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Comprehensive Assessment of Energy Efficiency within the Production Process

S. Kreitlein, N. Eder, A. Syed-Khaja, J. Franke

Abstract**—**The importance of energy efficiency within the production processes increases steadily. For a comprehensive assessment of energy efficiency within the production process, unfortunately no tools exist or have been developed yet. Therefore the Institute for Factory Automation and Production Systems at the Friedrich-Alexander-University Erlangen-Nuremberg has developed two methods with the goal of achieving transparency and a quantitative assessment of energy efficiency namely EEV (Energy Efficiency Value) and EPE (Energetic Process Efficiency). This paper describes the basics and state-of-the-art as well as the developed approaches.

Keywords**—**Energy efficiency, energy efficiency value, energetic process efficiency, production.

I. Introduction

THE importance of energy efficiency is steadily increasing in our everyday lives [4], [5]. There are several helpful tools at the disposal of the consumer for the support in purchase decisions. For example the EU energy label and CO_2 efficiency classes for cars [3], the labeling system for energy-efficient office equipment (EU Energy Star) [2]. These tools offer a possibility for users to assess up to what extent a product is energy efficient during its use. But can these tools estimate the efficiency during a production process and support in the cost assessment of a product and its environmental impact? Until today, no tool exists for a comprehensive assessment of energy efficiency during production processes. Such a tool or appliance, however, is definitely necessary. Due to the shortage of energetic resources, aspects of environmental protection, social as well as political demands faced by the industry and not least due to the rise of energy prices [2], it will be inevitable to have clarity about the energy efficiency during the production. Thus a relevant competitive advantage can be achieved. The theoretical objective would be to be able to compare two different products such as a multi-outlet power strip with a puncher concerning their energy efficiency within the production process.

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II. Basics and State–of-the-Art

A. Energy Efficiency

The DIN EN ISO 9000:2005 defines efficiency as follows: "the relationship between the result achieved and the resources used." Following this standard definition, energy efficiency represents the ratio of consumed energy (e.g. kWh) to the generated benefits (e.g. units produced or value). It corresponds to the productivity that describes the ratio of produced goods (output) to the consumed production resources (inputs) [6]. Another possibility for the definition of energy efficiency is the ratio of the real productivity to the ideal productivity. Here, the question is answered of how the actual produced goods (e.g. the amount) correspond with the defined energy input, i.e. the possible number under ideal conditions [8].

B. State of Research: "Cross-Efficiency Comparison"

After extensive research, it can be stated that the subject of cross-comparison of energy efficiency has not yet been explored. Only peripheral areas of this topic, such as the comparison of the same processes based on energy indicators in different companies in terms of energy efficiency have been addressed. These include the reports on "energy performance indicators for company comparisons" and "determination of energy indicators for plants, manufacturing processes and products." [11], [12]

The problem of the critical comparison of energy performance indicators is stated in the literature with the following different initial situation. [16] There are different operation-dependent factors concerning the process sequences ranging from the size of the plant to the quality of raw materials. Furthermore the balance area for the collection of energy data must be accurately delineated. Due to the wide range of enterprise specifics it is rather difficult to find two comparable partners where parameters and system boundaries are identical [12]. As of yet, there are no relevant performance indicators known that permit a cross and transferable energy comparison to implement possible energy efficiency benchmarking. [9]

C. Potential of the Project

From a business perspective, the possibility of cross-comparing and evaluating the energy efficiency in the production of technical products offers three main aspects in order to increase a company's success as follows: 1. The identification of units with low energy efficiency, 2. The derivation of optimization measures, and 3. The marketing or advertising by means of a climate and environmental protective argument.

All of these aspects require the implementation of the energy efficiency comparison as well as the subsequent disclosure of the results to several industry partners. Additionally, concerning the second aspect, an agreement for the analysis of the most energy-efficient production must take place in order to identify and analyze the key factors.

III. Requirements

A method being able to measure energy efficiency has to fulfil several requirements. These requirements as shown in Fig. 1 can be split up into three groups and are explained in the next paragraphs:

1. Fundamental requirements (A. – E.)
2. Requirements to ensure comparability across the actual energy efficiency (F. – J.)
3. Requirements for the operational applicability of a method assessing energy efficiency (K. – R.)

A. Based on a Model

High complexity can be controlled through the use of models. Therefor energetic relationships can be analyzed and assessed comprehensively. [7]

B. Consideration of Peripheral Systems

For the comprehensive assessment of energy efficiency it is not enough only to considering the particular machine centers, but peripheral systems also often have a huge influence on energy consumption as well as energy efficiency. [7]

C. Development of a Rating System Based on KPIs

It is necessary to evaluate the process based on Key Performance Indicators. This can be used as a basis for the assessment of optimization potential. [7]

D. Integration of Field Data Compilation

Field data has to be integrated in order to guarantee the use of correct date. [7]

E. Basis for Optimization

A pure assessment of energy efficiency is desirable. However, a derivation of aspects for optimization provides a bigger potential for the implementation of energy efficiency rating systems. [7]

According to studies performed at the Institute for Factory Automation and Production Systems (FAPS) at the University of Erlangen-Nuremberg, the above-mentioned requirements are not sufficient. Further requirements to ensure comparability across the actual energy efficiency are necessary:

F. Comprehensive Measurability of Energy

Energy exists in various forms, e.g. elevation energy, kinetic energy, thermal energy, radiant energy, chemical energy or electric energy. In order to assess energy efficiency comprehensively it is essential to consider all involved energy consumers. For this purpose appropriate instruments are needed.

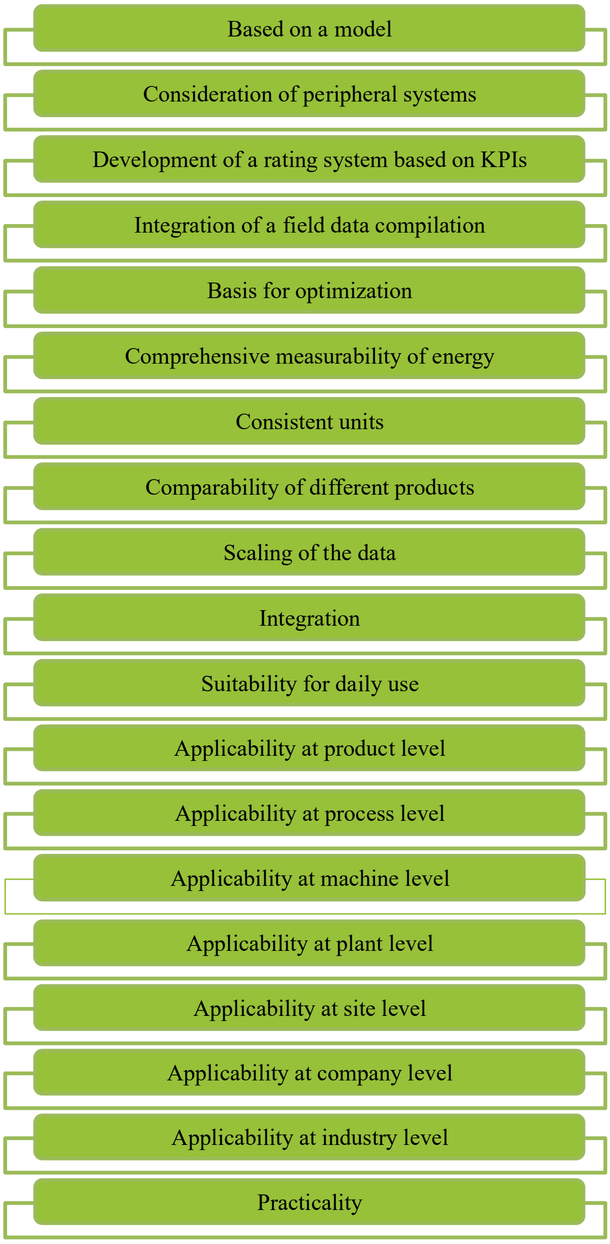

Fig. 1 Requirements for a method comprehensively assessing energy efficiency in a production process

G. Consistent Units

A good method for the assessment of energy efficiency has to be able to include primary energy carriers as well as electricity, compressed and radiant energy. For a correct determination of energy efficiency it is inevitable to convert all energy sources into a particular unit: kWh. This guarantees the comparability of different processes.

H. Comparability of Different Products

The aim of the method should be to compare different products in terms of the energy efficiency of their production process.

I. Scaling of the Data onto Different Levels (e.g. Product, Plant, Process)

Energy efficiency has to be measureable on the product-level. However, the energy-efficiency of an entire production process or even a production plant is very interesting and provides the basis for optimization. Furthermore, it has to be possible to scale the data onto different levels such as location, company, and industry.

J. Integration & Suitability for Daily Use

The method has to be suitable for daily use in any case and should be integrated into the daily production process.

Next to the above-mentioned requirements a third group is necessary to ensure the operational applicability of a method assessing energy efficiency.

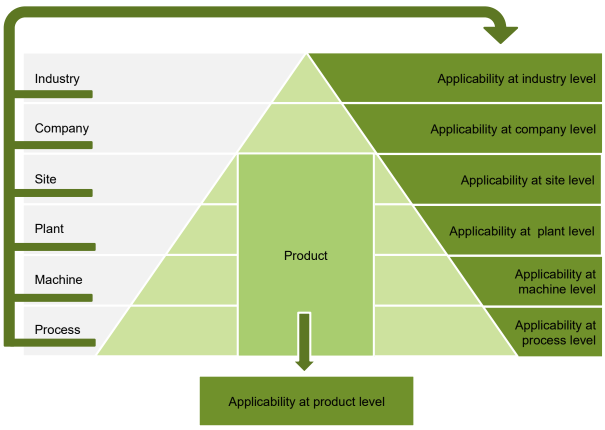

Fig. 2 Operational Applicability

K. Applicability at Product Level

It has to be the overall aim to be able to compare the energy efficiency of the production process of different products. But, however products of the same type can be produced using different manufacturing processes, which significantly affect the energy consumption and accordingly contribute to energy efficiency. Consequently a method for the comprehensive assessment of the energy efficiency has to provide a comprehensive comparison at product level [9], [10].

L. Applicability at Process Level

Different production processes, e.g. milling or joining, should be comparable despite different process parameters. The VDI (the Association of German engineers) claims within their guideline 4661 whether the considered method allows comparing the energy efficiency of different processes. [14]

M. Applicability at Machine Level

Furthermore, methods or KPIs are supposed to be useful at plant level as well. Even when using the same production processes, the use of different machines can have a high impact on the energy efficiency. Consequently it is necessary to be able to apply the method on different machines. [14]

N. Applicability at Plant Level

Many companies produce the same product at different production sites. Often, different production technologies or production processes are used. Therefore the method for assessing the energy efficiency should provide a comparison also on plant level. [9]

O. Applicability at Site Level

Different aspects such as e.g. environmental factors can have a high impact on the energy efficiency during production.
This leads to different energy efficiency at different sites – even if the same products are produces. [9]

P. Applicability at Company Level

Products can be produced using different tools, processes, machines, at different plants on different sites. At the moment companies struggle measuring energy efficiency comprehensively. Consequently a method for the comprehensive assessment of energy efficiency is supposed to be applied at company level. [9]

Q. Applicability at Industry Level

The goal is to develop a method being able to compare different industries concerning their energy efficiency.

E.g. it should be possible to make a statement saying company B from industry sector 1 produces more energy efficient product compared to company C from industry sector 2 as in Fig. 3.

R. Practicality

To ensure the operational applicability it is inevitable to ensure the practicality of the methods.

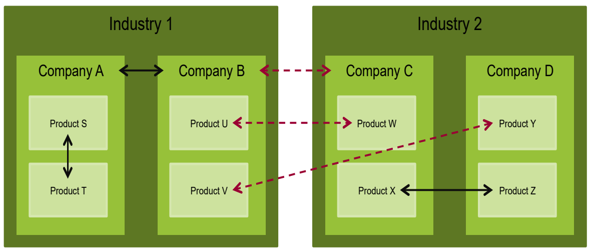

Fig. 3 Applicability at Industry Level

IV. Solution

To comprehensively assess energy efficiency within the production process, the above mentioned requirements should be fulfilled. Within a research study at the Institute FAPS two main approaches have being evaluated as being productive namely the so-called bottom-up (base: praxis) approach and the top-down approach (base: theory) as described in Fig. 4. Each of them leads to a method that can be used for assessing energy efficiency.

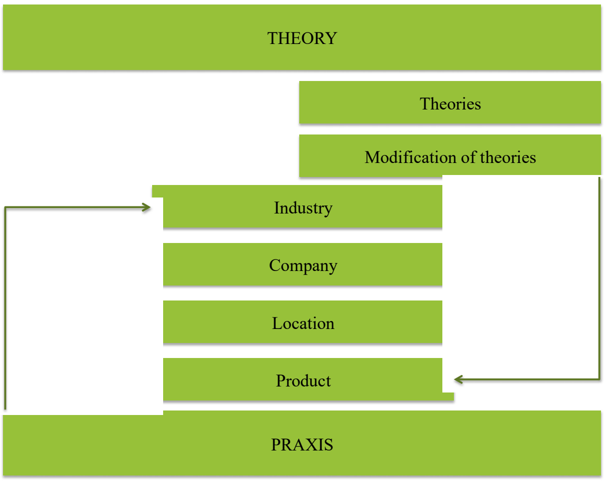

Fig. 4 Bottom-up and top-down approach

A. Bottom-up Approach

The bottom-up approach uses the following assumption,: 'if energy efficiency can be measured and compared regarding different products, it is supposedly to be possible to aggregate/ transfer this procedure onto other levels, such as a department, a production site, a company or even a whole industrial sector'.

Consequently it is inevitable to firstly assess energy efficiency at the product level and second to develop an approach for the transfer onto the other levels, see Fig. 5.

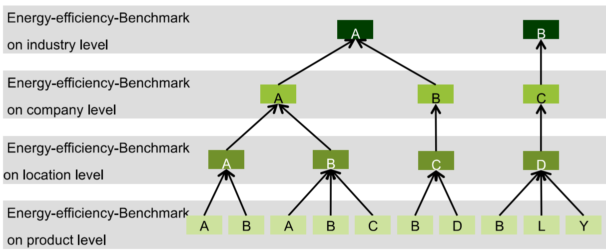

Fig. 5 Bottom-up Approach

This approach is based on the following assumption: 'if a system can be developed that allows for the comparison of different products in terms of energy efficiency in the production, then the procedure can be aggregated or transferred onto other levels (i.e. site, business, and industry)'.

A research study at the Institute FAPS has developed a concept for measuring energy efficiency on the product level, i.e. the Energy Efficiency Value (EEV).

B. Top-Down Approach

The second approach starts from a different perspective, namely that, theories from different areas (e.g. quality management, six sigma, Lean Production, etc.) might be able to help in developing a method that can be used to assess energy efficiency.

Based on this approach a research study at the Institute FAPS has tested more than 100 methods that are usually used within Six Sigma and Lean Production and put them into comparison with the above-mentioned requirements. This pre-selection showed that one method namely 'the process efficiency method' offers a very good base for transforming this method into a method being able to measure energy efficiency.

Compared to the available other methods/tools a modification of the Process Efficiency allows for a comprehensive assessment of energy efficiency within the production process.

V. Energy Efficiency Value (EEV)

The Energy Efficiency Value is a newly developed indicator within the E|Benchmark project in Green Factory Bavaria collaborative project in Germany. The core idea of this approach is the comparison and assessment of energy efficiency in the production of technical products based on the relation of the minimum required energy to the actually consumed energy. The procedure is divided into several sections. First, the calculation of the minimum energy required for the production of a product is performed. In the second step, the measurement of the energy consumed for manufacturing the product must be determined. This can be done with a measuring system connecting the system and the energy source. Finally, the theoretically calculated and actual consumed energy is set in relation. This results in the energy efficiency value. This value is between 0 and 1, where 1 represents the best achievable efficiency. However, in order to perform a cross-comparison, one further step depending on the desired viewing level must be performed (Fig. 6).

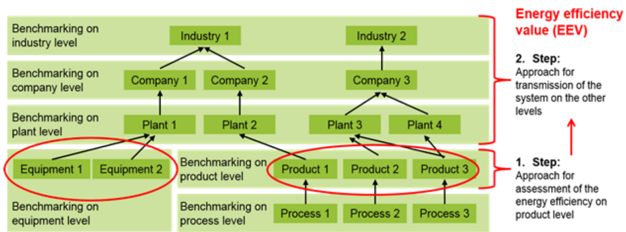

Fig. 6 EEV: Transmission of the system on other levels

If a comparison is planned at the plant level, the percentage of energy consumption per product on the basis of the total consumption of the plant has to be calculated. Next, the weighted EEV per product is calculated through multiplying the EEV with the percentage of energy consumption. By forming the sum of all weighted EEVs, the EEV is calculated at the plant level. [10]

A. Physical Minimum

The Energetic Physical Minimum (EPM) describes how much energy is required for chemical or physical laws to induce an intended transformation through a defined basic operation on or in the object under consideration. The physical minimum is calculated only on the basis of the specifications of the input and output material (E_m), (1). These assumptions are partly determined by the influence factor "environment," thus the factor "environment" is also included in this presentation. For example, the ambient temperature determines the temperature of the input material that has to be established for the calculation of energy consumption during melting. For the planned specifications of the input and output materials, an ideal quality has to be assumed.

$$EPM = \sum_{i=1}^{n} (E_m)_i \tag{1}$$

B. Technological Minimum

The Energetic Technological Minimum (ETM) describes the energy demand, which is minimally required to perform a basic operation by a technology. Here, the technology with which the transformation process is performed is also taken into account. From the chosen technology, consequently, the specific calculation method of the minimum value and the process specifications are determined. To calculate the minimum value, refer to (2) the optimization of all technological specifications (E_t) in terms of minimum energy consumption are required. However, the equipment-related losses are not yet taken into account.

For the implementation of a basic operation, usually different technologies can be considered. This will herein be explained in more detail using the example of the soldering process. The basic operation of melting the solder material is the heat input, which can be implemented by means of different technological processes. The heating may be affected by radiation, solid, gas, or liquid, as well as by the condensation of a vapor, infrared, or electrical induction. Depending on the selected type of heat input, the soldering technology as well as the calculation and the amount of the minimum value can be determined. [15].

$$ETM = EPM + \sum_{i=1}^{n} (E_t)_i \tag{2}$$

C. Real Minimum

The Energetic Real Minimum (ERM) describes the energy demand, which is minimally required to perform a basic operation by a technology with equipment. As the term "real minimum" illustrates – in addition to the calculated value – the minimal required energy demand for the implementation of a transformation process, with consideration of the state of the art, is described. The real minimum is an extension of the technological minimum of the equipment and is calculated by extending the calculated technological minimum to the losses of the equipment (E_e), refer to (3). In particular, the losses of efficiency for energy conversion have to be taken into account. For the calculation of the real minimum of the turning process, for example, the technological minimum has to be multiplied with the efficiency of the main drive axles for generating the rotating and feed motion. The technological minimum, in this case, is the required energy of the work piece for the clamping separation. To calculate the minimum value, the efficiency, which is maximally achievable under ideal conditions and by taking into account the state of the art, has to be chosen.

It is possible that the presented differentiation between technological and real minimum may not be clearly performed in all processes. If, for example, energy conversion losses have already been considered by calculating the technological minimum, then there is no separation of technological and real minimum.

$$ERM = ETM + \sum_{i=1}^{n} (E_e)_i \tag{3}$$

D. Combined Consideration and Action Recommendation

In Fig. 10 the stages of the minimum calculation are shown in the form of a shell chart which describes the influencing variables taken into account through the calculation of the minimum. The structure of the graph is divided into the following six shells (the core of the diagram is also termed "shell"):

- Shell 1: input and output material specifications
- Shell 2: selection of technology
- Shell 3: process specification
- Shell 4: equipment specification
- Shell 5: environmental influences
- Shell 6: measured energy consumption

The contents or influences of the inner shells are the basis for the outer shells. In each shell the considered factors or contents rise accordingly.

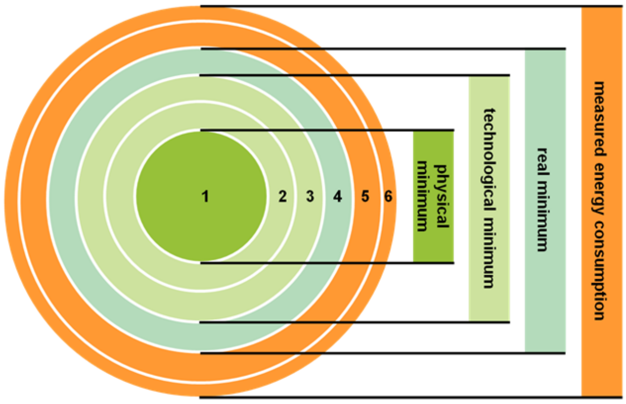

Fig. 7 Types of Minimum – Shell Chart

Its core consists of the specifications for the input and output material; these are material, geometry, state, quality, and position. Based on the specifications, the physical minimum is calculated. Shell numbers two and three determine the technological minimum. The general choice of technology, by which the transformation process has to be performed, is associated with the second shell. The method of calculation and the necessary process variables, which are symbolized by the third shell, are determined by the chosen technology. Shell four represents the energy losses that occur to the equipment during the technology implementation. If these losses are also included in the calculation, the real minimum can be determined. For the calculation of all kinds of minimum, assumptions have to be made regarding the environmental conditions, shown within the fifth shell. The measured energy consumption is determined by the actual existing conditions during the implementation and is symbolized through the outermost shell.

Generally speaking, for the calculation of the EEV, which should be used to compare and evaluate the energy efficiency of technical service provision, the minimum values of all three kinds of minimum can serve as a basis and can be set in relation to the energy consumption measured (ECM). However, the focus and the statement of the calculated EEV vary for each selected reference value:

- Basis Physical Minimum

If the physical minimum is put in relation to the measured energy consumption, the theoretically existing saving potential is demonstrated. It is expected that theoretical and measured energy consumption vary immensely. Operating a real production step, the physical minimum value is not reached.

$$EEV_P = EPM/ECM \quad (4)$$

- Basis Technological Minimum

An EEV with the technological minimum as a basis describes the losses due to the process specifications and the energy conversion. The technological minimum value is impossible to achieve in practice, since an efficiency of 100% percent is assumed in the energy conversion for calculation purposes.

$$EEV_T = ETM/ECM \quad (5)$$

- Basis Real Minimum

If the measured energy consumption is put in relation to the real minimum, the real saving potential is clarified. In contrast to the calculation of the technological minimum, a realistic efficiency of energy conversion is assumed in the calculation of the real minimum. The real minimum value is thus achievable during the performance of an actual production step under ideal conditions.

$$EEV_R = ERM/ECM \quad (6)$$

Therefore, it is recommended to use the real minimum value as basis for the calculation of the EEV for comparing and evaluating the energy efficiency of the technical service provision. This is justified by the fact that the EEV, based on the real minimum, focuses on the real saving potentials, which can be exploited if necessary. Furthermore, it can be assumed that the EEV varies less for different products, which increases their comparability and reduces the resignation threat that is expressed in negative outcomes.

For calculating the EEV of a product, the minimum value must be calculated and summed up for each production step. It then can be put into relation to the measured total energy consumption, which is calculated from the individual energy consumption per production step.

In order to ensure that the calculation of the minimum value is performed cross-product consistently, the method of computation and the relevant assumptions, which are necessary for the calculation, have to be defined depending on the type of transformation process. The following variables are established for each type of transformation process considering the requirements to the final product:

- environmental conditions (e.g. temperature)
- technology (e.g. shearing or laser beam cutting)
- process specification (e.g. feed)
- equipment specification (e.g. efficiency)

VI. Energetic Process Efficiency (EPE)

The Energetic Process Efficiency (EPE) is based on the modification of the process efficiency.

A. Basis: Process Efficiency

The Process Efficiency is described by the relation of value adding time to cycle time.

$$Process\ efficiency = \frac{value\ adding\ time}{cycle\ time} \quad (7)$$

The calculation of the process efficiency is divided up into four steps as shown in Fig. 8.

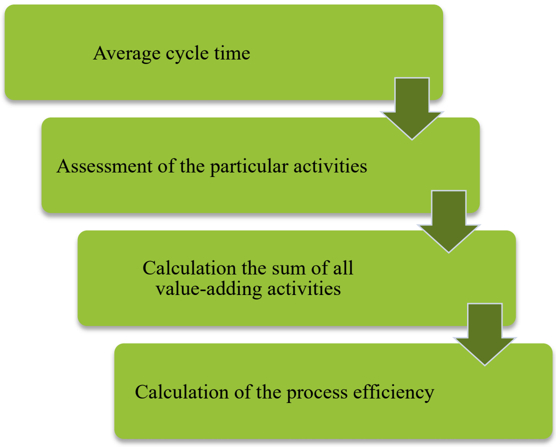

Fig. 8 Calculation of the Process Efficiency

At first, the cycle time has to be calculated. Afterwards the particular activities are assessed concerning the following: value adding, value enabling, or no value adding. According to the definition of process efficiency, only the value adding time is significant. To calculate the process efficiency above-mentioned formula is used. [13]

B. Modification

Based on the common Process Efficiency the time slices are substituted by energy.

$$Energetic\ Process\ Efficiency = \frac{Value\ adding\ energy}{Energy\ of\ a\ cycle}\ \% \quad (8)$$

Thereby it is possible to make a statement concerning the energy efficiency of the considered process. The strict separation into value adding, value enabling and no value adding has to be considered.

$$Value\ adding\ energy \quad (9)$$

$$= \textit{Measured energy consumption} - \sum \textit{Defficiency}$$
$$= \textit{Energy consumption during production}$$

Value adding energy is considered to be the energy used directly for the production process, thus equaling the measured energy consumption of the machine minus all appearing waste (equaling deficiency). Thereby value adding energy means the pure net energy being used for value performances.

$$\begin{aligned} &\textit{Energy of a cycle} \\ &= \textit{Energy for production} + \textit{Energy for transportatio} \\ &\quad + \textit{Energy for idle and waiting tim} \\ &\quad + \textit{Energy for adjustment} \\ &\quad + \textit{Energy for auxiliary processe} \\ &\quad + \textit{Energy for any additional processes} \end{aligned} \tag{10}$$

This calculation offers a comprehensive statement for a quantitative assessment of energy efficiency during the production process.

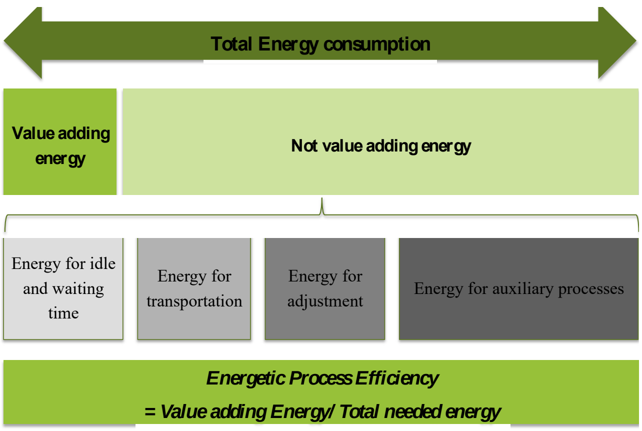

Fig. 9 Energetic Process Efficiency

C. Advantages

The Energetic Process Efficiency offers a method fulfilling all listed requirements:

1. Fundamental Requirements
- ✓ Based on a model
- ✓ Consideration of peripheral systems
- ✓ Development of a rating system based on KPIs
- ✓ Integration of a field data compilation
- ✓ Basis for optimization

2. Requirements to Ensure Comparability Across the Actual Energy Efficiency
- ✓ Comprehensive measurability of energy
- ✓ Consistent units
- ✓ Comparability of different products
- ✓ Scaling of the data onto different levels (e.g. product, plant, process)
- ✓ Integration & suitability for daily use

3. Requirements for the Operational Applicability of a Method Assessing Energy Efficiency
- ✓ Applicability at product level
- ✓ Applicability at process level
- ✓ Applicability at machine level
- ✓ Applicability at plant level
- ✓ Applicability at site level
- ✓ Applicability at company level
- ✓ Applicability at industry level
- ✓ Practicality

VII. Example

Above mentioned approaches, bottom-up as well as top-down, ended in one method each being able to use as a tool to measure energy efficiency within the production process. Both of these methods (EPE as well as EEV) have been tested for validation reasons.

The Research Association 3-D MID eV developed for demonstration purposes a demonstrator: the MIDster.

Fig. 10 MIDster [1]

The so-called MIDster, which is mainly produced at the Institute FAPS enables them to show the three key benefits of the MID technology: freedom of scope, economization and rationalization. [1]

Both methods, the Energy Efficiency Value as well as the Energetic Process Efficiency have been tested and validated for the MIDster. Due to this the applicability as well as practicality of the developed methods have been proofed.

VIII. Conclusion

For the future, it is absolutely necessary to know the energy efficiency of a production process as it enables companies to have a competitive advantage. It can be stated from the above mentioned methods, Energy Efficiency Value and Energetic Process Efficiency, two approaches have been developed for the assessment of energy efficiency of a production process.

Facing the decision concerning which of them to use in a given situation, the following recommendation can be given:

The EEV is based on an absolute minimum, which allows the user to compare different processes. Accordingly, the EEV is fixable by calculation. On the contrary, the EPE is the preferred suggestion for daily use, as less effort is needed for the calculations. It offers a great possibility to compare the energy efficiency of a production process over a given period of time. It is necessary to clearly specify the meaning of "value adding."

All in all this paper presents two different methods. The main difference is the reference value. EEV is calculated using an absolute reference value, which results in showing the theoretical potential for energy saving, however, it is more complex within its calculation. On the other hand side the EPE offers a great tool with less effort and good adaptability for a defined time range using a specifically created reference value. In the end, the decision, which one of these to use, depends on the goal of the person using it.

Acknowledgment

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FAPS – Institute for Factory Automation and Production Systems.
The Institute for Factory Automation and Production Systems (FAPS) was founded in 1982 under the supervision of Prof. Dr.-Ing. Klaus Feldmann as part of the newly established Production Technology field at Friedrich-Alexander-University Erlangen-Nuremberg (FAU). In 2009, Prof. Dr.-Ing. Jörg Franke took over management of the institute. The institute overarching objective is the integration of all the manufacturing factory functions for a comprehensive computer-integrated concept. FAPS - Friedrich-Alexander-University Erlangen-Nürnberg, Fuerther Str. 249, 90429 Nuremberg.