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Implementing Key Performance Indicators for Energy Efficiency in Manufacturing

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Abstract

Energy is an important input factor in today's manufacturing and measuring the efficiency of energy employment is essential for companies to meet ecological and economical goals. Despite the recent development in both academia and industry, there are multiple definitions and key performance indicators (KPIs) proposed which are confusing to use and thus lack of broad application. This paper proposes a generalized calculation methodology with a set of templates for measuring the energy efficiency of manufacturing activities from factory level to process and product level. Owing to the recent trend of implementing energy efficiency measures as well as on-site energy generation from renewable resources, new KPIs have been developed to quantify the benefits of those applications. The proposed KPIs and their development process are demonstrated with a case study of a pharmaceutical manufacturer in Australia.

Peer-review under responsibility of the scientific committee of the 49th CIRP Conference on Manufacturing Systems

Keywords: Key Performance Indicators; Energy Efficiency in Manufacturing; Renewable Energy

1. Introduction

The United Nations Framework Convention on Climate Change has recently set ambitious targets for slowing down global warming [1]. Being responsible for a significant share of CO_2^{eq} emissions [2], the manufacturing sector needs to foster a sustainable development. In this regard not only the direct emissions from production are of interest but especially the indirect emissions which are related to the companies' energy demand.

Against this background, companies pursue various energy efficiency measures such as retrofitting variable speed drives and energy efficient components, installing energy recovery systems and auto-switch-off devices etc. [3]. On-site energy generation facilities are another important option to reduce the environmental impact of a manufacturing company [4]. Key performance indicators (KPI) are required to assess and track the benefits of such energy efficiency measures. Moreover, they lay the foundation for a continuous improvement process as part of energy management and are, consequently, an enabler for further energy efficiency measures.

Hence, a methodology for the development of energy efficiency related KPIs with high significance has been developed. Specific attention is given to the exploration of energy efficiency KPIs for on-site energy generation [5]. Beforehand, selected background information about on-site energy generation facilities and KPIs for sustainability assessment is provided.

The application of the methodology is exemplarily employed in a case study at a manufacturing company of pharmaceutical goods, which features several on-site energy generation facilities. A selection of company-specific KPIs is presented to demonstrate the potentials for KPI application in plant management.

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2. Background

2.1. On-site Energy Generation

A growing number of manufacturing firms installs facilities to generate their own energy from renewable resources on-site. Goals are to become independent from energy prices and suppliers, to increase supply safety in emerging countries, and to reduce environmental impacts from production. Various systems for on-site energy generation can be distinguished which differ in availability and the provided form of energy (see Fig. 1).

On-site energy generation and conversion	Energy produced	Conversion efficiency	Availa-bility
Solar	electricity photovoltaic; heat solar thermic	max. 23%	during daytime / sunshine
Wind	electricity	max. 40%	steady wind speed
Biomass / Biogas	electricity, heat	35 – 45%*	24/7
Geothermics	electricity, heat**, cooling**	10 – 23% (45 – 75% w/ converters)	24/7
Cogeneration	electricity, heat	~ 85%	24/7
Trigeneration	electricity, heat, cooling	> 90%	24/7
Quadgeneration	electricity, heat, cooling, captures CO_2	> 90%	24/7

electricity cooling heat captures CO_2

* for e.g. co-firing with coal
** when used as heat pump

Fig. 1: On-site energy generation equipment; compiled based on [6-10]

Notably, locally generated power provides the opportunity to meet overriding goals from different areas. As an example, generating electricity by means of photovoltaic panels does not only reduce the company's CO_2 emissions, but also the energy intake from the grid. In return, this can result in cost-savings from a financial perspective.

The amount of energy produced on-site needs to be recorded and examined in order to carefully balance it with the power acquired from the grid. Influencing factors on this ratio and the respective supply strategy can be the grid electricity mix and related CO_2 emissions, the costs for electricity from the grid versus compensation for electricity fed into the grid, or the grid stability [11].

Measuring the performance of on-site energy generation requires specific assessment methods. As an example, an assessment for cogeneration should reflect the energy efficiency improvement on the one hand but also represent the optimum balance between on-site power generation and purchase from the utility on the other hand. Moreover, the adaption to demand changes from production should be reflected.

2.2. KPIs for Sustainability Assessment

Traditional KPIs in manufacturing generally emphasize criteria related to cost, time, and quality. Further supplements added dimensions like delivery time, safety, and risk assessment [e.g. 12-14]. With increasing awareness for energy-related costs as well as environmental impacts, companies focus more and more on indicators measuring their energy efficiency in particular. Goals are the reduction of product or factory carbon footprints and the identification of companywide improvement potentials to reduce energy losses and costs [15].

KPIs for the assessment of energy efficiency have at first been reviewed and discussed by Patterson. The focus is on (physical-) thermodynamic and economic indicators with respect to their applicability at the policy level [16]. Tanaka also addresses energy efficiency performance measures for policy but directly addresses the industry sector. KPIs such as absolute energy consumption, energy intensity, diffusion of specific energy-saving technology, and thermal efficiency are evaluated in regards of their reliability, feasibility, and verifiability [17]. Bunse et al. focus on energy efficiency in manufacturing and specifically on the integration of efficiency metrics in production management. It is stated that a low status of energy management and, consequently, lacking data for efficiency measure payback calculations are a barrier to energy efficiency. Energy efficiency KPIs and benchmarking systems are identified as industry needs for future research [18]. The importance of benchmarking KPIs for monitoring the performance and deriving improvement potentials is emphasized by Lindberg et al. who recommend to identify process signals that are strongest correlated with the KPI for process improvements. In addition to energy KPIs, further indicators as for raw material, operations, equipment etc. are considered [19]. May et al. have the objective to support companies in the development of energy-based performance indicators to overcome identified gaps such as difficulties in benchmarking or the lack of guidelines and well-developed energy management tools. The proposed 7-step method [20] is on the one hand comprehensive but on the other hand very complex. This might be a barrier to implementation especially in smaller companies.

It is obvious that the implementation of suitable KPIs for measuring energy efficiency is indispensable. However, KPIs need to be adjusted to company structures and manufacturing conditions to be most effective. The successful application of a KPI depends on its continuous measurability. Furthermore, data accuracy together with its availability in a timely manner is also important to calculate indicators on a regular basis. In order to compare current and target state, every KPI needs to be unambiguous regarding its expressiveness and should be assigned to a certain person or department responsible for reporting to higher management levels. Therefore, a generalized approach to categorize KPIs and to systematically develop KPIs is required.

3. Development of KPIs for Energy Efficiency Assessment

The proposed methodology for development of suitable energy efficiency KPIs is characterized by two parallel processes. As visualized in Figure 2, both processes interact with each other during the entire development period. The design process focuses on the creation of new indicators by following a predefined series of necessary steps. Simultaneously, the prevailing data souring strategy needs to be analyzed with regards to the availability, collection and storage of data required to run the KPI system most effectively. The following sub-sections focus on the design process and broach the issue of their calculation and validation. The data sourcing process is exemplarily illustrated in the subsequent industrial case study.

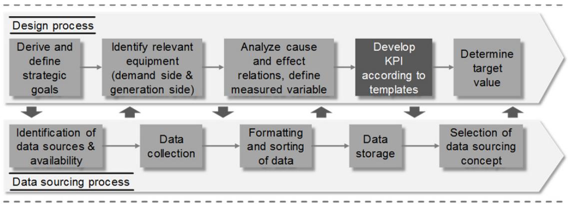

Fig. 2: Processes for KPI development

3.1. Design process for key performance indicators

As a KPI system is in general supposed to track a company's performance in the respective area of focus. Hence, the first step contains the analysis of the super ordinate company strategy and goals. This is the basis for the derivation of detailed objectives with a focus on energy efficiency which motivate and justify the KPI system.

In a next step, processes and more importantly the relevant equipment in regards of energy efficiency have to be identified. This includes on the one hand the manufacturing equipment on the energy demand side. Prioritization strategies such as the application of energy portfolios [21] should be employed to focus on the most relevant energy demanding processes. On the other hand, the supply side requires careful consideration. This includes all forms of energy acquired from the grid and also the company's energy generation facilities that are located on-site.

In order to successfully create new KPIs, it is crucial to analyze and understand the underlying cause and effect relationships as well as interdependencies between processes, equipment, and energy efficiency. Once these are fully understood, concepts for monitoring and tracking energy efficiency strategies and measures can be developed. As part of this step, measured variables need to be defined which represent key parameters and reflect the cause and effect relations. At this point, a close link to the data sourcing process is important because data availability and measurability for such parameters are important prerequisites for the following step.

On the basis of these preliminary assessments, the actual KPI development can be performed. As the super ordinate company strategy has to be broken down to hierarchical goals for the different management and factory levels, the KPIs have to suit these levels. Four different levels (factory, process line, machine, product) should be distinguished during the design process. KPIs on factory level are recommended in particular to gain a holistic view, including major interactions between departments, total energy consumption and related expenses or the overall performance. In contrast, indicators on product or machine level enable a more detailed assessment of the energy consumption and costs per manufacturing step. In addition, the evaluation on process line level provides the opportunity to compare similar processes and adjust the on-site power plant together with the production program. The interactions between these different levels should generally be considered during KPI development. To facilitate the KPI development process, a set of templates for five KPI types is provided. The templates can easily be adapted to suit the needs of individual companies. Their calculation is described in detail in sub-section 3.2.

- Type 1: Energy […] per […]
- Type 2: Site energy […]
- Type 3: On-site energy efficiency or efficiency increase
- Type 4: Improvement or savings of energy […]
- Type 5: Total value of energy […]

To close the loop towards the definition of strategic goals in the first step of the design process, the last step focuses on the determination of target values for the newly developed KPIs. This enables company management to effectively track results of implemented energy efficiency measures.

3.2. Templates for the generic calculation of KPIs

TYPE 1 KPIs describe energy costs, consumption or share related to a specific quantity. Depending on the level of detail, this could refer to a single unit and product or machine, process line, and so on. At this point, it has to be clarified that energy share is defined as the respective amount of energy provided per source, such as electricity from the grid, natural gas or solar power to state only some of them. In brief, this method facilitates the establishment of various KPIs on different management levels along with the required resolution. After choosing the correct formula for the developed indicator, a pre-selection of the required information input has to take place before performing the calculation properly. Therefore, several alternatives are provided to pick the matching calculation path as shown in Figure 3, according to the company's data availability and measuring instruments installed.

TYPE 2 KPIs (see Fig. 4) can be established by directly extracting data from monthly bills at best. As long as this path is used for calculating overall energy costs on site level, the invoice's values solely need to be summed up. In general, this indicator aims at measuring overall energy costs, consumptions, shares and CO_2 emissions from a holistic point of view. Thus, it is mainly designed to support top management in running and aligning the business operations in a sustainable way. Moreover, a rough calculation and multiplication of the energy peak demand and its related peak prices helps to estimate potential cost savings.

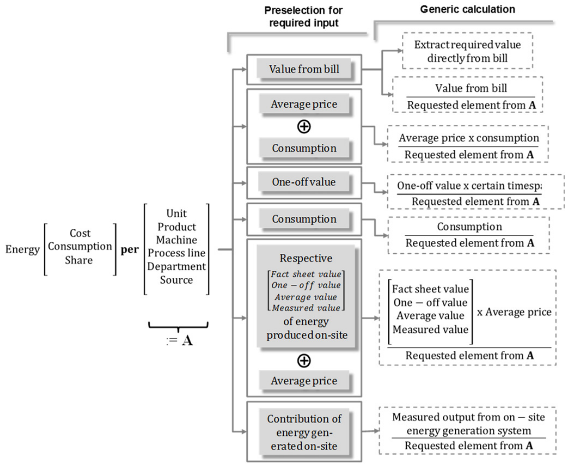

Fig. 3: Calculation method KPI Type 1

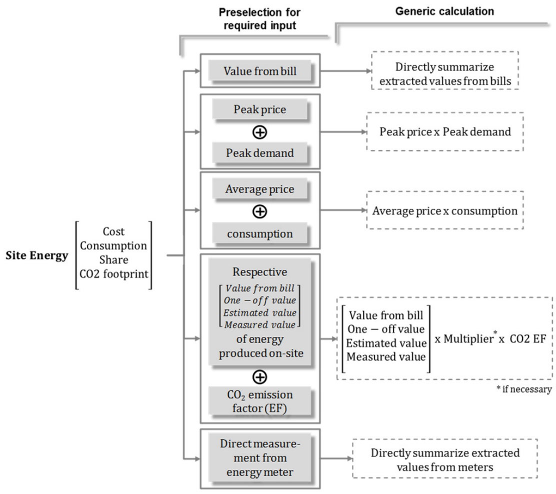

Fig. 4: Calculation method KPI Type 2

As already mentioned, this generic calculation aims at a holistic evaluation on site level. In this context, taking a closer look at an interrelated method is worthwhile to examine the ratio of energy produced locally versus power obtained from the grid. To calculate this indicator, the respective values of both contributions are required first. Subsequently, each share is divided by the total sum of self-produced and purchased energy as depicted in Figure 5. This indicator's purpose is primarily to highlight the proportions of energy acquired and generated on-site.

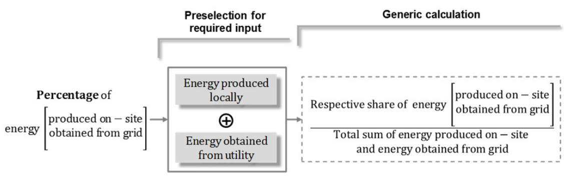

Fig. 5: Interrelated calculation method KPI Type 2

TYPE 3 KPIs focus on the efficiency of equipment installed. Therefore, the produced energy output is divided by the necessary input, mostly in forms of natural gas and/or electricity from the national grid. In general, it would be most significant if measured on a daily basis. Especially when taking a closer look at trigeneration plants, the consideration of conversion factors is crucial for a valid calculation of its efficiency. Against this background, defining a target unit is essential, e.g. in Gigajoule, so that each term of the equation can be converted by using the appropriate multiplier or conversion factor respectively. As shown in Figure 6, enhancing efficiencies is of interest particularly for purpose-built on-site energy generation systems. The applicable generic formula rests upon a quotient consisting of the value from a current time slot in the numerator and the corresponding period from a previous month or year in the denominator. Moreover, both values of the quotient can be calculated in relation to a basic parameter. In order to get the accurate percentage value, the quotient's result needs to be subtracted from the figure one before being multiplied by 100. Depending on the outcome's positive or negative algebraic sign, an efficiency increase or decrease is indicated accordingly. In line with superior environmental objectives, this KPI can be implemented on factory level or on machine level to reflect the efficiency.

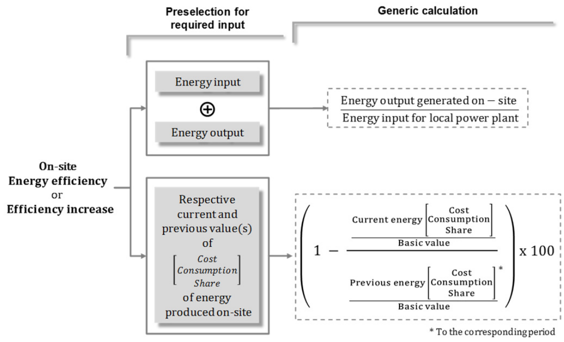

Fig. 6: Calculation method KPI Type 3

TYPE 4 KPIs (see Figure 7) describe the improvement or savings of energy costs, consumption or the equivalent share. To quantify advancements due to local power generation, a comparison between values from the current period to the previous period is drawn. This KPI type might be of importance for operational management in particular to determine energy savings in line with the manufacturing demand on a daily or weekly basis. To display cost and consumption savings on process line or factory level with a new KPI, the second formula provides the opportunity to compare the post-installation energy usage with the so-called baseline usage. To determine the baseline, historic data is helpful to assess the original energy demand before the implementation of additional on-site power plants took place. The parameter 'adjustments' might have to be included into the calculation to represent further impacts such as higher manufacturing load or varying operating hours.

TYPE 5 KPIs (see Figure 8) reflect the fact that companies might have several systems implemented to self-generate power. This indicator type summarizes costs, consumptions or the application's contribution to display the respective amount of energy generated on-site. It is mainly designed to serve on factory and process line level in order to align the daily energy mixture according to internal and external influences. As an example, changing weather conditions could result in obtaining more electricity from photovoltaic panels while the intake from the national grid is reduced at the same time.

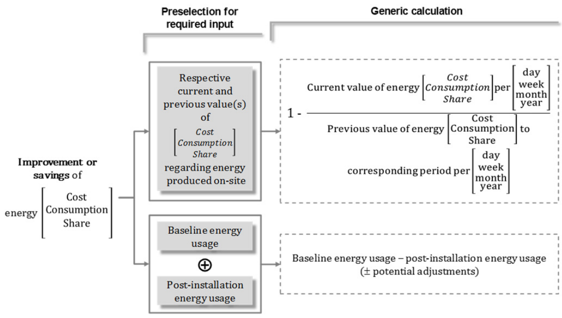

Fig. 7: Calculation method KPI Type 4

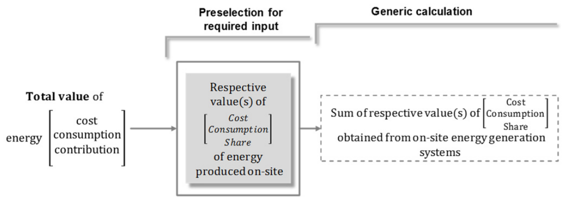

Fig. 8: Calculation method Type 5

3.3. Validation of generic calculation

Before implementing developed KPIs, their accuracy has to be validated first. Thus, final plausibility checks guarantee that the selected metric is applicable and supportive to reach strategy-related targets. This procedure, visualized in Figure 9, is essential to avoid misinterpretations, unwanted redundancies, obscurities or failure. The validation also verifies the quality of each developed KPI in terms of its benefits for decision-making on different management levels.

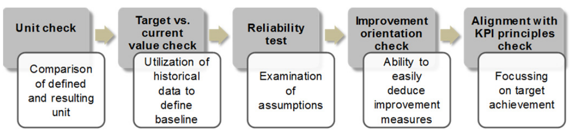

Fig. 9: Procedure for validating the KPI's calculation

The first check inspects the KPI's resulting unit. A thorough analysis of units, conversion factors and multipliers applied might help to reveal inconsistencies in case both units differ. The second check is based on a comparison between the desired and current value of the new indicator. In order to set the baseline in accordance with the as-is situation, using historical data could be helpful as an initial reference. In this context, the examination of the indicator's reliability is vital to present the measured performance correctly. The reliability takes into consideration the necessary assumptions which have to be made while creating the KPI. In general, an indicator can be regarded as reliable if only a few minor assumptions are necessary in advance. This also accounts for data and further information provided for the chosen computational logic. Another important aspect is the indicator's improvement orientation. Consequently, the validation process should analyze the indicator's ability to easily deduce potential improvement measures along with related fields of action to enhance the company's performance and energy efficiency on various levels. Last, a final check is conducted based on major principles outlined in sub-section 3.1. Especially the KPI's alignment with specific or overall objectives is of interest to verify if target achievement is realistic. Admittedly, no clear guidelines can be provided for these checks due to the multitude of derivable KPIs from the templates.

4. Industrial Case Study

The methodology of developing and employing a KPI system has been conducted for a company from the healthcare sector. Figure 10 illustrates the principal process chain with demanded energy inputs and the TBS system. Characteristic for the company is their on-site trigeneration system with two 1 MW natural gas-driven electric generators that provide power for the whole manufacturing plant. Further locally produced electricity derives from photovoltaic panels supplying the headquarter building.

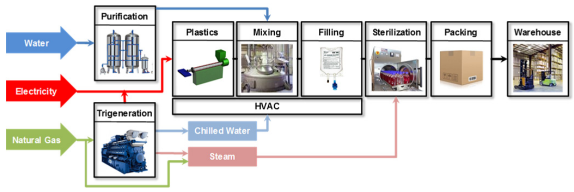

Fig. 10: Energy and material flows in case company

14 sustainability-related KPIs have been developed according to the described methodology with its KPI templates for the case company. These are listed in the following whereas Table 1 provides detailed insight on the calculation method for selected KPIs.

- Energy costs per carrier
- Energy costs per kL produced
- Energy share by carrier
- Energy consumption per kL produced
- Energy consumption per energy carrier
- Corporate carbon footprint
- Total water consumption per term
- Steam KPI [kg/kL produced]
- Trigeneration efficiency [%]
- Output [L produced]
- Water usage KPI [L of production water / L produced]
- Electricity used from on-site energy generation [%]

- Energy improvement to the corresponding month of the previous year [%]
- Throughput improvement to the corresponding month of the previous year [%]

Table 1. Details about selected developed KPIs.

KPI name	Type	Calculation	Level
Energy costs per kLp	1	energy costs by type / kilolitres produced	Factory
Energy consumption per kilolitre produced	1	energy consumption / kilolitres produced	Factory
Energy consumption per energy carrier	1	directly taken from monthly invoices	Site
Electricity used from on-site energy generation	2	(electricity produced by trigen. + PV) / (sum of electricity produced on-site + electricity purchased for MFG, HQ, Admin, Pharma)	Site
Trigeneneration efficiency	3	(Electricity produced + HRSG output + absorption chiller) / (generators gas consumption)	Machine
Energy improvement to the corresponding month of the previous year	4	1-((sum of energy purchased in curr. month) / (sum of energy purchased in corresponding month of prev. year))	Site

The developed KPIs help plant management and operating staff to effectively track current developments regarding the company's goals for cost- and eco- efficiency improvements of the on-site energy generation systems. However, it has to be stated that the data availability is partly insufficient to establish more detailed KPIs especially for the machine level. This comes due to a lack of energy meters on single aggregates. Nevertheless, the presented set of KPIs has already laid the basis for deriving improvement potentials and for monitoring the results.

5. Conclusion and Outlook

A rising number of companies make use of on-site energy generation systems. A comprehensive methodology for developing KPIs to assess their efficiency and further related sustainability goals has been developed and successfully employed in a case company.

Perspectively, the significance and fields of applicability of the developed KPI system could be extended, if a denser network of energy meters is installed on the machine level. A live visualization might enable staff to adapt machine operations to the availability of renewable energies in order to save costs and reduce emissions that are related to energy from the grid.

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References

[1] United nations conference on climate change 2015. http://www.cop21.gouv.fr/en/; accessed 2015-12-17.

[2] Bundesministerium für Wirtschaft und Energie. Energiedaten: Gesamtausgabe. 2015. https://www.bmwi.de/BMWi/Redaktion/PDF/E/energiestatistiken-grafiken.

[3] Yoon H-S, Kim E-S, Kim M-S, Lee G-B, Ahn S-H. Towards greener machine tools – A review on energy saving strategies and technologies. Renewable and Sustainable Energy Reviews 2015 (48); 870-891.

[4] United States Environmental Protection Agency (EPA). On-Site Renewable Energy Generation. 2014. http://www3.epa.gov/statelocalclimate/documents/pdf/OnSiteRenewables508.pdf.

[5] Ghadimi P, Kara S, Kornfeld B. Renewable energy integration into factories: Real-time control of on-site energy systems. CIRP Annals-Manufacturing Technology 2015.

[6] Australian Institute of Energy. How Do Wind Turbines Work?. 2004. http://www.aie.org.au/AIE/Documents/FS7_WIND_ENERGY.pdf; accessed 2015-12-17.

[7] Clark J. The Trigeneration Data Center: What is it?. 2012. http://www.datacenterjournal.com/facilities/the-trigeneration-data-center-what-is-it/; accessed 2015-12-17.

[8] Dougherty D. Energy Efficiency, Geothermal Heat Pumps and "Negawatts". 2013. http://www.renewableenergyworld.com/rea/news/article/2013/01/energy-efficiency-geothermal-heat-pumps-and-negawatts; accessed 2015-12-17.

[9] Office of Energy Efficiency & Renewable Energy. Geothermal FAQs. 2015. http://energy.gov/eere/geothermal/geothermal-faqs; accessed 2015-12-17.

[10] IEA - International Energy Agency. Biomass for Power Generation. 2007. http://www.iea.org/publications/freepublications/publication/iea-energy-technology-essentials-biomass-for-power-generation-and-chp.html; accessed 2015-12-17.

[11] Herrmann C, Kara S, Thiede S, Luger T. Energy Efficiency in Manufacturing–Perspectives from Australia and Europe. Proceedings of the 17th CIRP International Conference on Life Cycle Engineering (LCE 2010), Hefei, China (pp. 23-28).

[12] Ahmad MM, Dhafr N. Establishing and improving manufacturing performance measures. Robotics and Computer-Integrated Manufacturing 2002; 18(3–4); 171-176.

[13] Chen CC. An objective-oriented and product-line-based manufacturing performance measurement, Int J Production Economics 2008; 112(1); 380-390.

[14] Li W. Risk assessment of power systems: models, methods, and applications. John Wiley & Sons 2014.

[15] Chen D, Schudeleit T, Posselt G, Thiede S. A State-of-the-art Review and Evaluation of Tools for Factory Sustainability Assessment, Procedia CIRP, Volume 9, 2013. p. 85-90.

[16] Patterson, MG. What is energy efficiency?: Concepts, indicators and methodological issues. Energy Policy 1996; 24(5); 377-390.

[17] Tanaka K. Assessment of energy efficiency performance measures in industry and their application for policy. Energy Policy 2008; 36(8); 2887-2902.

[18] Bunse K, Vodicka M, Schönsleben P, Brülhart M, Ernst FO. Integrating energy efficiency performance in production management – gap analysis between industrial needs and scientific literature. J Cleaner Production 2011; 19(6–7); 667-679.

[19] Lindberg, CF, Tan S, Yan J, Starfelt F.. Key Performance Indicators Improve Industrial Performance. Energy Procedia 2015; 75; 1785-1790.

[20] May G, Barletta I, Stahl B, Taisch M. Energy management in production: A novel method to develop key performance indicators for improving energy efficiency. Applied Energy 2015; 149; 46-61.

[21] Thiede S, Bogdanski G, Herrmann C. A Systematic Method for Increasing the Energy and Resource Efficiency in Manufacturing Companies. Procedia CIRP 2012 (2); 28–33.