: p. 13.
[84] Steinhilper, R., Freiberger, S., Kübler, F.Böhner, J., *Development of a Procedure for Energy Efficiency Evaluation and Improvement of Production Machinery*, in *Leveraging Technology for a Sustainable World*, D. A. Dornfeld and B. S. Linke, Editors. 2012, Springer Berlin Heidelberg. p. 341-346.
[85] Duflou, J. R., Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M.Kellens, K., *Towards energy and resource efficient manufacturing: A processes and systems approach.* CIRP Annals - Manufacturing Technology, 2012. **61**(2): p. 587-609.
[86] Karnouskos, S., Colombo, A.W., Martinez Lastra, J.L., Popescu, C., *Towards the energy efficient future Factory*, in *7th IEEE International Conference on Industrial Informatics*2009: Piscataway, NJ.
[87] Dietmair, A.Verl, A., *Energy Consumption Forecasting And Optimisation For Tool Machines.* MM Science Journal, 2009. **3**: p. 63-67.
[88] Dörr, M., Wahren, S.Bauernhansl, T., *Methodology for Energy Efficiency on Process Level.* Procedia CIRP, 2013. **7**(0): p. 652-657.
[89] Jaffe, A.Stavins, R., *The energy-efficiency gap What does it mean?* Energy Policy, 1994. **22**(10): p. 804-810.
[90] Larek, R., Brinksmeier, E., Meyer, D., Pawletta, T.Hagendorf, O., *A discrete-event simulation approach to predict power consumption in machining processes.* Production Engineering, 2011. **5**(5): p. 575-579.
[91] Koopmans, C.te Velde, D., *Bridging the energy efficiency gap: using bottom-up information in a top-down energy demand model.* Energy Economics, 2001. **23**(1): p. 57-75.
[92] Schleich, J., *Barriers to energy efficiency: A comparison across the German commercial and services sector.* Ecological Economics, 2009. **68**(7): p. 2150-2159.
[93] Brecher, C., Herfs, W., Heyers, C., Klein, W., Triebs, J., Beck, E.Dorn, T., *Ressourceneffizienz vonWerkzeugmaschinen im Fokus der Forschung: Effizienzsteigerung durch Optimierung der Technologien zum Komponentenbetrieb: Werkzeugmaschinen, Produktionstechnik, Forschung*, in *wt Werkstattstechnik online* 2010.
[94] Kellens, K., Dewulf, W., Deprez, W., Yasa, E.Duflou, J. *Environmental analysis of SLM and SLS manufacturing processes*. in *Proceedings of LCE2010 Conference*. 2010.

[95] Wanke, A.Trenz, S., *Energiemanagement für mittelständische Unternehmen: rationeller Energieeinsatz in der Praxis; Arbeitsschritte, Planungshilfen, Lösungsbeispiele*2001: Dt. Wirtschaftsdienst.
[96] Stasinopoulos, P., *Whole system design: an integrated approach to sustainable engineering*2008: Earthscan.
[97] Abele, E., Sielaff, T., Schiffler, A.Rothenbücher, S., *Analyzing energy consumption of machine tool spindle units and identification of potential for improvements of efficiency*, in *Glocalized Solutions for Sustainability in Manufacturing*2011, Springer. p. 280-285.
[98] Lindemann, U., *Haupt-Stromfresser sind die Elektromotoren*, in *Konstruktion, Spezial Antriebstechnik* 2008.
[99] Abele, E., Kuhrke, B., Rothenbücher, S., *Maximierung der Energieeffizienz von Werkzeugmaschinen* in *MM Maschinenmarkt* 2010, Vogel Verlag: Würzburg. p. 26-29.
[100] Kuhrke, B., Rothenbücher, S., Dervisopoulos, M., *Die Energiebilanz muss stimmen*, in *Werkstatt und Betrieb* 2007.
[101] Dietmair, A., Verl, A.Huf, A., *Wie Automatisierung Energie spart. Direkte und indirekte Massnahmen in der Gerätetechnik* in *Energy 2.0* 2009.
[102] Schäfer, R., *Analyse ermöglicht Auswahl des wirtschaftlichsten Antriebs.* , in *MM Maschinenmarkt* 2008. p. 42.
[103] Neugebauer, R., Westkämper, E., Klocke, F., Kuhn, A., Schenk, M., Michaelis, A., Spath, D., Weidner, E, *Energieeffizienz in der Produktion. Untersuchung zum Handlungs- und Forschungsbedarf*2008: Fraunhofer Gesellschaft
[104] Schischke, D.-I. K., *Energy-Using Product Group Analysis*, 2010, Lot.
[105] Hegener, G., *Energieeffizienz beim Betrieb von Werkzeugmaschinen–Einsparpotenziale bei der Auswahl der Fertigungstechnologie.* Heisel, U.; Gadow, R.; Liewald, M, 2010: p. 281-292.
[106] Thiede, S., Posselt, G.Herrmann, C., *SME appropriate concept for continuously improving the energy and resource efficiency in manufacturing companies.* CIRP Journal of Manufacturing Science and Technology, (0).
[107] Schischke, K., Hohwieler, E., Feitscher, R., König, J., Kreuschner, K., Wilpert, P.Nissen, N., *Machine tools and related machinery: Task1 report - definition: Energy-using product group analysis - lot 5*, 2012.
[108] Tönshoff, H. K., *Werkzeugmaschinen: grundlagen*1995: Springer DE.
[109] Weck, M., *Werkzeugmaschinen 4-Automatisierung von Maschinen und Anlagen*. Vol. 4. 2006: Springer DE.
[110] Kellens, K., Dewulf, W., Overcash, M., Hauschild, M.Duflou, J., *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.* The International Journal of Life Cycle Assessment, 2012. **17**(2): p. 242-251.
[111] Herrmann, C., Bogdanski, G.Zein, A. *Industrial smart metering–application of information technology systems to improve energy efficiency in manufacturing*. in *43rd CIRP International Conference on Manufacturing Systems, Wien, pp. na*. 2010.
[112] Dahmus, J., Gutowski, T. *An Environmental Analysis of Machining* in *ASME International Mechanical Engineering Congress and RD&D Expo, IMECE2004*. 2004.
[113] Centre, E., *Ecoinvent database 2012*, 2010.
[114] VDI, *VDI 4602 Blatt 1*, in *Energy management - Terms and definitions*2007, Beuth Verlag GmbH.
[115] ISO, D., *Energy managment systems - Requirements with guidance for use* in *ISO50001:2011)*2011, Beuth Verlag GmbH.
[116] Schischke, K., *Energy-Using Product Group Analysis - Lot 5 Machine tools and related machinery* 2012: Berlin.
[117] Ernst, J., *Daimler Sustainability Report 2012* 2012 Daimler AG.
[118] Damme, G., *Gemeinsame Umwelterklärung 2010/Joint Environmental Statement 2010. Volkswagen and Volkswagen Commercial Vehicles.*, 2011, Volkswagen AG.
[119] Thiede, S., Seow, Y., Andersson, J.Johansson, B., *Environmental aspects in manufacturing system modelling and simulation—State of the art and research perspectives.* CIRP Journal of Manufacturing Science and Technology, 2013. **6**(1): p. 78-87.
[120] Thiede, S., Bogdanski, G.Herrmann, C., *A Systematic Method for Increasing the Energy and Resource Efficiency in Manufacturing Companies.* Procedia CIRP, 2012. **2**(0): p. 28-33.

[121] Szargut, J., Morris, D.Steward, F., *Energy analysis of thermal, chemical, and metallurgical processes.* 1988.
[122] Gutowski, T., Dahmus, J.Thiriez, A. *Electrical energy requirements for manufacturing processes*. in *13th CIRP international conference on life cycle engineering, Leuven, Belgium*. 2006.
[123] Kordonowy, D., *A power assessment of machining tools*, 2002, Massachusetts Institute of Technology.
[124] O'Driscoll, E.O'Donnell, G. E., *Industrial power and energy metering – a state-of-the-art review.* Journal of Cleaner Production, 2013. **41**(0): p. 53-64.
[125] Brecher, C., Triebs, J., Heyers, C.Jasper, D., *Effizienzsteigerung von Werkzeugmaschinen durch Optimierung der Technologien zum Komponentenbetrieb–EWOTeK.* Verbundprojekt im Rahmenkonzept „Forschung für die Produktion von morgen–Ressourceneffizienz in der Produktion “des Bundesministeriums für Bildung und Forschung (BMBF), Aachen: Apprimus, 2012.
[126] Siemens. *DOConWEB*. 2014 11.02.2014]; Available from: http://www.automation.siemens.com/doconweb/.
[127] Byrne, G., Dornfeld, D., Inasaki, I., Ketteler, G., König, W.Teti, R., *Tool Condition Monitoring (TCM) — The Status of Research and Industrial Application.* CIRP Annals - Manufacturing Technology, 1995. **44**(2): p. 541-567.
[128] Weiss, M., *Datenauswertung von Energiemanagmentsystemen*2010: Publicis Publishing, Erlangen.
[129] E.O'Driscoll, D. O. C., G.E. O'Donnell, *Implementation of energy metering systems in complex manufacturing facilities - A case study in a biomedical facility*, in *5th CIRP Conference on High Performance Cutting 2012*2012, Procedia CIRP 1 (2012) p. 541 - 546.
[130] Behrendt, T., Zein, A., Min, S., *Development of an energy consumption monitoring procedure for machine tools.* CIRP Annals - Manufacturing Technology, 2012. **61**: p. 43-46.
[131] Avram, O. I., Xirouchakis, P., *Evaluating the use phase energy requirements of a machine tool system.* Journal of Cleaner Production, 2010. **19**: p. 699-711.
[132] Kuhrke, B., *Methode zur Energie- und Medienbedarfsbewertung spanender Werkzeugmaschinen* PTW "Innovation Fertigungstechnik"2011: Prof. Eberhard Abele.
[133] Avram, O., *Machine tool use phase: modeling and analysis with environmental considerations*, 2010, ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE.
[134] Vijayaraghavana, A., Dornfeld, D., *Automated energy monitoring of machine tools.* CIRP Annals - Manufacturing Technology, 2010. **59**: p. 21-24.
[135] Bornholdt, M., Bründl, A., Deutsch, N.Noll, C., *Branchenmonitor Energieeffizienz 2013*, 2013.
[136] Fluke, *Mit anderen Netz- und Stromversorgungsanalysatoren verschwenden Sie nur Energie.* , 2014.
[137] Arnoux-Chauvin, *The experience of the Qualistar, ensuring high performance*, 2014.
[138] Siemens, *Elektrische Messwerte und Energie zuverlässig und präzise im Blick - Multifunktionsgeräte SENTRON PAC*, 2009.
[139] Bosch-Rexroth, *Energy Analyse Case Datenlogger - Betriebsanleitung*, in *R911341416*2013, Bosch Rexroth
[140] Klingauf, W. *Monitoring, measurement, documentation*. 2013; Available from: http://www.kometgroup.com/index.php?id=830&L=1&pmID=177.
[141] Siemens *Energetische Maschinen- und Anlagenanalyse*. 2013.
[142] Radgen, P., Blaustein, E., *Compressed Air Systems in the European Union, Energy, Emissions, Saving Potentials and Policy Actions*2001, Stuttgart: LOG-X Verlag GmbH.
[143] Curtner, K., O'Neill, P., Winter, D., Plaza, H., Bursch, P.Hanover, M. *Simulation-based Features of the Compressed Air System Description Tool XCEED* in *Proceedings of International BUilding Peiformance Simulation Association Conference*. 1997.
[144] Sweeney, R., *Cutting the cost of compressed air.* Machine design, 2002. **74**(21): p. 76-78.
[145] Klabunde, S., *Hydrostatic Seal for Rotary Machine Tool Spindles* 1972, Google Patents.
[146] Yuan, C., Zhang, T., Rangarajan, A., Dornfeld, D., Ziemba, B.Whitbeck, R., *A decision-based analysis of compressed air usage patterns in automotive manufacturing.* 2006.
[147] Saidur, R., Rahim,N.A., Hasanuzzaman, M., *A review on compressed-air energy use and energy savings.* Renewable and Sustainable Energy Reviews 2009. **14**(2010): p. 1135-1153.

[148] Kellens, K., Dewulf, W.Duflou, J., *Preliminary Environmental Assessment of Electrical Discharge Machining*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach and C. Herrmann, Editors. 2011, Springer Berlin Heidelberg. p. 377-382.
[149] Herrmann, C.Thiede, S., *Process chain simulation to foster energy efficiency in manufacturing.* CIRP Journal of Manufacturing Science and Technology, 2009. **1**(4): p. 221-229.
[150] Radgen, P., *Druckluft Effizient-Messkampagne besatigt Einsparpotenziale der EU-Studie zu Druckluftsystemen*, 2004, Drucklufttechnik.
[151] Salonitis, K.Ball, P., *Energy Efficient Manufacturing from Machine Tools to Manufacturing Systems.* Procedia CIRP, 2013. **7**(0): p. 634-639.
[152] Tönshoff, H. K., Friemuth, T.Becker, J. C., *Process Monitoring in Grinding.* CIRP Annals - Manufacturing Technology, 2002. **51**(2): p. 551-571.
[153] Kim, H. Y., Ahn, J. H., Kim, S. H.Takata, S., *Real-time drill wear estimation based on spindle motor power.* Journal of Materials Processing Technology, 2002. **124**(3): p. 267-273.
[154] Siemens, *ET 200SP - PROFIenergy product information* 2014.
[155] Behrendt, T., Zein, A.Min, S., *Development of an energy consumption monitoring procedure for machine tools.* CIRP Annals - Manufacturing Technology, 2012. **61**(1): p. 43-46.
[156] O'Driscoll, E., Cusack, D.O'Donnell, G., *Implementation of Energy Metering Systems in Complex Manufacturing Facilities–A Case Study in a Biomedical Facility.* Procedia CIRP, 2012. **1**(0): p. 524-529.
[157] Hu, S., Liu, F., He, Y.Hu, T., *An on-line approach for energy efficiency monitoring of machine tools.* Journal of Cleaner Production, 2012. **27**(0): p. 133-140.
[158] Singh, G. K.Ahmed Saleh Al Kazzaz, S. a., *Induction machine drive condition monitoring and diagnostic research—a survey.* Electric Power Systems Research, 2003. **64**(2): p. 145-158.
[159] Timperley, J. E., *Incipient Fault Identification Through Neutral RF Monitoring of Large Rotating Machines.* Power Apparatus and Systems, IEEE Transactions on, 1983. **PAS-102**(3): p. 693-698.
[160] *DMG Mori - CELOS - von der Idee zum fertigen Produkt*. 2015 10.02.2015]; Available from: http://ch-de.dmgmori.com/produkte/celos#CELOS---APPs.
[161] *Harting - HARTING smart Power Networks*. 2015 12.02.2015]; Available from: http://www.harting.com/spn/das-system/.
[162] Brecher, C.Weck, M., *Werkzeugmaschinen, Mechatronische Systeme, Vorschubantriebe, Prozessdiagnose*, 2006, Springer.
[163] Draganescu, F., Gheorghe, M.Doicin, C. V., *Models of machine tool efficiency and specific consumed energy.* Journal of Materials Processing Technology, 2003. **141**(1): p. 9-15.
[164] Augste, J., Holub, M., Knoflíček, R., Novotný, T.Vyroubal, J., *Monitoring of Energy Flows in the Production Machines*, in *Mechatronics 2013*, T. Březina and R. Jabłoński, Editors. 2014, Springer International Publishing. p. 1-7.
[165] Neugebauer, R., Wittstock, V., Meyer, A., Glänzel, J., Pätzold, M.Schumann, M., *VR tools for the development of energy-efficient products.* CIRP Journal of Manufacturing Science and Technology, 2011. **4**(2): p. 208-215.
[166] Neugebauer, R., Wabner, M., Rentzsch, H.Ihlenfeldt, S., *Structure principles of energy efficient machine tools.* CIRP Journal of Manufacturing Science and Technology, 2011. **4**(2): p. 136-147.
[167] Wohlgemuth, V., *Einsatz der Software UMBERTO in angewandter Forschung und Praxis*. Anwendungsfälle und Praxisbeispiele des UMBERTO Competence Centers Berlin (UCC Berlin)2012.
[168] Sproedt, A., Plehn, J.,, *Environmental Value Stream Map as a Communicative Model for Discrete-Event Material Flow Simulation*, in *International Annual EurOMA Conference*2012: Amsterdam, Netherlands.
[169] Linnhoff, B.Hindmarsh, E., *The pinch design method for heat exchanger networks.* Chemical Engineering Science, 1983. **38**(5): p. 745-763.
[170] Gutowski, T., Dahmus, J., Thiriez, A., Branham, M.Jones, A. *A thermodynamic characterization of manufacturing processes*. in *Electronics & the Environment, Proceedings of the 2007 IEEE International Symposium on*. 2007. IEEE.
[171] Li, W., Zein, A., Kara, S.Herrmann, C., *An Investigation into Fixed Energy Consumption of Machine Tools*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach and C. Herrmann, Editors. 2011, Springer Berlin Heidelberg. p. 268-273.

[172] Akbari, J., Oyamada, K.Saito, Y. *LCA of machine tools with regard to their secondary effects on quality of machined parts*. in *Environmentally Conscious Design and Inverse Manufacturing, 2001. Proceedings EcoDesign 2001: Second International Symposium on*. 2001.
[173] Diaz, N., Redelsheimer, E.Dornfeld, D., *Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use*, in *Glocalized Solutions for Sustainability in Manufacturing* 2011, Springer Berlin Heidelberg. p. 263-267.
[174] Franke, S., *Nachhaltiges Produktionsmanagement: Entwicklung eines Produktionsleitstandes*2001: Deutscher Universitäts-Verlag.
[175] Bruns, A., Neumann, M.Constantinescu, C., *Energiedatensimulationssoftware in der Fabrikplanung am Beispiel "Total Energy Efficiency Managment (TEEM)"*. Handbuch - Ressourcenorientierte Produktion, Carl Hanser Verlag München Wien: Neugebauer, R.
[176] Reich-Weiser, C., Vijayaraghavan, A.Dornfeld, D. *Metrics for sustainable manufacturing*. in *ASME 2008 International Manufacturing Science and Engineering Conference collocated with the 3rd JSME/ASME International Conference on Materials and Processing*. 2008. American Society of Mechanical Engineers.
[177] ISO, *ISO 12500-1:2007 - Filters for compressed air -- Test methods -- Part 1: Oil aerosols*, 2007.
[178] *VP Instruments - VPFlowMate User Manual*, 2011.
[179] Kircher, C., Geisler, R.Börsch, W. *Maßnahmen zur Gestaltung energieeffizienter spanender Werkzeugmaschinen*. in *Fertigungstechnisches Kolloquium*. 2010.
[180] Domschke, W.Scholl, A., *Grundlagen der Betriebswirtschaftslehre: eine Einführung aus entscheidungsorientierter Sicht; mit 79 Tabellen*, 2005, Darmstadt Technical University, Department of Business Administration, Economics and Law, Institute for Business Studies (BWL).
[181] Kroll, A., *Grey-box models: Concepts and application*. New Frontiers in Computational Intelligence and its Applications2000, Amsterdam: IOS Press.
[182] Bi, Z. M.Wang, L. H., *Energy Modeling of Machine Tools for Optimization of Machine Setups.* Ieee Transactions on Automation Science and Engineering, 2012. **9**(3): p. 607-613.
[183] Eisele, C., Schrems, S.Abele, E., *Energy-Efficient Machine Tools through Simulation in the Design Process*, in *Glocalized Solutions for Sustainability in Manufacturing* 2011, Springer Berlin Heidelberg. p. 258-262.
[184] Herrmann, C., Zein, A., Winter, M.Thiede, S., *Procedures and tools for metering energy consumption of machine tools.* Zeszyty Naukowe Politechniki Poznańskiej. Budowa Maszyn i Zarządzanie Produkcją, 2011: p. 87-102.
[185] Schultz, A., *Methode zur integrierten ökologischen und ökonomischen Bewertung von Produktionsprozessen und-technologien*, 2002, Otto-von-Guericke-Universität Magdeburg, Universitätsbibliothek.
[186] Herrmann, C., Thiede, S., Zein, A., Ihlenfeldt, S.Blau, P. *Energy efficiency of machine tools: extending the perspective*. in *42nd CIRP Conference on Manufacturing Systems, Grenoble*. 2009.
[187] Shao, G., Kibira, D.Lyons, K. *A virtual machining model for sustainability analysis*. in *ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. 2010. American Society of Mechanical Engineers.
[188] Verl, A., Abele, E., Heisel, U., Dietmair, A., Eberspächer, P., Rahäuser, R., Schrems, S.Braun, S., *Modular Modeling of Energy Consumption for Monitoring and Control*, in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach and C. Herrmann, Editors. 2011, Springer Berlin Heidelberg. p. 341-346.
[189] *Safety requirements for electrical equipment for measurement, control and laboratory use - Part 2-201: Particular requirements for control equipment (IEC 61010-2-201:2013); German version EN 61010-2-201:2013 + AC:2013*, 2014, ISO-International Organization for Standardization.
[190] *ISO 8573-1:2010 - Compressed air -- Part 1: Contaminants and purity classes*, 2010, ISO-International Organization for Standardization.
[191] Götze, U., Helmberg, C., Rünger, G., Schubert, A., Goller, S., Krellner, B., Lau, A.Sygulla, R. *Integrating energy flows in modelling manufacturing processes and process chains of powertrain components*. in *Tagungsband energieeffiziente Produkt-und Prozessinnovationen in der Produktionstechnik, 1. Internationales Kolloquium des Spitzentechnologieclusters eniPROD, Chemnitz*. 2010.
[192] International Electro technical Commission, I., *International Standard IEC 60300-3-3 - Kife Cycle Costing*, in *Dependability Management Part 3-3 Application Guide 2nd Edition*2005.

[193] Santo, A., Calado, M.Cabrita, C., *Dynamic simulation of electromagnetic actuators based on the co-energy map.* Applied Computational Electromagnetics Society Journal, 2010. **25**(12): p. 1118-1128.
[194] Kienzle, O.Victor, H., *Spezifische Schnittkräfte bei der Metallbearbeitung.* Werkstatttechnik und Maschinenbau, 1957. **47**(5): p. 224-225.
[195] Avram, O., Stroud, I.Xirouchakis, P., *A multi-criteria decision method for sustainability assessment of the use phase of machine tool systems.* The International Journal of Advanced Manufacturing Technology, 2011. **53**(5-8): p. 811-828.
[196] Kara, W. L. a. S., *An empirical model for predicting energy consumption of manufacturing processes: a case of turning process.* Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2011. **225:1636**.
[197] Sheng, P., Bennet, D., S., T.von Turkovich, B. F., *Environmentally-Based Systems Planning for Machining.* CIRP Annals – Manufacturing Technology, 1998. **47**(1): p. 409--414.
[198] Narita, H., Kawamura, H., Norihisa, T., Chen, L., Fujimoto, H.Hasebe, T., *Development of prediction system for environmental burden for machine tool operation.* JSME International Journal Series C, 2006. **49**: p. 1188-1195.
[199] Bi, Z.Wang, L., *Energy modeling of machine tools for optimization of machine setups.* Automation Science and Engineering, IEEE Transactions on, 2012. **9**(3): p. 607-613.
[200] Roman, F.Bras, B. *Towards an effective approach to reduce manufacturing environmental burdens via process planning*. in *Proceedings of the ASME International Mechanical Engineering Congress and Exposition, Orlando, FL*. 2005.
[201] Rajemi, M. F., Mativenga, P. T.Aramcharoen, A., *Sustainable machining: selection of optimum turning conditions based on minimum energy considerations.* Journal of Cleaner Production, 2010. **18**(10–11): p. 1059-1065.
[202] Meadows, D., *The limits to growth a report for the Club of Rome's project on the predicament of mankind*. A Potomac Associates book1972, London: Earth Island. 205 S.
[203] Dornfeld, D. A., *Green Manufacturing*2013: Springer.
[204] Kellens, K., *Energy and Resource Efficient Manufacturing - Unit Process analysis and optimisation*, in *Faculty of Engineering Science* 2013, KU Leuven.
[205] Schischke, K., *Energy-Using Product Group Analysis, Lot 5: Machine tools and related machinery, Task 1 Report* in *Sustainable Industrial Policy - Building on the Ecodesign Directive - Energy-using Product Group Analysis 2*2010: Fraunhofer IZM, IPK Berlin.
[206] Fuchs, E.Masoum, M., *Preface*, in *Power Quality in Power Systems and Electrical Machines*, E. F. Fuchs and M. A. S. Masoum, Editors. 2008, Academic Press: Burlington. p. v-vi.
[207] Neubauer, R. E., Reichert, K.Nipkow, J., *Messen von Betriebsparametern elektrischer Antriebe*1996: Bern : Bundesamt für Konjunkturfragen
[208] Frohne, H., Löcherer, K.-H., Müller, H., Harriehausen, T.Schwarzenau, D., *Moeller Grundlagen der Elektrotechnik*. Vol. 22. 2011: Vieweg & Teubner.
[209] Hering, E., Gutekunst, J.Martin, R., *Elektrotechnik für Maschinenbauer : Grundlagen*. Vol. 3. 1999, VDI: Springer Berlin
[210] Lerch, R., *Elektrische Messtechnik*. Analoge, digitale und computergestützte Verfahren2012: Springer Berlin Heidelberg.
[211] Ellis, R.Eng, P., *Power System Harmonics–A Reference Guide to Causes, Effects and Corrective Measures.* An Allen-Brandley Series of Issues and Answers-Rockwell Automation, 2001: p. 3.
[212] Paetzold, J., *Messung elektrischer Energie – Grundlagen und Erfahrungen* 2011, TU Chemnitz, Professur für Werkzeugmaschinen und Umformtechnik
[213] O'Driscoll, E.O'Donnell, G., *Industrial power and energy metering – a state-of-the-art review.* Journal of Cleaner Production, 2013. **41**(0): p. 53-64.
[214] *TDK-Lambda UK Ltd. - Understanding peak power* in *Ref. 12/09 LA8062*2009.
[215] *DEWETRON GmbH - Power Measurement Instruments - DEWE-5000-PM-1000 data sheet* DE-B10040E, Editor 2015.
[216] Gontarz, A., Weiss, L., Wegener, K., *Energy Consumption Measurement with a Multichannel Measurement System on a machine tool*, in *International Conference on Innovative Technologies IN-TECH* Proceedings of the International Conference on Innovative Technologies, Editor 2010: Prague, Czech Republic. p. 499-502.
[217] Gontarz, A., Hänni, F., Weiss, L.Wegener, K., *Machien tool optimization strategies for ecologic and economic efficiency.* Hournal of Engineering Manufacture, 2013. **227**(1): p. 54-61.

[218] *Windows Corp. - About Processes and Threads*. 2014 [05.09.2014]; Available from: http://msdn.microsoft.com/en-us/library/windows/desktop/ms681917%28v=vs.85%29.aspx.
[219] *Christ-Elektronik GmbH - Machine Tool energy measurement and findings* 2005.
[220] *Accuenergy - Acuvim II Series - Intelligent Power Meter*, D. sheet, Editor 2015.
[221] *Zhuhai Pilot Technology Co., Ltd M - PMAC903 datasheet V1.* 2015.
[222] Gauchel, W., *Energy-saving pneumatic systems.* Ölhydraulik und Pneumatik, 2006. **50**: p. 1-22.
[223] Hütter, J., *Effiziente Druckluftproduktion*, in *International Rotating Equipment Conference 2008*2008: Düsseldorf.
[224] Hinsenkamp, G., Reinhardt, J., Hager, M., *Druckluft . Strömungsfreie, kostengünstige und energieeffiziente Bereitstellung* in *Implus-Programm Ravel NRW*2012, Energieagentur NRW: Wuppertal.
[225] *Fraunhofer-Institut für System- und Innovationsforschung (ISI) - Kampagne "Druckluft effizient".* 2013: p. www.druckluft-effizient.de.
[226] Schmidt, C.Kissock, K., *Modeling and simulation of air compressor energy use.* ACEEE Summer Study on Energy in Industry, West Point, NY, July, 2005: p. 19-22.
[227] D'Antonio, M., Epstein, G., Moray, S.Schmidt, C. *Compressed air load reduction approaches and innovations*. in *Proceedings of the twenty-seventh industrial energy technology conference, New Orleans*. 2005.
[228] Züst, S., Gontarz, A.Wegener, K., *Energy Equivalent of Compressed Air Consumption in a Machine Tool Environment*, in *11th Global Conference on Sustainable Manufacturing*, G. Seliger, Editor 2013: Berlin.
[229] Hirano, K., Shida, S., Tominaga, T.Kitaichi, S., *Development Of A High Efficiency Dual Compressor For Air Conditioner.* 2010.
[230] *DIN Fundamental Technical Standards Committee (NATG) - Reference conditions, normal conditions, normal volume; concepts and values*, 1990, Beuth Verlag GmbH: DIN German Institute for Standardization.
[231] Radgen, P., *Efficiency through compressed air energy audits.* , in *Energy Audir Conference*2006. p. www.audit06.fi.
[232] Lang, M., *Potentialanalyse von energetischen Modellierungsansätzen*, in *MAVT - Institute of machine tools and manufacturing (IWF)* 2011, ETH Zürich: Internal document
[233] Altintas, Y., Verl, A., Brecher, C., Uriarte, L.Pritschow, G., *Machine tool feed drives.* Cirp Annals-Manufacturing Technology, 2011. **60**(2): p. 779-796.
[234] Shnayder, V., Hempstead, M., Chen, B., Allen, G.Welsh, M., *Simulating the power consumption of large-scale sensor network applications*, in *Proceedings of the 2nd international conference on Embedded networked sensor systems*2004, ACM: Baltimore, MD, USA. p. 188-200.
[235] Gontarz, A., Züst, S., Weiss, L., Wegener, K., *Energetic machine tool modeling approach for energy consumption prediction*, in *10th Global Conference on Sustainable Manufacturing 2012*2012: Istanbul, Turkey.
[236] Guzzella, L.Sciarretta, A., *Vehicle propulsion systems*. Vol. 1. 2007: Springer.
[237] Vanhooydonck, D.Kalenda, N., *D2.1 Document 7: Literature Survey: Losses in electrical drives*, 2012, estomad - Energy Software Tools for Sustainable Machine Design: EC - 7th Framework Programme
[238] Dürr, A.Wachter, O., *Hydraulik in Werkzeugmaschinen*1968: Hanser.
[239] Siemens, *SINUMERIK 840D - C-PLC-Programmierung*. Hersteller-Dokumentation 1996.
[240] Yuan, C. Y., Zhang, T. , *A Decision-Based Analysis of Compressed Air Usage Patterns in Automotive Manufacturing.* Journal of Manufacturing Systems, 2007. **25**(4).
[241] Herrmann, C., Thiede, S., Kara, S., Hesselbach, J., *Energy oriented simulation of manufacturing systems - Concept and application.* CIRP Annals - Manufacturing Technology, 2011. **60**(2011): p. 45-48.
[242] Thiede, S., Seow, Y., Andersson, J., Johansson, B., *Environmental aspects in manufacturing system modelling and simualtion - State of the art and research perspectives.* CIRP Journal of Manufacturing Science and Technology, 2012. **6**(2013): p. 78-87.
[243] Avram, O., Xirouchakis, P., *Evaluating the use phase energy requirements of a machine tool system.* Journal of Cleaner Production, 2010. **19**(2011): p. 699-711.
[244] *AirMaster+ Software Tool Brochure*, 2010, U.S. Departement of Energy: EERE Information Center
[245] Kissock, K., *AirSim compressed air simulation software* in *Department of Mechanical Engineering*2003, University of Dayton

[246] Plehn, J., Züst, R., Kimura, F., Sproedt, A.Schönsleben, P., *A method for determining a functional unit to measure environmental performance in manufacturing systems.* Cirp Annals-Manufacturing Technology, 2012. **61**(1): p. 415-418.
[247] Kleiser, L., Rösgen, T.Jenny, P., *Fluiddynamik I/II - Skript zur Vorlesung.* , 2008: ETH Zürich.
[248] Barber, A., *Pneumatic handbook*. 8th ed 1997, Kidlington, Oxford etc.: Elsevier Advanced Technology. 659 S.
[249] Colebrook, C. F., White, C.M., *Experiments with fluid friction in roughened pipes.* Proceedings of the Royal Society of London, 1937. **161**(906): p. 367-381.
[250] Brkic, D., *Review of explicit apporoximation to the colebrook relation for flow friction* Journal of Petroleum Science and Engineering 2011. **77**(1): p. 34-48.
[251] Fordel, P., *Copmressed Air Manual*, in *Atlas Copco Airpower NV*2010.
[252] Miller, D. S., *Internal flow systems*. Technology & Engineering ed. B. F. Engineering1978.
[253] Ruppelt, E., Hobusch, G., Piendl, S., Bahr, M., *Druckluftseminar.* , 2011, KAESER Kompressoren GmbH.
[254] Siekmann, H. E., Thamsen, P.U., , *Strömungslehre für den Maschinenbau* 2009: Springer
[255] Bellinger, G., Castro, D.Mills, A., *Data, information, knowledge, and wisdom.* 2004: p. 47.
[256] Maeda, O., Cao, Y.Altintas, Y., *Expert spindle design system.* International Journal of Machine Tools and Manufacture, 2005. **45**(4–5): p. 537-548.
[257] Abele, E., Altintas, Y.Brecher, C., *Machine tool spindle units.* CIRP Annals - Manufacturing Technology, 2010. **59**(2): p. 781-802.
[258] *Safety of machinery - Electro-sensitive protective equipment - Part 1: General requirements and tests*, 2013, ISO-International Organization for Standardization.
[259] European Commission, E., *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 (1)*, 2010.
[260] European Commission, E. *EU boosts energy performance of domestic electrical goods*. 2011 13.11.2014]; Available from: http://ec.europa.eu/environment/ecoap/about-eco-innovation/policies-matters/eu/387_en.htm.
[261] European Commission, E., *DIRECTIVE 1999/94/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 December 1999, relating to the availability of consumer information on fuel economy and CO2 emissions in respect of the marketing of new passenger cars*, 2000.
[262] Gontarz, A., Hänni, F., Weiss, L.Wegener, K., *Machine tool optimization strategies for ecologic and economic efficiency.* Journal of Engineering Manufacture 2012.
[263] Gontarz, A., Hänni, F., Weiss, L.Wegener, K., *Machine Tool Optimization Strategies - Evaluation of Actual Machine Tool Usage and Modes*, in *Proceedings of the 9th Global Conference on Sustainable Manufacturing*2011.
[264] Gontarz, A., Weiss, L.Wegener, K. *Evaluation approach with function-oriented Modeling of Machine Tools*. in *Proceedings of the International Conference on Sustainable Intelligent Manufacturing SIM*. 2011. Leiria, Portugal.
[265] Pahl, G., Beitz, W., Feldhusen, J.Grote, K.-H., *Pahl/Beitz Konstruktionslehre: Grundlagen erfolgreicher Produktentwicklung. Methoden und Anwendung*. Vol. 10. 2006: Springer DE.
[266] Götsch, M., Buschak, D.Jäger, A., *DEMAT online survey - Dematerialised Manufacturing Systems* 2013, ISI Fraunhofer Karlsruhe.
[267] Ayres, R.Ayres, L., *A handbook of industrial ecology*2002: Edward Elgar Publishing.
[268] Gontarz, A., Weiss, L.Wegener, K., *Evaluation approach with function-oriented modeling of machine tools*2012: Institute of Machine Tools and Manufacturing (IWF), ETH Zurich, Switzerland.
[269] Amzallag, C., Gerey, J. P., Robert, J. L.Bahuaud, J., *Standardization of the rainflow counting method for fatigue analysis.* International Journal of Fatigue, 1994. **16**(4): p. 287-293.
[270] Radaj, D.Vormwald, M., *Ermüdungsfestigkeit Grundlagen für Ingenieure*. Dritte, neubearb. und erw. Aufl. ed2007, Berlin: Springer. 688 S.
[271] Kuno, E., *Evaluation of statistical precision and design of efficient sampling for the population estimation based on frequency of occurrence.* Researches on Population Ecology, 1986. **28**(2): p. 305-319.
[272] Yitzhaki, S., *Relative Deprivation and the Gini Coefficient.* The Quarterly Journal of Economics, 1979. **93**(2): p. 321-324.
[273] Jovanovic, B., *Selection and the Evolution of Industry.* Econometrica, 1982. **50**(3): p. 649-670.

[274] Lauven, L., Wiedenmann, S.Geldermann, J., *Lebenszykluskosten als Entscheidungshilfe beim Erwerb von Werkzeugmaschinen*2010: Schwerpunkt Unternehmensführung, Georg-August-Univ.
[275] Bünting, F., *Lebenszykluskostenbetrachtungen bei Investitionsgütern*, in *Lebenszykluskosten optimieren*, S. Schweiger, Editor 2009, Gabler. p. 35-50.
[276] Pasquire, C.Connolly, G. *Design for manufacture and assembly*. in *11th Annual Conference of the International Group for Lean Construction*. 2003.
[277] Phillips, P.Phillips, J., *Return on Investment*, in *Handbook of Improving Performance in the Workplace: Volumes 1-3*2010, John Wiley & Sons, Inc. p. 823-846.
[278] Maynard, H., Stegemerten, G.Schwab, J., *Methods-time measurement*1948: McGraw-Hill New York.
[279] *REFA-Verband für Arbeitsstudien - Planung und Gestaltung komplexer Produktionssysteme.* München: Carl Hanser, 1990.
[280] Seiler, A., *BWL in der Praxis. 2. Financial management*1999: Orell Füssli.
[281] Warnecke, H. J., *Wirtschaftlichkeitsrechnung für Ingenieure*1996: Hanser.
[282] Volkhart, R., *Skript eCF-get involved in Corporate Finance*. Statische Investitionsrechnung2010, Universität Zürich.
[283] Herrmann, C., *Ganzheitliches Life Cycle Management*, ed. VDI-Buch2010: Springer-Verlag
[284] McKane, A., *Thinking Globally: How ISO 50001 - Energy Management can make industrial energy efficiency standard practice*, 2010.
[285] Sextl, A., *Nachhaltiges Energiemanagement in der BMW Group am Beispiel des Werkes „Achskomponenten und Fahrwerk"*, in *Die energieeffiziente Werkzeugmaschine*, P. Darmstadt, Editor 2010: METAV Düsseldorf.
[286] Gontarz, A., Hampl, D., Weiss, L.Wegener, K., *Resource Consumption Monitoring in Manufacturing Environments*, in *12th Global Conference on Sustainable Manufacturing*, G. Selinger, Editor 2014: Johor Bahru, Malaysia.
[287] Gontarz, A., Plehn, J., Sproedt, A., Weiss, L.Wegener, K., *Resource Consumption Measurement in Manufacturing Environments*, in *10th Global Conference on Sustaible Manufacturing*, G. Seliger, Editor 2012: Istanbul, Turkey. p. 557--563.
[288] Sproedt, A.Plehn, J. *Environmental value stream map as a communicative model for discrete-event material flow simulation*. 2014. 4th World P&OM Conference/19th International Annual EurOMA Conference.
[289] Bundesamt für Energie, B., *Infoblätter Druckluft - Infoblatt Thermodynamik*, in *Effiziente Druckluft Schweiz,* 2006, BFE, Fraunhofer ISI. p. 3-4.
[290] Altintas, Y.Erol, N. A., *Open Architecture Modular Tool Kit for Motion and Machining Process Control.* CIRP Annals - Manufacturing Technology, 1998. **47**(1): p. 295-300.
[291] Klingauf, W., *Der schnelle Draht zwischen PC und CNC - WB110030*, in *Werkstatt + Betrieb, WB*2009, Carl Hanser Verlag, München.
[292] Gosbell, V., Perera, S.Smith, V., *Power Quality Monitoring - Plant investigations*, E. E. P. Q. a. R. Centre, Editor 2002.
[293] *OPC foundation - Description IEC62541*. [cited 2014 17/09]; Available from: https://opcfoundation.org/wp-content/uploads/2014/05/OPC-UA_Security_EN.pdf.

List of Publications

Conferences

- A. Gontarz, D. Hampl, L. Weiss, K. Wegener. Resource Consumption Monitoring in Manufacturing Environments. Procedia CIRP, Volume 26, 12th Global Conference on Sustainable Manufacturing – Emerging Potentials, Johor Bahru, Malaysia, September 2014. ISSN 2212-8271, Pages 264-269.

- A. Gontarz, T. Schudeleit, K. Wegener. Framework of a Machine Tool Configurator for Energy Efficiency. Procedia CIRP, Volume 26, 12th Global Conference on Sustainable Manufacturing – Emerging Potentials, Johor Bahru, Malaysia, September 2014. ISSN 2212-8271, Pages 706-711.

- J. Um, A. Gontarz, I. Stroud. Developing energy estimation model based on Sustainability KPI of machine tools. Procedia CIRP, Volume 26, 12th Global Conference on Sustainable Manufacturing – Emerging Potentials, Johor Bahru, Malaysia, September 2014. ISSN 2212-8271, Pages 217-222.

- J. Larreina, A. Gontarz, V. Nguyen, C. Giannoulis, B. Sinceri, P. Stavropoulos. Smart Manufacturing Execution System (SMES): The Possibilities to evaluate the Sustainability of a Production Process. Proceedings of the 11th Global Conference on Sustainable Manufacturing, Berlin, Germany, September 2013, ISBN 9798-3-7983-2606-4, Pages 467-472.

- S. Züst, A. Gontarz, K. Wegener. Energy Equivalent of Compressed Air Consumption in a Machine Tool Environment. Proceedings of the 11th Global Conference on Sustainable Manufacturing, Berlin, Germany, September 2013, ISBN 9798-3-7983-2606-4, Pages 394-399.

- A. Gontarz, C. Elbe, L. Weiss, K. Wegener. Standby Indication and Energy Management on Machine Tools (poster). ICT for Sustainability - The Challenge of Making It Real, Zürich, Switzerland, February 2013, DOI http://dx.doi.org/10.3929/ethz-a-007337628.

- A. Gontarz, J. Plehn, A. Sproedt, L. Weiss, K. Wegener. Resource Consumption Measurement in Manufacturing Environments. Proceedings of the 10th Global Conference on Sustainable Manufacturing, Istanbul, Turkey, October 2012, ISBN 978-605-63463-0-9, Pages 557-563.

- J. Plehn, A. Sproedt, A. Gontarz, J. Reinhard, From Strategic Goals to focused Eco-efficiency Improvement in Production - Bridging the gap using Environmental Value Stream Mapping. Proceedings of the 10th Global Conference on Sustainable Manufacturing, Istanbul, Turkey, October 2012, ISBN 978-605-63463-0-9, Pages 551-556.

- A. Gontarz, S. Züst, L. Weiss, K. Wegener. Energetic machine tool modeling approach for energy consumption prediction. Proceedings of the 10th Global Conference on Sustainable Manufacturing, Istanbul, Turkey, October 2012, ISBN 978-605-63463-0-9, Pages 652-658.

- J. Hentz, V. Nguyen, D. Panarese, J. Gunnink, A. Gontarz, P. Stravropoulos, K. Hamilton, J. Hascoët. An enabling digital foundation towards smart machining, Procedia CIRP, Volume 12, 8th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Ischia, Italy, October 2012, Pages 240-245.

- K. Wegener, L. Weiss, A. Gontarz. Methods and Tools for Evaluation of Energy Efficiency in Production. 2nd International Chemnitz Manufacturing Colloquium ICMC 2012 / 2. eniPROD-Kolloquium, Fraunhofer IWU, Chemnitz, Germany, April 2012, Pages 247-267.

- A. Gontarz, F. Hänni, L. Weiss, K. Wegener. Machine Tool Optimization Strategies - Evaluation of Actual Machine Tool Usage and Modes. Proceedings of the 9th Global Conference on Sustainable Manufacturing, St. Petersburg, Russia, September 2011, Pages 133-138.

- A. Gontarz, L. Weiss, K. Wegener. Evaluation Approach with Function-oriented Modeling of Machine Tools, Proceedings of the International Conference on Sustainable Intelligent Manufacturing SIM, Leiria, Portugal, June 2011, ISBN 978-989-8481-03-0, Pages 61-68.

- A. Gontarz, N. Jufer, J. Bathelt, L. Weiss, K. Wegener. Determination and Evaluation of CO_2 as a Sustainable Performance Measure on the Basis of a Typical Lathe, 1st International Conference on Sustainable Intelligent Manufacturing, 2011, Leiria, Portugal, ISBN 978-989-8481-03-0, Pages 203-210.

- A. Gontarz, L. Weiss, K. Wegener. Energy Consumption Measurement with a Multichannel Measurement System on a machine tool. Proceedings of the International Conference on Innovative Technologies IN-TECH , Prague, Czech Republic, September 2013, Pages 499-502.

Book chapter

- A. Gontarz, P. Bosshard, L. Weiss, K. Wegener. Compressed air system assessment for machine tool monitoring, Green Design, Materials and Manufacturing Processes – Bártolo et al. (eds.), 2013, Taylor & Francis Group, London, ISBN 978-1-138-00046-9, Pages 173-178.

Journals

- A. Gontarz, F. Hänni, L. Weiss, K. Wegener. Machine Tool Optimization Strategies for Ecologic and Economic Efficiency, Journal of Engineering Manufacture - Volume 227 Issue 1, 2012, United Kingdom, DOI 10.1177/0954405412464932, Pages 54-61.

Technical reports

- R. Züst, L. Weiss, A. Gontarz, J. Hauenstein. Best Practice Guide, Energieeffizienz, Produktionseffizienz, Materialeffizienz. Galedia Verlag AG. Eco-effiziente Produktionsmaschinen in moderner Haustechnik bei METTLER TOLEDO, Zürich, Switzerland, 2013, Pages 17-20.

- A. Gontarz. Energie- und Ressourcenmessungen an Produktionssystemen
- umfassende Bewertung: schnell, einfach und universell messen, VDW Branchenreport, Germany, Juni 2014.

Press articles

- A.Gontarz. Mehrkanalmessung erlaubt effektive Datenerfassung, Technische Rundschau Issue 04/2015, 10.04.2015, Page 73.

- A. Gontarz. Den Ressourcenverbrauch sichtbar machen in Werkstatt und Betrieb (W+B), Carl Hanser Verlag, Issue 5/2014, Pages 89-92.

- A. Gontarz. Energie- und Ressourceneffizienz in der Produktion überwachen, in Maschinen Markt (MM Vogel), Issue week 25, Pages 44-46.

- A. Gontarz. Measurement & Monitoring: Resources Assessment on Machine Tools, CNC-Arena eMagazine Edition 2/2013, 2014, Page 10.

- A. Gontarz. WP7 Implementation of EMon on GFAC Machine Tool - A Monitoring system for EDM machining, FoFdation FOCUS, Issue 7, January 2014, Page 1.

- A. Gontarz. Aufbau einer mobilen Messeinrichtung zur Messung des Energie- und Ressourcenverbrauchs, SWISSMEM: Network, issue 4/2013, Page 15.

Talks

- A. Gontarz. Energieeffizienz an Werkzeugmaschinen - systematisch messen, analysieren und optimieren, PRODEX 2014. Internationale Fachmesse für Werkzeugmaschinen, Werkzeuge und Fertigungsmesstechnik. SWISSMEM Thementag: BlueCompetence, 2014, Basel, Switzerland.

- A. Gontarz. Energieeffizienz bei Werkzeugmaschinen - schnell und effektiv messen, Praxisseminar – Industrie- und Technozentrum Schaffhausen (IST), 2014, Schaffhausen, Switzerland.

- A. Gontarz. Efficience en matière d'énergie et de ressource des machine-outils, méthodes de mesure et de surveillance. EURESEARCH, L'Usine du Futur - EPHJ Palexpo-Genève, 2014, Geneva, Switzerland.

- A. Gontarz. Messung, Analyse und Optimierung von Werkzeugmaschinen und Produktionssystemen auf Basis Multikanalmessung. Forum Efficiency Arena Messe Hannover, 2014, Hanover, Germany.

- A. Gontarz. Leistungs- und Energiemessung in der Produktion: Messung - Analyse – Optimierung. ManuFuture CH - Technologie Apéro "Energieeffizienz", 2014, Zürich, Switzerland.

- A. Gontarz. Leistungs- und Energiemessung in der Produktion: Messung – Analyse – Optimierung. Fertigungstechnisches Kolloquium, Institut für Werkzeugmaschinen und Fertigung, ETH, 2013, Zürich, Schweiz.

- A. Gontarz. Energy- and Resource consumption measurement in manufacturing, EMO Hannover 2013 - VDW Blue Competence, 2013, Hanover, Germany.

- A. Gontarz. EcoDesign - Design of energy-efficient machines, Eco Design - umweltgerechte Produktgestaltung, lecture, 2012, ETH Zurich, Switzerland.

- A. Gontarz. Design of energy-efficient machines. Methods and Tools for the Development of Structured Mechatronic Products, lecture, 2011, ETH Zurich, Switzerland.

- A. Gontarz. Energieeffizienz in der Fertigungstechnik, Fertigungstechnischen Kolloquium am Institut für Werkzeugmaschinen und Fertigung, ETH Zürich, 2010, Zurich, Switzerland.

Patents

- A. Gontarz, D. Hampl. Multichannel Monitoring System for Energy and Power Monitoring, Based on Multisource Data acquisition, INSPIRE AG 2013.

List of Supervised Theses

The following theses (unpublished) were supervised by the author.

- N. Schlegel. Energy Efficiency Mapping of Machine Tools. Semester thesis, 2014.
- L. Geissmann. Energieeffizienz in der Produktion durch Latentspeicher. Semester thesis. 2013.
- P.h. Roh. Implementation of an energy monitoring system in manufacturing. Bachelor thesis, 2013.
- P.Bosshard. Development and verification of a compressed air simulation on machine tools. Bachelor thesis, 2013.
- C. Elbe. Analysis Method for Energy and Resources Management in Manufacturing. Semester thesis, 2012.
- A. Krättli. Modellbildung von hydraulischen Maschinenkomponenten im Rahmen eines Energiemodells. Semester thesis, 2012.
- H. Stark. Benutzerschnittstelle für Energiesimulation I. Semester thesis, 2012.
- M. Nick. Benutzerschnittstelle für Energiesimulation II. Semester thesis 2012.
- M. Lang. Potentialanalyse von energetischen Modellierungsansätzen. Mater thesis, 2012.
- D. Michel. Anwendung der ISO14955 Norm zur Energieeffizienz von Werkzeugmaschinen. Bachelor thesis. 2012.
- K. Neugebauer. Ermittlung wirtschaftlicher Kenngrössen zur Beurteilung von Retrofitmassnahmen zu Energie- und Ressourceneffizienz bei Werkzeugmaschinen. Bachelor thesis, 2012.
- F. Hänni. Energieeffzienzoptimierung durch Retrofit - am Beispiel Hydraulik. Semster thesis, 2012.
- S. Züst. Erstellen und Verifizieren eines Energiemodells anhand einer Drehmaschine. Master thesis, 2012.
- T. Bormuth. Concept of a Sustainable Manufacturing Execution System (SMES). Semester thesis, 2011.
- M. Töpfer. Sustainability in Production - Performance Indicators, Monitoring & Assessment. Semester thesis, 2011.