Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 15 (2014) 141 – 146
www.elsevier.com/locate/procedia

21st CIRP Conference on Life Cycle Engineering

Hierarchical Evaluation of Environmental Impacts from Manufacturing System and Machine Perspective

Tim Heinemann[a]*, Philipp Schraml[b], Sebastian Thiede[a], Christian Eisele[b], Christoph Herrmann[a], Eberhard Abele[b]

[a] *Sustainable Manufacturing and Life-Cycle-Engineering Research Group, Institute of Machine Tools and Production Technology, Technische Universität Braunschweig, Langer Kamp 19b, D-38106 Braunschweig, Germany*
[b]*Institute of Production Management, Technology and Machine Tools, Technische Universität Darmstadt, Otto-Berndt-Str. 2, D- 64287 Darmstadt, Germany*
* Corresponding author. Tel.: +49-531-391-7602; fax: +49-531-391-5842. *E-mail address:* t.heinemann@tu-braunschweig.de

Abstract

Methods and tools for evaluating energy efficiency of machines and manufacturing lines have become available recently. These are e.g. manufacturing system simulation approaches and detailed machine performance simulation approaches. However, there is a lack of applicable tools for the evaluation of whole factory systems. The above mentioned simulation approaches can deliver valuable input for methods and tools for the environmental evaluation of entire factory systems. This paper presents a hierarchical approach and a case study for a synergetic combination of tools for simulating machine behavior and manufacturing line performance as well as for the calculation of Total Cost of Ownership and environmental impacts of factory systems.

Selection and peer-review under responsibility of the International Scientific Committee of the 21st CIRP Conference on Life Cycle Engineering in the person of the Conference Chair Prof. Terje K. Lien

Keywords: Life Cycle Evaluation; Total Cost of Ownership; Life Cycle Assessment; Factory Evaluation; Energy Efficiency; Simulation, Machine Tools

1. Motivation

Energy and resource consumption are topics of growing relevance in manufacturing companies. Reasons are the rising prices of energy and resources as well as the associated environmental impact which is connected to rising customer awareness and legislative regulations. In order to cope with the arising challenges whole factory systems need to be designed appropriately. However, it is a big challenge to evaluate the energy efficiency and environmental impact of entire factory systems in a way that enables the derivation and assessment of improvement measures. It is even more challenging to make prognoses about the environmental impact of factory projects which are in an early planning phase. This is also true for the economical evaluation of future factories in terms of total cost of ownership (TCO) [1].

In order to make factory systems more sustainable, the impact over the entire life cycle needs to be forecasted and evaluated. A factory can be decomposed to subsystems like the building shell, technical building services and production equipment. Beside the subsystems also their dynamic system behavior has to be considered [2].

Against this background this paper provides a framework for the synergetic application of simulation and evaluation tools that tackle energy efficiency at different hierarchical system levels of manufacturing enterprises. Besides presenting the methodological background and interfaces between the tools, the paper demonstrates applicability and benefits through a case study of an enterprise which produces one work piece in a process chain of four sub processes.

2. Theoretical Background

Respecting that factories are systems which contain diverse system elements on different hierarchical layers, possible concepts for the description of manufacturing hierarchies will be described in the following. Methods and tools for energy efficiency investigations as well as their individual scopes and

2212-8271
Selection and peer-review under responsibility of the International Scientific Committee of the 21st CIRP Conference on Life Cycle Engineering in the person of the Conference Chair Prof. Terje K. Lien
doi:10.1016/j.procir.2014.06.063

performance indicators will be introduced for different hierarchical levels within factory systems.

2.1. Hierarchy of manufacturing

From a systems perspective, manufacturing consists of different levels of hierarchy with the goal "to produce goods and services of right quality and quantity at the right time and right manufacturing cost" [3]. Two possible approaches for the classification of different layers from process to value chain (a) and from workstation to plant level (b) are presented in Figure 1 [4] [5].

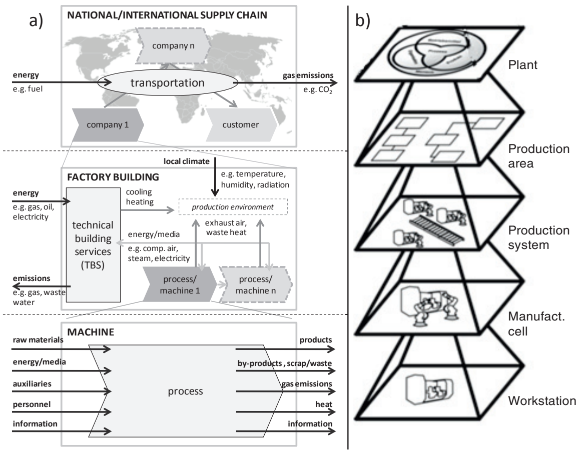

Figure 1: Different hierarchical levels of manufacturing systems [4] [5]

The actual value adding takes place on the process level which physically "transforms inputs into outputs" [6] and is typically conducted or supported by technical equipment like (production) machines. Those machines demand energy related to their specific state. Technical products normally involve several processes which form process chains as logically linked sequence of successive or parallel single processes [7]. From a factory perspective, Technical Building Services (TBS) need to be considered since they support the value adding (intra-company) process chains through providing necessary energy and media (e.g. compressed air, steam) and production conditions (temperature, moisture, purity, etc.). Furthermore they need a significant amount of energy themselves. Thus, the cumulative energy demand of the factory as a whole (in form of a load profile) is determined by the interaction of all production machines and the TBS [8]. On the highest level of aggregation, national or international inter-company process chains are composed of different companies which work together to produce the product.

Each of these hierarchical levels is quite different regarding the necessary knowledge, methods and tools for planning, design and controlling. Each level also involves several possibilities to influence the energy and resource efficiency which are, again, very different regarding their individual effects. Specifically in the context of energy and resource consumption typically different disciplines (e.g. production engineering, industrial engineering, business administration, thermodynamics, material science) and internal (different departments, management) and external stakeholders (e.g. customer, supplier, politics) have their specific set of objectives. This leads to a complex system of systems with dynamic interactions and interdependencies that need to be balanced from a holistic point of view in order to avoid problem shifting and local optimization [4] [9].

2.2. Environmental Evaluation on Factory Level

There are manifold challenges to deal with as a factory is a very complex system and there are various uncertainties regarding the mode of operation and unexpected events that can affect the cost and environmental impact of a factory during its entire life cycle [1]. Due to this fact there are only a few approaches dealing with the evaluation of entire factory systems. Corporate Carbon Footprints can be used in order to evaluate the resulting impact of the energy and media consumption of factory systems [10]. Nevertheless they are usually only used retrospectively in order to make up the balance for the status quo of the enterprise as a basis for improvement activities. Some approaches focus on the static evaluation of the factory's building shell and augment this perspective with average sets of installed equipment [11]. This perspective allows conclusions about the static system behavior but does not give an insight in the dynamic system behavior, which is needed in order to holistically identify measures for improvement. A more dynamic and system oriented perspective gets delivered by life cycle oriented and time period based factory evaluated approaches like the Life Cycle Evaluation Tool which will be applied in this paper [1].

2.3. Environmental Evaluation of Manufacturing Systems

Factories may contain one or more manufacturing systems, which can be described as in-house value chains. The involved sub processes can be evaluated by using material flow balance sheets (life cycle inventories or material flow models in software tools like Umberto™). Following another rather static approach energy data of known production processes can be aggregated ex post to specific average process performance data, which can then be used for energy oriented production planning procedures [12].

However, energy oriented process chain simulation approaches offer a more detailed insight into the dynamic process interdependencies and therefore into possible starting points for improvement campaigns. These simulation approaches can be distinguished into energy oriented material flow simulation approaches that also consider the interaction with technical building services or into the combination of single-process oriented machine models [2] [13] [14].

In the following course of this paper an energy oriented material flow simulation will be applied in order to assess dynamic interdependencies of intra-factory process chains. This process chain model will use the results of single-process oriented machine models, which predict the energetic performance of the system elements of the process chain.

2.4. Environmental Evaluation of Production Machines

Production machines are responsible for a major part of the energy demand within the industrial production [15]. Therefore energy savings on machine level potentially have a big impact on the energy demand on factory level. Studies have shown that the optimization at machine and component level has a high energy saving potential. By optimal dimensioning of functional modules, the use of energy-efficient components, the introduction of demand and process oriented component controls and an overall process optimization, the energy demand of a machining center could be reduced by more than 50% [16]. For evaluating the energy demand of production machines which are not physically accessible for local measurements (during machine procurement, machine development, factory planning, etc) energy demand approximation tools are needed. Up to now mainly two different approaches for approximating the energy demand of production machines can be distinguished:

- Assumption of constant energy demands based on historical measurement data: under assumption of a certain constant energy demand of each functional module and each possible machine state, the overall energy demand of the machine can be derived [17].
- Detailed dynamic simulation: based on mathematical equations and basic physical interrelationships, detailed simulation models of functional modules are used to compute the energy demand of the entire production machine [18] [19] [20].

Due to the fact that no historical measurement data is needed, the simulation approach will be used within this paper to estimate the energy demand on machine level to provide a greater scope of application.

3. Hierarchical Evaluation of Environmental Impacts from Manufacturing System and Machine Perspective

Against the theoretical background this paper aims at introducing a joint application of the introduced system-level-specific methodologies and tools for energy evaluation of factory system elements. As the introduced methodologies and tools have the ability to forecast the energy performance of factory system elements, the joint application will offer manifold opportunities for factory planning projects to design and evaluate the most efficient factory system

3.1. Hierarchical Levels for Energy Evaluation in Factories

Taking a top-down perspective, the factory as a whole consists of three major domains, which need to be addressed in top level factory evaluations (see Figure 2):

- production equipment,
- technical building services,
- building shell [2].

The group of production equipment often gets further sub-divided into single process chains or production lines, which consist of a sequence of manufacturing machines.

The energetic performance of the individual machines in this process chain depends on the specific load dependent behaviour of its installed components. Based on this idea the energetic performance of entire factory systems over their life cycle depends on the individual behaviour of the smallest installed energy consuming entities. Tool or tool chains for the energetic evaluation of factories therefore need to address also this level of detail in order to enable a holistic assessment.

Thus, the following section will describe the tools which can be applied on the individual system levels and their specific input and output variables. It will close with a description of a synergetic joint application of such tools for a hierarchical evaluation of environmental impacts from manufacturing system and machine perspective.

3.2. Tools and Interfaces

3.2.1. Energy oriented machine simulator

The basis for simulating the energy demand of production machines builds a simulation model library of standard machine tool hardware components developed within the simulation environment MathWorks Simscape. Besides the mechanical, hydraulic or pneumatic behavior the simulation

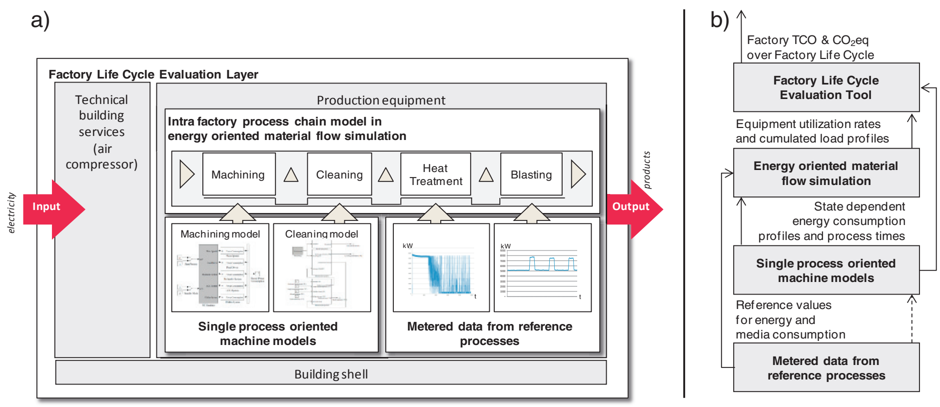

Figure 2: a) System elements of a manufacturing system, corresponding evaluation layers and tools; b) information flows for a hierarchical factory evaluation

models are capable of computing the electric power demand. Machine components can be combined freely to functional modules and/or entire production machines and thus the specific energy demand can be accumulated. The developed approach focuses on the exclusive use of publicly available data sheet details provided by the component manufacturers for simulation model parameterization. As an example this data can be a single parameter like the stator resistance of an induction machine as well as characteristic diagrams for e.g. a centrifugal pump. This approach guarantees the complete independence from local energetic measurements. Instead of following a hardware-in the-loop approach a NC-Emulator was developed capable of reading DIN 66025/ISO 6983 conform G-Code including certain machine depending M-Commands for controlling the simulation models. In combination with a simple cutting force model basing on [21] the energy demand of feed drives and spindle units can be estimated.

3.2.2. Energy oriented material flow simulation

The results of energy oriented machine simulation approaches (state dependent energy consumption and process times) can give valuable input to energy oriented material flow simulation approaches, which concern single machines as black boxes and therefore enfold their potential analysing the interaction of several interlinked processes on manufacturing system level. By doing so also the effects of material flow rules and e.g. bottle neck situations can be integrated in an energy assessment of a whole factory. Therefore not only the cumulated, dynamic load profiles of whole production lines can be calculated but also the utilization of the single machines and the share of productive and non productive process times.

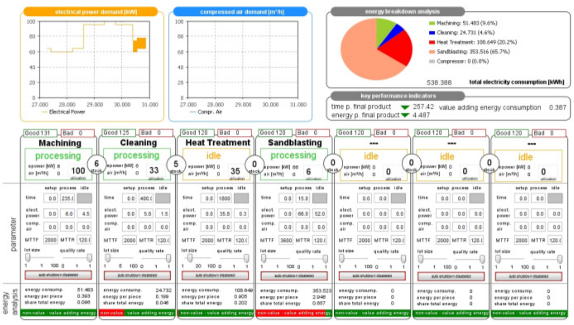

Figure 3: Sample screenshot from energy oriented material flow simulation

Thiede provides an energy oriented material flow simulation approach, which has been modified in order to increase the user friendliness and decrease barriers for applying simulation experiments also by non-experts (see figure 3) [2] [8].

3.2.3. Factory Life Cycle Evaluation Tool

On the highest hierarchical level of a factory system a Life Cycle Evaluation (LCE) tool can be used in order to accumulate all physical flows which pass through a factory system during the entire life cycle (including the build up and disposal phase) [1]. Afterwards these flows can be translated into economical and environmental impacts by pricing them with impact factors (e.g. € and CO_2eq. per flow category).

Facing the challenge that data about the real and dynamic energy and media flows of production machines and lines as well as their real utilization rates are usually unknown when planning a factory, these data can be prepared through the application of the afore mentioned simulation approaches and further processed in the LCE tool. As these consumption patterns are highly dynamic and also very relevant for the total impact of a factory system, the high level life cycle evaluation of factories can benefit from the joint application of the tools through an increase in data accuracy compared to a usage of only static or average energy and media consumption data. This becomes relevant for expected volatile production volumes and resource demands.

3.2.4. Tool interaction

Figure 2 visualizes the interaction of the joint application of the energy oriented machine simulator, the energy oriented material flow simulation and the factory life cycle evaluation tool. In order to calculate the total cost of ownership and environmental impacts of factory systems the LCE tool benefits from the pre-calculated dynamic load profiles and utilization rates. Those are provided by the energy oriented material flow simulation as well as from the state dependent loads which result from the application of the energy oriented machine simulator. These state dependent load profiles as well as process times are also an input to the energy oriented material flow simulation. If available as a bypass, both simulation tools for the machine as well as for the manufacturing system level can make use of metered reference consumption patterns for single processes.

Therefore, the flexibility of the presented tools enables the user to assess factory systems as well as single machines and manufacturing lines also if there is only a heterogeneous data base of metered energy, media and time consumption profiles. Missing data on each hierarchical level of the factory system can be estimated through the application of the individual simulation approach. Therefore, through this joint application, realistic values for the total energy and media consumption of the factory systems as well as single machines can be derived without neglecting technical feasibility, dynamic system behavior and logistic linkage of system elements.

4. Case Study

To show the seamless integration of the three presented tools to one holistic evaluation of economical and environmental impacts from manufacturing system and machine perspective an exemplarily case study has been conducted. By combining different but widely used processes within the mechanical engineering industry a general adaptability is ensured.

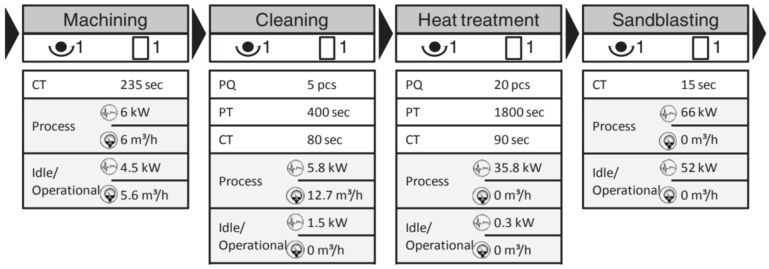

Figure 4: Exemplary considered process chain, baseline scenario, power demand results from energy oriented machine simulator

4.1. Work piece, process chain, peripheral equipment and building shell

The exemplary considered work piece is based on a reference work piece: a cast iron block which is machined in a first process step with a single clamping fixture: two milling (face and edge milling) and five drilling operations [16]. To prepare the work piece for a following heat treatment process a wet cleaning process is introduced. Afterwards the work piece is heat treated and finally sandblasted. The resulting process chain is shown in figure 4. The last process has to wait 10 s before each new batch can enter the process.

The process chain is situated in a building shell that consists only of aerated concrete walls (without windows) and covers one single floor. One air compressor represents the technical building services. Due to simplification reasons transportation processes, further technical building services (lighting, heating,…) as well as installations (pipes, wiring,…) are not considered but can be modeled as well.

4.2. Production scenarios

The presented tools have been applied jointly in order to evaluate five different improvement scenarios for the considered factory system. The impact of these scenarios gets compared using the output of the top level LCE tool in terms of total Cost of Ownership as well as CO_2eq. The proposed improvement measures tackle the factory system through technical as well as organizational measures on diverse levels of hierarchy. Table 1 gives an overview over the main parameters of the developed scenarios, already including the results from the two simulation approaches (power demand during process and idle mode, utilization rates). For simplification reasons at the machine level only electricity consumption will be regarded.

Table 1: Case study scenarios and results from machine and material flow simulation

Baseline Scenario	**Reference work piece production** • Factory: 1 building shell, aerated concrete walls, 1 floor, no windows • TBS: 1 medium sized air compressor (80kW) • Machines: ○ 4-Axis machining center: cooling lubricant system, constant volume flow during process (pressure-less circulation), one piece flow ○ Small sized single bath cleaning system: bath temperature 75°C ○ Heat treatment oven ○ Sandblasting system, one piece flow, idling between batches • Electricity: 0.112 €/kWh; 0.559 kg CO2eq/kWh
Improvement Scenarios	**Scenario A: Improved cleaning process parameters** Decreased bath temperature (55°C) to reduce heat loss to the ambience. Result of mach. simulation: P(Process) = 4.6kW; P(Idle)= 0.65kW
	Scenario B: Demand controlled cooling and lubricating-system Reduction of energy losses when system is not running at full load. Result of machine simulation: P(Process) = 5,23 kW; P(Idle) = 3,13kW
	Scenario C: Optimized lot size for sandblasting and heat treatment Improving the bottleneck situation, switching of the process during waiting times between batches. Lot size sand blasting = 10; lot size heat treatment = 40. Results from energy oriented material flow simulation: Heat Treatment: -49 % processing times, -25 % idling times; Sand blasting: -83 % processing times, -36% idling times.
	Scenario D: Adjusted design of building shell Integration of Windows in the building shell leads to a little reduction of CO_2eq during the setup phase of the factory and to an increase during the disposal phase [22].
	Scenario E: Re-dimensioning of air compressor Usage of more efficient air compressor (connected load = 60 kW)

4.3. Results

The scenarios have been calculated by using the proposed sequence of simulation and calculation tools. Therefore the state dependent energy consumption and process times of the machines (result from energy oriented machine simulator, see figure 4) have been further processed in the energy oriented material flow simulation in order to calculate the processes' utilization rates along the process chain (see table 2).

Table 2: Utilization rates of machines, calculated by energy oriented material flow simulation.

Machining: 100 %	Heat Treatment: 35 %
Cleaning: 33 %	Sand Blasting: 6 %

Resulting from the LCE tool, using the input from the simulation approaches, the total cost of ownership of the factory (including machine replacements, energy consumption and building shell installation costs) sums up to 4.04 Mio. € over an observed period of 30 years in the baseline scenario. The global warming potential, which results from the build up and disposal of the factory building as well as from the energy consumption during the use phase of the factory, sums up to 21.340 t CO_2eq. Figure 5 and figure 6 show the results of an evaluation of the above mentioned improvement scenarios in the LCE tool. The economic as well as environmental impact gets depicted over the entire observation period (under the given simplifications, not regarding other installations and TBS like space heating, piping, etc.).

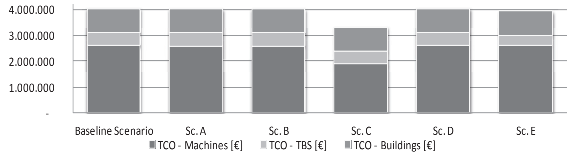

Figure 5: Economic scenario evaluation: Total Cost of Ownership [€]

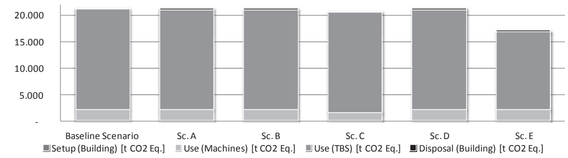

Figure 6: Environmental scenario evaluation: CO2eq. saving potential [t CO2eq.]

It gets clear that single machine oriented measures (Sc.A, Sc.B) or minor changes in the design of the building shell (Sc.D) have a relatively smaller impact than measures for improving the TBS (Sc.E) or significant reductions in machine running times through organizational measures (Sc.C). Sc.C shows a higher impact on the TCO as through the reduced machine running times not only energy is saved but also the amount of necessary machine replacements can be reduced. Sc.E shows a higher impact on CO_2eq as the compressors energy consumption gets reduced dramatically.
The improvement scenarios are hypothetical. However, the conducted case study can show the feasibility of the presented hierarchical evaluation approach. Accordingly, it is not the purpose of this paper to give absolute advice about the selection of measures. Nevertheless, the potential of a holistic evaluation along the whole life cycle of the observed object and along all hierarchical levels becomes understandable.

5. Conclusion and Outlook

This paper presents a scheme for a synergetic application of different assessment tools for energy efficiency and environmental impacts on different levels of a factory system. A simplified case has been conducted to demonstrate the application. The different tools are able to handle the heterogeneous data availability on the different system levels. In an interacting application each tool generates important input data for the next hierarchical level. Future work is necessary in order to enhance interfaces between the software tools. By doing so a software family can be generated that enables factory planners as well as industrial engineers for a holistic evaluation of multiple performance indicators without losing information about technical feasibility, monetary values and logistical performance.

6. Acknowledgements

The research leading to these results has received funding from the European Community's Seventh Framework Program (FP7/2007-2013) under grant agreement n° 285363. The funded project's title is "Eco Manufactured Transportation Means from Clean and Competitive Factory".

References

[1] Heinemann T., Thiede S, Müller K, Berning B, Linzbach J, Herrmann C. Life Cycle Evaluation of Factories: Approach, Tool and Case Study. In: Proceedings of the 11th Global Conference on Sustainable Manufacturing. Berlin; 2013. pp. 529-534.
[2] Thiede S. Energy Efficiency in Manufacturing Systems. Berlin: Springer-Verlag; 2012.
[3] Kumar S A, Suresh N. Production and Operations Management. New Age International Publishers.
[4] Herrmann C, Kara S, Thiede S, Luger T. Energy Efficiency in Manufacturing – Perspectives from Australia and Europe. In: Proceedings of the 17th CIRP International Conference on Life Cycle Engineering. Hefei; 2010. pp. 23-28.
[5] Wiendahl H-P. Veränderungsfähigkeit von Produktionsunternehmen - Ein morphologischer Ansatz. In: Zeitschrift für wirtschaftlichen Fabrikbetrieb 2009; 104:1. pp 32-37.
[6] ISO 9000:2000, 3.4.1.
[7] Kuhn A. Handbuch Logistik. Berlin: VDI-Verlag, Springer; 2002.
[8] Herrmann C, Thiede S, Kara S, Hesselbach J. Energy oriented simulation of manufacturing systems – Concept and application. In: Annals of the CIRP 2011; 60:1; pp. 45-48.
[9] Jamshide M. System of Systems Engineering - New Challenges for the 21' Century. In: IEEE A&E SYSTEMS MAGAZINE 2008; 23:5; pp. 4-19.
[10] DIN EN ISO 14064-1.
[11] Reichardt J, Mersmann T, Reinema C, Kuhlmann T, Gottswinter C, Kliewer E, Nyhuis P. Ecofabrik - Internetbasierte Methode zur Bewertung der Energieeffizienz von Fabriken. In: Wissenschaftliche Schriftenreihe des Institutes für Betriebswissenschaften und Fabriksysteme. Chemnitz: Technische Universität Chemnitz Eigenverlag; 2011.
[12] Weinert N. Vorgehensweise für Planung und Betrieb energieeffizienter Produktionssysteme. Berlin: Fraunhofer Verlag; 2010.
[13] Abele E, Schrems S, Schraml P. Energieeffizienz in der Fertigungsplanung - Frühzeitige Abschätzung des Energieverbrauchs von Produktionsmaschinen in der Mittel- und Großserienfertigung. In: Werkstattstechnik online: wt 2012;, 102:1/2. pp. 38-42.
[14] Junge M. Simulationsgestützte Entwicklung und Optimierung einer energieeffizienten Produktionssteuerung, Universität Kassel, Produktion & Energie, 2007: 1.
[15] Müller E, Engelmann J, Löffler T, Strauch J. Energieeffiziente Fabriken planen und betreiben. Berlin: Springer-Verlag; 2012.
[16] Abele E, Sielaff T, Beck M. Konfiguration energieeffizienter Werkzeugmaschinen - Energieeffiziente Auslegung von Werkzeugmaschinen und Bearbeitungszentren für die Großserienfertigung. In: wt Werkstattstechnik online 102 (2012), 5, pp. 292-298.
[17] Dietmair A, Verl A, Wosnik M. Zustandsbasierte Energieverbrauchsprofile – Eine Methode zur effizienten Erfassung des Energieverbrauchs von Produktionsmaschinen, In: wt Werkstattstechnik online, 98 (2008), 7/8, pp.640-645.
[18] Abele E, Eisele C, Schrems A. Simulation of the Energy Consumption of Machine Simulation of the Energy Consumption of Machine Tools for a Specific Production Task. In: Leveraging Technology for a Sustainable World, Springer-Verlag, 2012, pp. 233-237.
[19] Abele E, Schraml P, Eisele C. Abschätzung des Energieverbrauchs durch Kennfelder. In: PRODUCTIVITY Management, GITO Verlag, Berlin, 17 (4) (2012), pp. 26-28.
[20] Schmitt R, Bittencourt J, Bonefeld R. Modelling Machine Tools for Self-Optimisation of Energy Consumption. In Glocalized Solutions for Sustainability in Manufacturing. Berlin: Springer-Verlag, 2011, pp. 253-257.
[21] Kienzle O, Victor H. Spezifische Schnittkräfte bei der Metallbearbeitung. In: Werkstofftechnik und Maschinenbau 47 (1957), Nr. H5, pp. 224–225.
[22] www.pe-international.com/services-solutions/green-building/building -lca/ (01.11.2013