INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

DEVELOPMENT OF A SYSTEM FOR PRODUCTION ENERGY PROGNOSIS

Stetter, Ralf (1); Witczak, Piotr (1); Witczak, Marcin (2); Kauf, Florian (1); Staiger, Benjamin (3); Spindler, Claudius (1)
1: University of Applied Sciences Ravensburg-Weingarten, Germany; 2: University of Zielona Góra, Poland; 3: Kirchner Konstruktionen GmbH, Germany

Abstract

This paper, based on a current research project, describes the development of a system that addresses the issue of the prognosis of energy efficiency. The energy consumption in production is determined very early in the product development process by designers and engineers, for example through selection of raw materials, explicit and implicit requirements concerning the manufacturing and assembly processes, or through decisions concerning the product architecture. Today, developers and engineers have at their disposal manifold design and simulation tools which can help to predict the energy consumption during operation relatively accurately. In contrast, tools with the objective to predict the energy consumption in production and disposal are not available. This paper presents the development and realization of a system which is integrated in a commercial CAD system and supports an early evaluation of the energy spent during the production of a product.

Keywords: Design engineering, prognosis, Integrated product development

Contact:
Prof. Dr.-Ing. Ralf Stetter
University of Applied Sciences Ravensburg-Weingarten
Mechanical Engineering
Germany
ralf.stetter@hs-weingarten.de

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

This paper, based on a current research project, describes the development of a system that addresses the issue of the prognosis of energy efficiency. Today, the energy a product requires during its operation is the subject of many activities in research and development. However, the energy necessary for the production of goods is very often not analysed in comparable depth. In the field of electronics, studies come to the conclusion that about 80% of the total energy used by a product is from its production (Williams 2004). The energy consumption in production is determined very early in the product development process by designers and engineers, for example through selection of raw materials, explicit and implicit requirements concerning the manufacturing and assembly processes, or through decisions concerning the product architecture. Today, developers and engineers have at their disposal manifold design and simulation tools which can help to predict the energy consumption during operation relatively accurately. In contrast, tools with the objective to predict the energy consumption in production and disposal are not available. This paper presents the development and realization of a system which is integrated in a commercial CAD system and supports an early evaluation of the energy spent during the production of a product.

The structure of this paper follows. Section 2 summarizes the background and importance of this approach. In section 3 the state of the art is clarified and described. Section 4 explains the analytical approach toward energy consumption prognosis. The challenges and procedure of programming is described in Section 5. Section 6 describes example products which were analysed. The paper is summarized and an outlook is given in Section 7.

2 BACKGROUND AND IMPORTANCE

The energy necessary for the production of goods, e. g. the energy for raw material generation, for casting or for milling, can very often not be analysed in depth in early stages of product development processes., This is because current tools used for today's product development, such as geometry generating CAD tools (computer aided design tools), do not have the ability to support designers and engineers in this endeavour (Stetter et al. 2013, Stetter et al. 2014c). The energy consumption in production and disposal is determined very early in the product development process by designers and engineers, for example, through the selection of raw materials, explicit and implicit requirements concerning the manufacturing and assembly processes, or by decisions concerning the product architecture. Today, designers and developers must more or less "blindly" decide, because it is impossible in today’s industrial reality to predict the energy consumption in the production. It is hypothesized that intelligent tools and procedures, which allow a prognosis of the energy consumption in production, can shift the knowledge concerning production energy consumption into earlier phases and can increase the potential for energy savings (compare Bernard and Stetter 1997). It is, for instance, only possible to change the architecture of a product i. e. the logical arrangement, early in the conception phase. Similarly, if a raw part is made by casting or cutting, the decision has to be made very early in the process and has immense consequences concerning the energy necessary for production. Figure 1 shows a representation, which is based on similar representations in the area of early determination of product properties (compare Bernard and Stetter 1997), in which it is clearly recognizable that in the early phases of the product development, the energy consumption can be influenced significantly more through product changes and which also results in considerably smaller change costs.

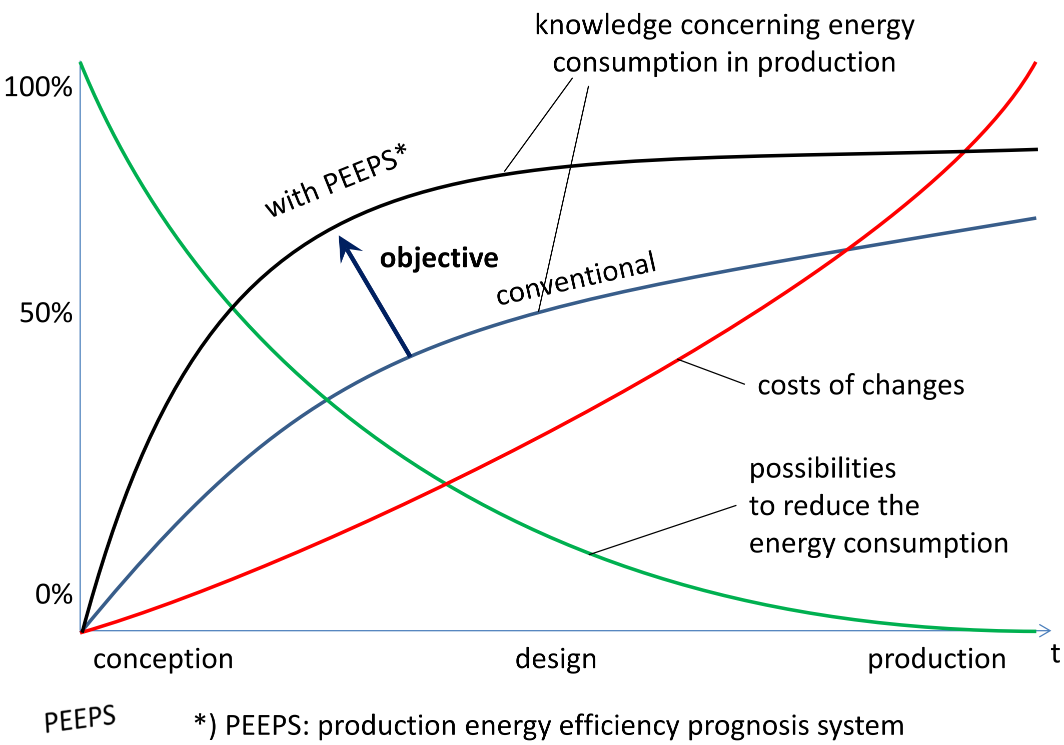

Figure 1. Early evaluation of production energy consumption (Stetter et al. 2014a)

The manufacturing and assembly processes of products consume a considerable amount of the overall energy consumed during the lifetime of a product, ranging from 20% for conventional products, such as cars (compare Schröder 2009), up to 80% for products with a large share of electronic components (compare Williams 2004). In the production of goods, several processes lead to the consumption of energy. Figure 2 lists the different sources of energy consumption in the production of parts together with possibilities to achieve a prognosis of this energy.

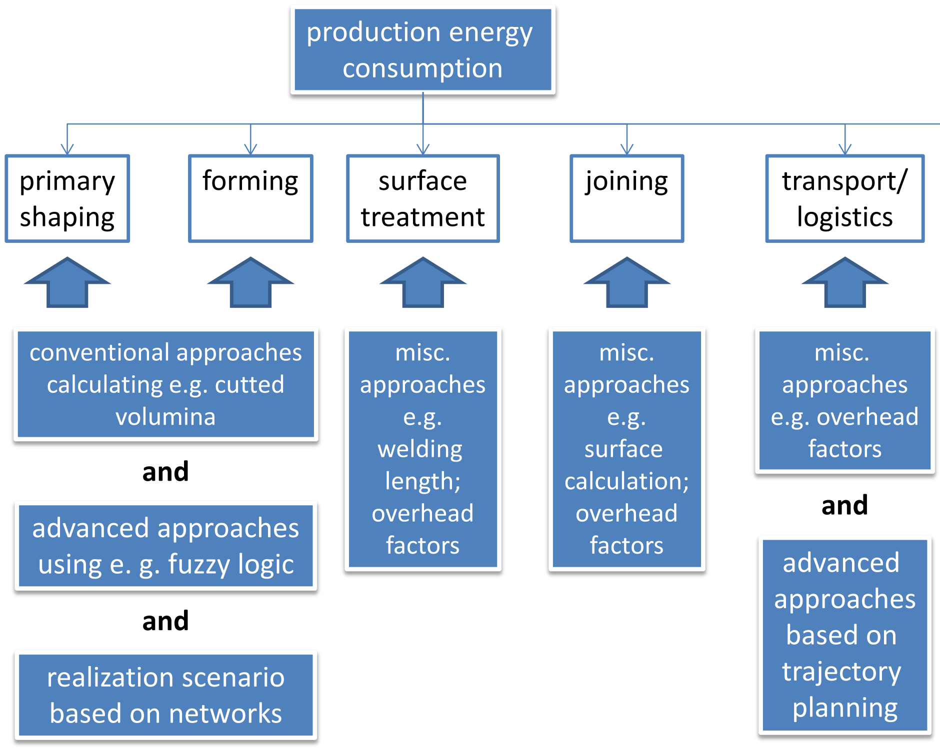

Figure 2. Sources of energy consumption and possibilities to achieve a prognosis

For typical manufacturing operations, conventional approaches can be applied, which are, for instance, based on the volume to be removed by a cutting operation. One example of how this approach is carried out is described in Section 4. The processes of surface treatment (e. g. painting), joining (e. g. welding) and logistics (e. g. transportation with vehicles of any kind) can be taken into consideration roughly by means of overhead factors estimating typical energies used in such processes. These approaches were realized in a software prototype, here referred to as PEEPS (Production Energy Estimation and Prognosis System).

In some cases, the application of prognosis methods can be complicated by the complexity of today's products. Alternatives to the purely analytical methods are approaches which are, for instance, based on fuzzy logic. Such approaches were explored in the underlying project together with realization scenarios based on work done through networks of engineers and companies (Stetter et al. 2014a).

A certain amount of the energy in production is spent on transportation processes. A promising possibility for a more refined energy prognosis of such processes is the application of trajectory planning methods in order to improve estimation capabilities; such approaches were also the emphasis of the underlying project (Stetter et al. 2014b).

The vision is that all investigated approaches can be combined in a future system, as all of them exhibit certain strength and weaknesses. The most straightforward approach, however, is based on the analytical approach described in section 4. The first prototype is based on this approach.

3 STATE OF THE ART

Numerous research activities belong to the state of the research in the area of eco design. Tischner et al. (2000) offer a good overview. In these activities, energy consumption plays usually a central role, and in the frame of the Life Cycle Assessment (LCA), the production is also considered as a part of the life cycle (for example, see Finnveden et al. 2009). Especially in this scientific area, the international standard ISO 14031 is to be cited, which supports a comprehensive judgment of the sustainability. Notable are the works of Herrmann et al. (2007) which connect the methodologies of the life cycle assessment, multi-criterion analysis and environment achievement indicators. In recent years, the so-called "exergie" has moved into the centre of interest as a central measurement means for sustainability (Coatanéa et al. 2007). Current works, such as Thompson et al. (2012), show first integrations of sustainability considerations and tools also into CAD systems, however, an integration is solely achieved by means of integrating check lists. A current project at the TU Chemnitz focuses on the IT support of energy sensitive product development. However, the main focus here is on the aspects of product data management (PDM) and Enterprise Resource Planning (ERP) (Reichel et al. 2010). Prior works, which also need to be considered, concern the integration of information about the energy consumption in the first production steps of the raw materials. The CAD systems Autodesk Inventor and Solidworks offer expansions which should allow the estimation of the resource consumption already in the design phase. The current version of Autodesk Inventor 2012 offers the expansion Eco Material Adviser, which, by means of an Internet-based database, can, amongst other possibilities, provide information concerning the materials, the raw material fabrication procedure, the energy consumption, the CO2-emission and the water consumption. The database is operated in collaboration with Granta design and includes information about 3,000 materials and selected fabrication procedures. Besides Inventor 2012, the current version of Solidworks also offers an expansion "Sustainability", which provides information concerning the CO2 emission and the energy consumption. The expansion "Sustainability" additionally offers the possibility to automatically find materials which combine more favourable environmental characteristics with similar mechanical and/or physical characteristics. Both systems mainly consider the final weight of the part; decisive aspects of the product geometry and product origin are not analysed in these systems.

4 ANALYTICAL APPROACH

Calculations of the energy consumption in the production can conventionally be based on certain volumes and/or the weights of the components or of certain sections of the components. For example, the milling volume for milling operations can be used in order to determine the energy necessary for this milling operation. Research in production technology these days can provide the necessary tables and equations to determine this energy, if only the milling volume and the milling operation are defined accurately enough (Stetter 2013). The geometry is developed today almost exclusively in three-dimensional CAD systems. In such systems, the volumes and weights of all components are available today; therefore, the extension is very promising to couple future systems with CAD systems. It is important to note that most of the current CAD systems (CREO, CATIA, NX, …; but excluding CoCreate) build up the products in a tree-like structure and add features to a certain "starting" geometry in order to achieve the final geometry. Usually, these features are representatives of manufacturing operations, e. g. a hole might be representative of a drilling operation. Therefore, these features are appropriate objects for analysing the energy necessary for certain manufacturing steps. Figure 3 elucidates this hypothesis, which is central for the research work described in this paper.

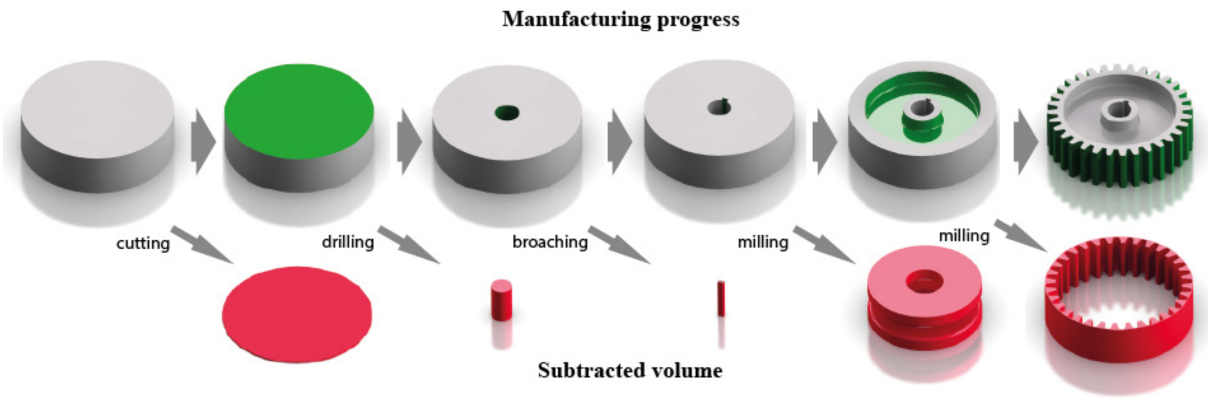

Figure 3. Feature based volume substraction

Many research works have described energies for certain manufacturing operations, such as drilling, milling and grinding. Very often, the resulting equations have a general form similar to equation 1 describing the ideal material removal energy (compare Deneka and Tönsdorf 2011):

$$E_c = k_{c1.1} \cdot \left(\frac{h}{h_0} \right)^{-m_c} \cdot \Delta V \tag{1}$$

with: $k_{c1.1}$ specific cutting force
m_c increase value
H chip thickness
ΔV removed volume

The energy for manufacturing is usually higher because of several sources of losses and additional processes which can be necessary or superfluous. The influence of these losses can be accounted for using equation 2:

$$E_G = E_R + E_F + E_M + E_I + E_A \tag{2}$$

with: E_R: initial object creation energy
E_F: ideal final object creation energy
E_M: energy lost by the machine
E_I: energy for the infrastructure
E_A: assembly energy

Some of the tasks are done in PEEPS and some in the CAD system. Figure 4 shows the distribution of work. The Production Energy Estimation and Prognosis System (PEEPS) is shown in blue colour. The implementation was realized by means of a plug-in for the chosen commercial CAD system CREO 2 (shown in orange colour) and was programmed in C. For the calculation specific material data (density, tear strength, …) are available in the CAD System. A part of a product is usually manufactured out of the semi-finished product by means of manufacturing steps which are described in the CAD system. Additional parameters (such as direct manufacturing parameters, assembly parameters and machine data and infrastructure data) are stored in PEEPS. The assembly of modules is described in the CAD-system. The calculation done by PEEPS is divided into three parts. At first an ideal energy E_B is calculated which consists of the initial object creation energy E_R and the ideal final object creation energy E_F. Additional energies which are calculated are the direct losses of the manufacturing machine E_M, the energy necessary for assembly E_A and the energy for infrastructure E_I such as buildings and transportation processes. Specific data concerning manufacturing machines used in the actual production and machines tools can be concretized for more accurate prognoses, if they are already known, which may be the case in certain situations. Additional energies which are not a direct part of the process such as energy for raw material and recycling can be found using the volume of the raw materials or semi-finished products (such in other approaches for energy prognosis). They are shown separately. The advantage of this detailed procedure and the separation in several calculation entities are stand-alone calculation results, which can be used for further information processing (e. g. expert systems for consulting of designers).

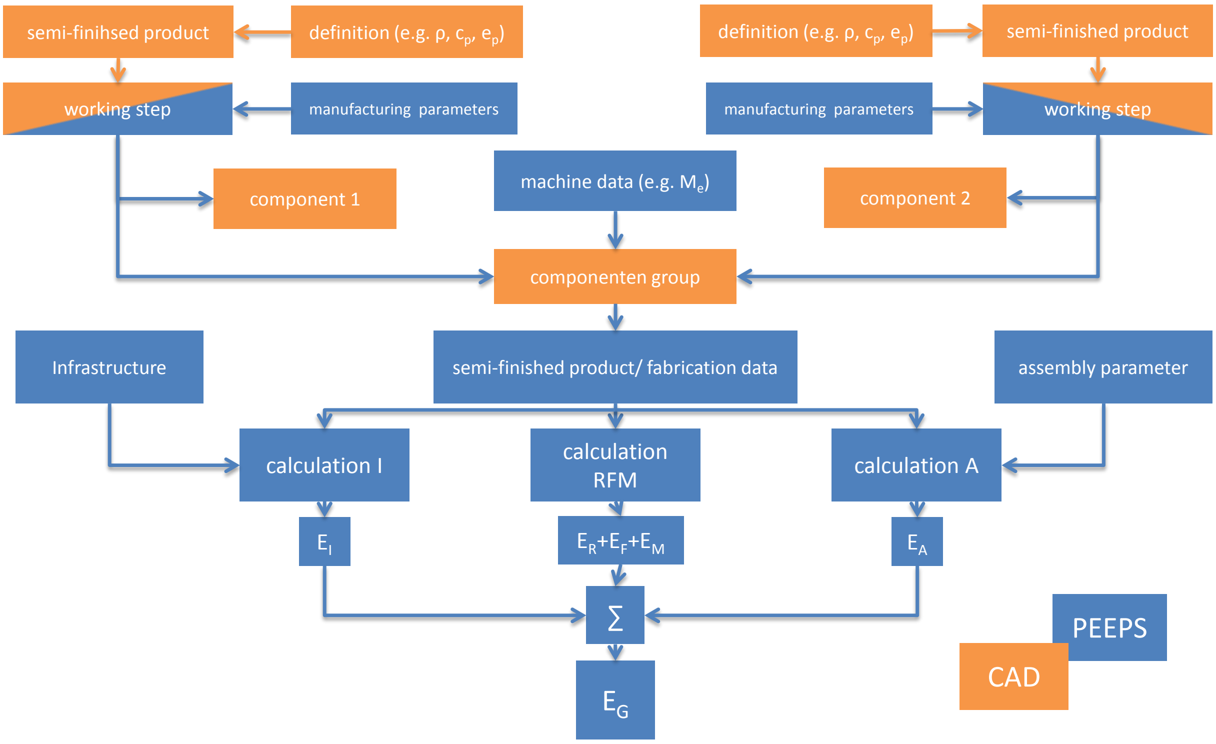

Figure 4. Distribution of Tasks between the CAD-System and PEEPS

The feature which describes subtracted volume can be understood and described as an information object, thus allowing object oriented programming. CREO 2.0 offers the possibility to program additional functionalities (comparable products such as CATIA or NX also offer this) using the ProToolkit. Therefore, it is possible to integrate the functionalities of PEEPS smoothly into CREO – the user will experience the tool as an additional functionality of his/her well-known CAD system. This system was implemented as a functional prototype throughout 2014 and is currently tested, optimised and expanded.

5 CHALLENGES AND PROCEDURE OF PROGRAMMING

The Production Energy Estimation and Prognosis System software (further in this section referred as PEEPS) has been designed as a transparent tool for the developers which is integrated in a commercial CAD system. PEEPS was defined as a tool to help users with normally difficult and time-consuming operations and therefore it was crucial to make it easy to use. Along with user experience (UX), the form of plug-in was chosen as a platform for the software. Subsequently few CAD systems from different vendors have been studied. This enlisted PTC Creo 2.0 (further referred as Creo) as a target. Therefore it needs to meet particular requirements as well as follow some programming patterns and a set of good practices. Firstly it may only use Application Programming Interface (API) of Creo. Thus it is compatible only with versions of Creo with the matching API version. Secondly to maintain transparency the User Interface (UI) should be very similar to an original Creo interface. As the API was used, the overall look was maintained. Number and positions of windows has been chosen according to the UX practices.

Agile development and the progress in estimation evaluation phases led to a three staged prototype implementation. The first prototype (pre-alpha) was developed only for purposes of proving stability of API. This was important in scope of fluent work with subsequent prototypes as well as exhibits drawbacks of API. Those were removed or suppressed in the second implementation (alpha). In the meantime a new description of demands of the estimation techniques appears, thus by using agile methods it was incorporated into alpha version. This prototype evaluated an approximate complexity of calculations required to estimate consumed energy, thus exhibits main weaknesses of the API. In this version all main functions, such as “material removal energy estimation”, “features properties tuning” and “reporting results to the end user” were implemented. No secondary functionalities were incorporated as it was assumed they have no influence on the system behaviour. In this stage as secondary functionalities were perceived: “export report to an *.csv file”, “highest energy consumption recognition” and “external user-defined consumptions”. Tests in this stage exhibit potential flaws in calculations, UI or UX. Knowledge gathered from these tests was subsequently used to improve the beta version of PEEPS.

Finally, the third stage was reached. At this time, the next version of the evaluation algorithm was employed. In the scope of new theoretical developments, the beta version of PEEPS consists of energy estimation for material removal processes (sawing, milling, turning, etc.) and material addition processes (like casting), as well as required parameters for the features representing them. It also incorporates the secondary functionalities in full range. Figure 5 shows a screen shot of the application.

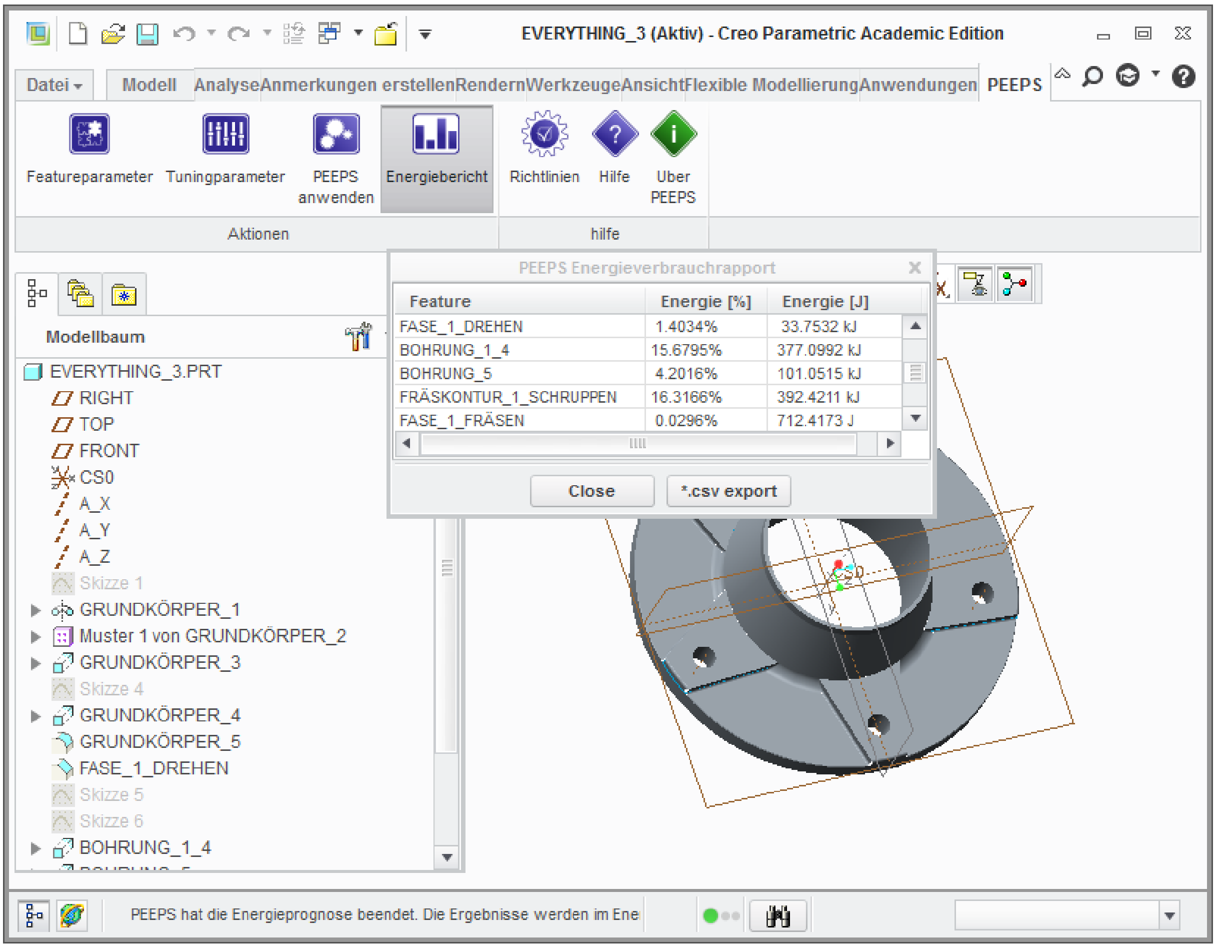

Figure 6. Screenshot Production Energy Estimation and Prognosis System (PEEPS)

6 EXAMPLE APPLICATION

In the scope of the project several sample calculations were performed and documented. The following section shows a sample calculation for the prognosis of the energy consumption of the manufacturing process plastic injection molding. Main points are the explanation of the procedure, the relevant assumptions and the sources. The energy consumption prediction is performed on a standard injection molded part, a terminal pin; the CAD model is shown in Figure 6.

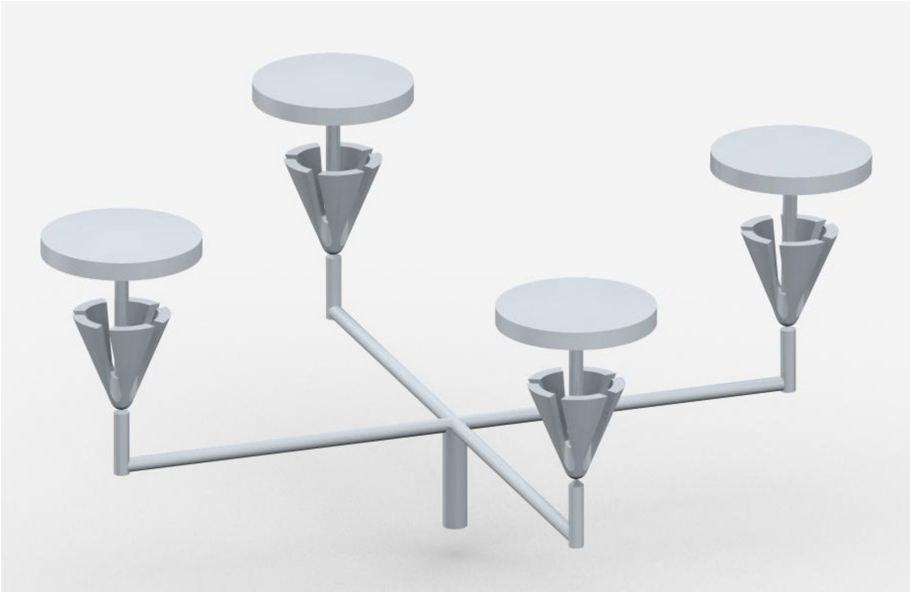

Figure 6. Sample part: injection molded terminal pin

The number of compartments of a tool is an individual decision and depends on various influences. For instance, the necessity to ensure a complete filling of the mold under consideration of the maximum shot volume is critical for the design of the tool. In the example it is assumed that the terminal pin is fabricated in four cavities and a connecting runner. The melting energy of the plastic is determined with a basic equation from thermodynamics. Equation 3 allows determining the amount of energy that is necessary to heat the plastics material and to melt.

$$E_S = m \cdot c_p \cdot (T_S - T) + m \cdot h_s \qquad (3)$$

With this power consumption equation it is determined how much energy is consumed to heat the plastic granulate in the production process and to melt it. The amount of energy is calculated from the material-specific parameters and the given data from the CAD model geometry. The example component is made of a standard quality plastic, for the purpose of calculating a PA 6 is selected. The component weight is determined using the CAD - volume and density; also, the weight of the runner can be determined. The melting energy of a plug rod arises as to 14.021 kJ. The calculation of the energy consumed for the entire plastic injection molding is determined taking into account the machine efficiency and the complexity of the component. This factor is determined using the relevant process parameters; for the terminal pin a consumed energy of 59.23 kJ was obtained.

For another example component a comparison with a detailed calculation results of ARBURG, an injection molding machine manufacturer, was possible. The deviation of the results in this case was there less than 10 %. In a further calculation the energy consumption in sheet metal bending was determined. The bending energy of a 90 ° bend in a sheet of aluminum was determined theoretically. It was shown that the deformation work for a simple 90 ° bend lies in a plausible order of 0.84 kJ.

7 CONSCIOUS IMPROVEMENT OF THE DESIGN

It is the main merit of the presented system to allow a designer an early insight concerning the energy consumption of the product he/she is developing in the production of this product. On appealing fact is that the designer in the phase can rather easily generate alternative solutions and can compare their quality in terms of production energy consumption. Usually geometry is connected to manufacturing processes, so the designer may check, for instance, if it is better to cast a part or to weld it from semi-finished goods. Also the designer can generate variants which use differential design and variants which use integral design and can also compare the energy consumption in production. For lightweight design usually less energy is used in the operation of a product. A designer can analyse if this advantage will compensate the possible additional energy consumption in production and can therefore design products with superior overall sustainability.

8 SUMMARY AND OUTLOOK

Product development engineers currently have nearly no support concerning the consumption of energy in the later production when they are determining product architecture and product geometry. This paper explored approaches which present a basis to develop tools which can provide engineers with a prognosis of the energy consumption in production very early in the product development process. One main possibility is analytical approaches based on product geometry and choice of material.

Today, the information about all steps in manufacturing and assembly is present in the numerous systems which build up the digital factory. However, the connection with and processing of this information is missing. The presented research is a first step into the direction of enhanced prognosis possibilities. In the further course of the research path, detailed mathematical formulations and verifications are planned to provide assistance to engineers who must make far-ranging decisions in the early phases of product design.

One approach for applying the proposed method in industry is the formulation of rules (compare Stetter et al 2014c). The authors believe that such a procedure will be a good start to enhancing the prognosis possibilities for production energy consumption. However, in the long run, intelligent, learning systems may lead to superior performance. The process of realizing this (Figure 7) is generally comparable to a data mining approach.

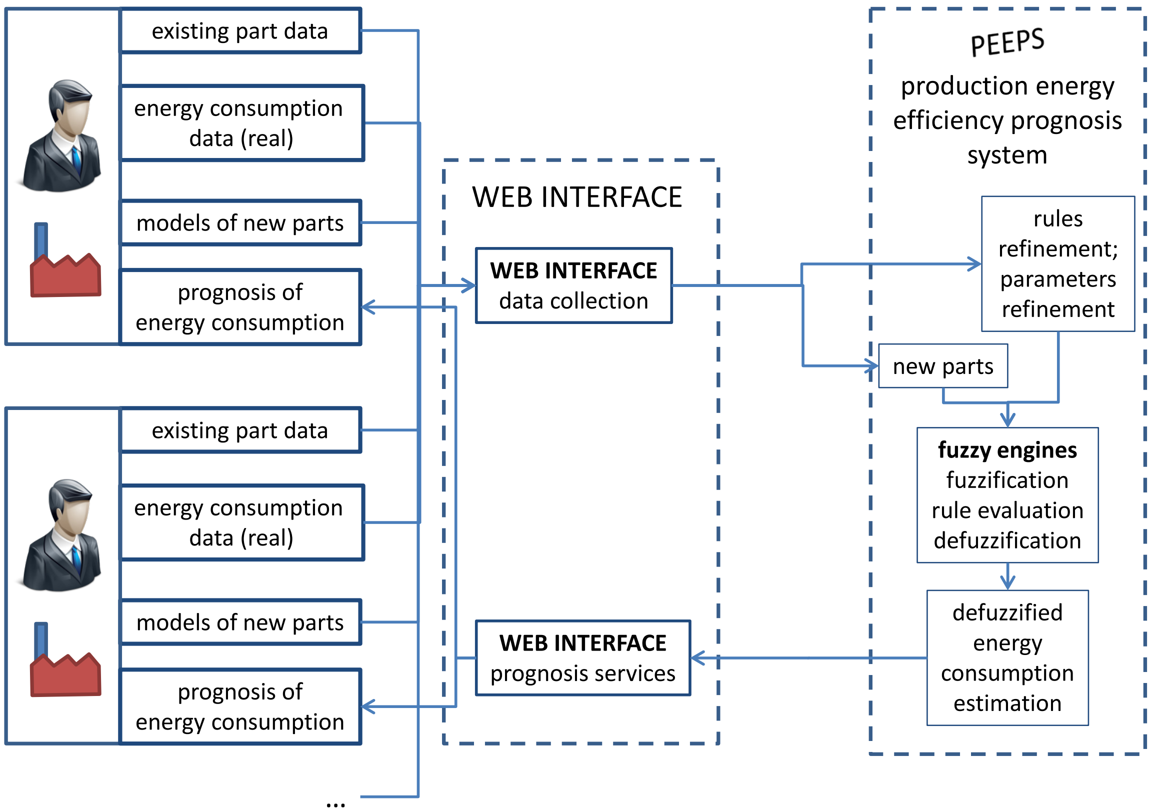

Figure 7. Web-based realization scenario

Today, the information systems of leading companies could assign the energy consumption of the whole production segment to the single product components with relative accuracy. In the simplest case, where only one component is built in serial production, the overall energy consumption could just be divided by the number of components built. Today, companies have the technology to determine how much energy is needed to produce a certain component, as well as all spatial information concerning this component in CAD system. However, these companies cannot know WHY they need this amount of energy, and therefore cannot produce a prognosis for future components. The idea presented here is that many companies will enter this kind of information (component description and production energy consumption) into a web application. The component data could be entered in the fuzzy system as described by Stetter et al. (2014a). The results can then be compared to the real results also provided by the companies. The difference between the results of the prognosis and the real consumption can then be used to modify rules and parameters of the fuzzy system. In this manner, a continuously improving prognosis system can be built. Companies which provide their information about existing products could also use the web application to get an accurate estimate of the energy consumption of future product components (compare Figure 7).

REFERENCES

Bernard, R.; Stetter, R.: Early Determination of Product Properties. In: Hubka, V. (Hrsg.); et al.: Proceedings of ICED 97, Tampere. Zürich: Edition Heurista, 1997, S. 2/675 - 2/680.

Coatanéa, E., Kuuva, M., Nordlund, H., Makkonen P. E., Saarelainen, T., "A uniform environmental metric based on exergy for early design evaluation", International Journal of Environmentally Conscious Design & Manufacturing, Vol. 13, No. 2, 2007.

Denkena, B.; Tönsdorf, H.K.: "Spanen" Berlin Heidelberg: Springer, 2011.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., "Recent developments in Life Cycle Assessment", Journal of Environmental Management, Vol. 92, 2009, pp. 1-21.

Hermann, B. G., Kroeze, C., Jawjit, W., "Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators", Journal of Cleaner Production vol. 15, 2007, pp. 1787-1796.

Reichel, T, Rünger, G.; Steger, D.; Xu, H.: IT-Unterstützung zur energiesensitiven Produktentwicklung. TU Chemnitz, Fakultät für Informatik: Chemnitzer Informatik-Berichte, Juli 2010.

Schröder, C. "Green Carbody Technologie" will 50 Prozent Energie in der Produktion einsparen. In: ATZ-Online, 22.06.2009.

Stetter, R.; Witczak, P.; Staiger, B.: Fuzzy Logic for Production Energy Efficiency Estimation. In: Marjanović, D., Štorga, M., Pavković, N., Bojčetić, N. (Eds.): Proceedings of the 13th International Design Conference DESIGN 2014, Dubrovnik, 2014. (Stetter et al. 2014a)

Stetter, R.; Paczynski, A.; Witczak, P.; Staiger, B.: "Advanced Trajectory Planning for Production Energy Estimation". In: Pomiary Automatyka Robotyka nr 2/2014, pp. 70-77, ISSN 1427-9126. (Stetter el al. 2014b)

Stetter, R.; Witczak, P.; Staiger, B.; Spindler, C.; Hertel, J.: Application of advanced methods for the prognosis of production energy consumption. In: Proceedings of the Conference of Advanced Control and Diagnosis ACD 2014, 13. und 14. November 2014, Berlin. (Stetter et al. 2014c)

Stetter, R.: Prognose des Energieverbrauchs in der Produktion. In: Forschungsreport für den Maschinenbau in Baden-Württemberg. Bingen: Public, 2013.

Thompson A. W., Hallstedt S., Isaksson O.: Introductory Approach for Sustainability Integration in Conceptual Design. In: Marjanović, D., Štorga, M., Pavković, N., Bojčetić, N. (Eds.): Proceedings of the 12th International Design Conference DESIGN 2012, Dubrovnik: 2012, pp. 1151 - 1160.

Tischner, U.; Schmincke, E.; Rubik, F.: Was ist EcoDesign. Ein Handbuch für ökologische und ökonomische Gestaltung. Frankfurt am Main: form Praxis, 2000.

Williams, E.D.: Revisiting energy used to manufacture a desktop computer: hybrid analysis combining process and economic input-output methods.. Conference Record 2004 IEEE International Symposium on Electronics and the Environment, pp. 80- 85.

ACKNOWLEDGMENTS

This project is supported by a grant from the European Regional Development Fund and the Ministry of Science, Research and the Arts of Baden-Württemberg, Germany (information under: www.rwb-efre.baden-wuerttemberg.de).