

## **FUZZY LOGIC FOR PRODUCTION ENERGY EFFICIENCY ESTIMATION**

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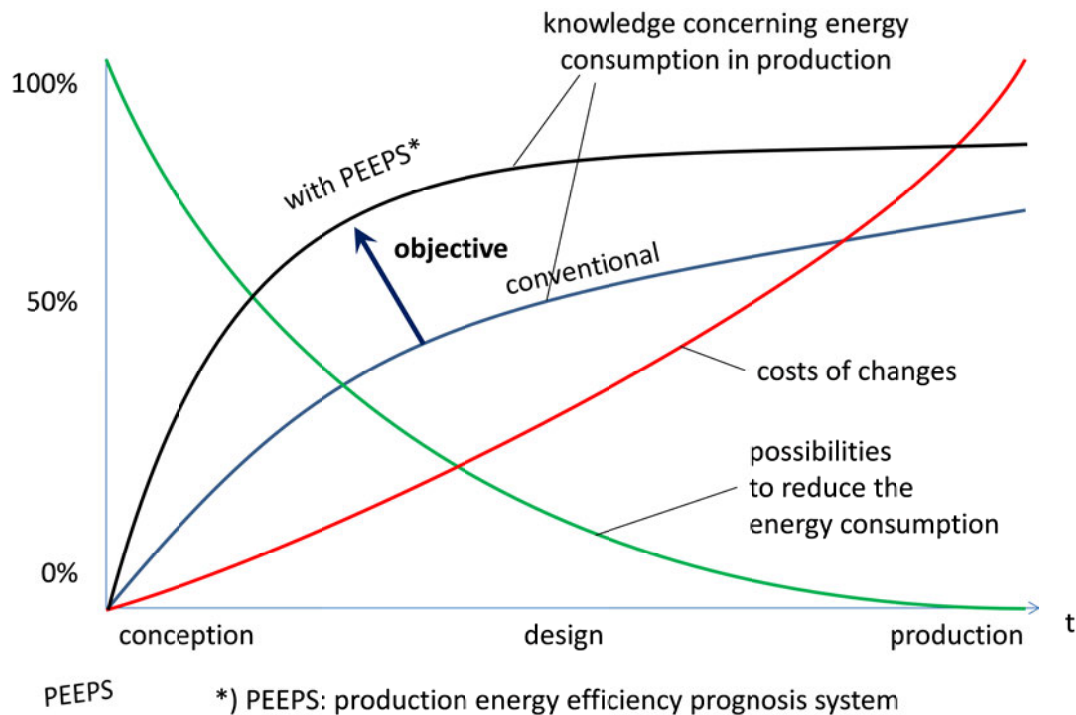
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### **1. Introduction**

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 analyzed in depth in early stages of product development processes, because today the common tools of product development, such as geometry generating tools called CAD-systems (computer aided design) do not offer any possibility to support designers and engineers in this endeavor. The importance of the energy for production becomes apparent, for instance, in the field of passenger cars. In this field, even conservative studies [Brake 2009], [Schröder 2009] reach the conclusion that about 20 % of the total energy required for a product is for its production and about 10% for its disposal. For other products, such as mobile phones, the portion of energy use for production can rise up to 80 %. The energy consumption in production and disposal is determined very early in the product development process by designers and engineers; for example by selection of raw materials, explicit and implicit requirements concerning the manufacturing and assembly processes, or by 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. For instance, the energy consumption of a car under development is expressed in litres per 100 km and can be predicted with an accuracy of 0,1 litres years before this specific car will be built. Large expenditures are frequently invested only to achieve relatively small improvements of the energy consumption in operation. In the area of motor vehicles, methods such as the start-stop-systems or hybrid systems are applied which can achieve improvements of the energy efficiency to an accuracy within the one percent digit area.

In contrast, tools with the objective to predict the energy consumption in production and disposal are not available apart from the first material databases, such as Eco Materials Adviser in Autodesk. Moreover, initial investigations in this research project showed that the available databases deviate for identical materials and weights up to orders of magnitude of 50 % from one another (I didn't change anything here, but when you use the term "orders of magnitude", you should quantify to what magnitude i.e. of 50 %, 100 %). A conscious view of the energy consumption in the production will most likely lead to obvious energy savings. This statement cannot currently be quantified in this area; however, an analogy concerning systems for costs prognosis can underline the potential. In this area, the conscious consideration of costs during design in the past led to cost savings of up to 70 % without restricting the functionality of the components and products [Ehrlenspiel et al. 2007]. Energy saving potential in production to a similar order of magnitude could lead to improvements in the two-digit percent area of the entire energy balance of a product; improvements of this dimension today can hardly be reached in the energy consumption in the operation. Today designers and developers must more or less decide "blindly", because in today's industrial reality, it is impossible to predict the energy consumption in production. It is hypothesized that intelligent tools and procedures can shift the

knowledge concerning production energy consumption into earlier phases and massively increase the potential for improvement (Figure 1).



**Figure 1. Early evaluation of production energy consumption**

In this representation, which is based on similar representations in the area of early determination of product properties (compare [Stetter and Bernard 1997]), it is clearly recognizable that in the early phases of the product development, the energy consumption can be heavily influenced through product changes and this in connection with considerably small change costs.

It is important to note that at this time in the product development process, not all details of the manufacturing process are known. It is also not realistic to plan the complete manufacturing processes in this early phase. Still, designers must assess the possibility of producing a part and usually also need to determine product costs in this phase. It is therefore realistic to assume that designers know the decisive manufacturing steps. Current CAD systems allow the collection/input of much of this information through different features which adapt the part geometry or store the raw part geometry. It is a basic hypothesis of the presented approach that this knowledge, together with intelligent systems, will allow a sensible prognosis of the production energy and lead to more conscious decisions concerning the product architecture and geometry.

## 2. State of the Art

Numerous research activities in the area of eco design belong to the state of the research. Tischner et al. [2000] offer a good overview. In these activities, the energy consumption usually plays a central role. In the frame of the Life Cycle Assessment (LCA), the production is also considered as a part of the life cycle (see for example [Finnveden et al. 2009]). In this scientific area, the international standard ISO 14031 [1999] is to be cited in particular, 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 also become of interest as a central measurement means for sustainability [Coatanéa et al. 2007]. Current works, such as Thompson et al. [2012], show the first integrations of sustainability considerations and also sustainable tooling 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 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 permit 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 CO<sub>2</sub>-emission and the water consumption. The database is operated in collaboration with Granta design and includes information to 3,000 materials and selected fabrication procedures. Next to Inventor 2012, the current version of Solidworks also offers an expansion called “Sustainability” which also provides information concerning CO<sub>2</sub> emissions and the energy consumption. The “Sustainability” expansion additionally offers the possibility to automatically find materials, which more favourably combine 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 analyzed in these systems.

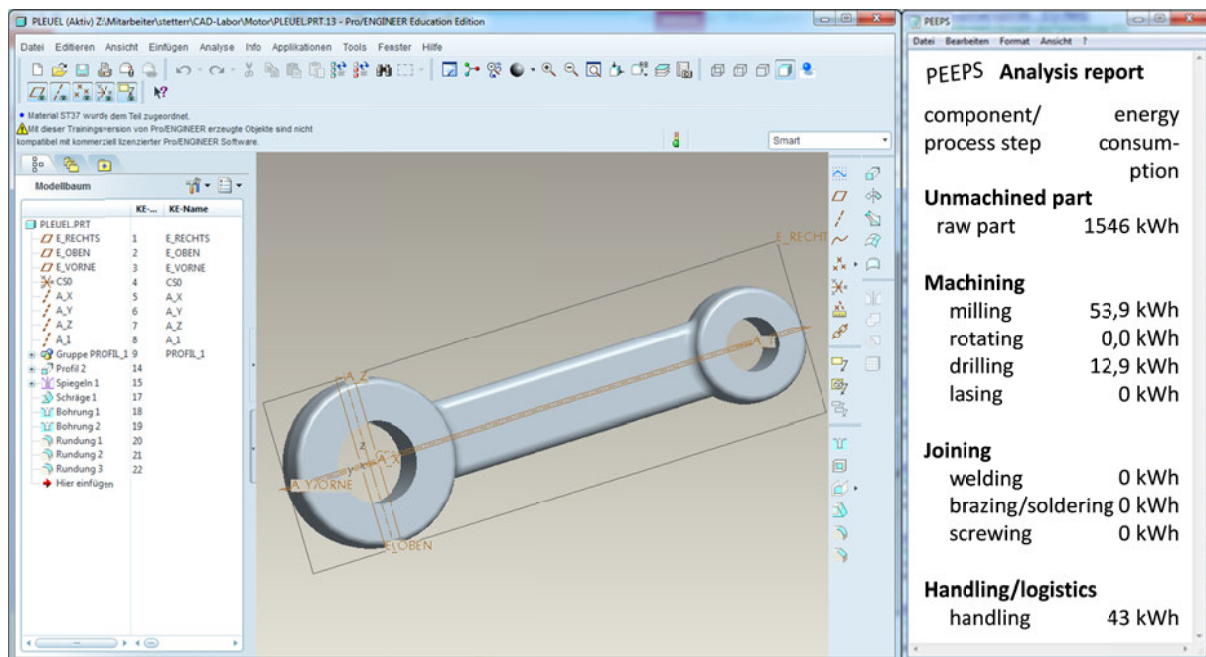
This paper focuses on the application of fuzzy logic for the prognosis of production energy consumption. Fuzzy logic has the potential to integrate human decision-making ability into technical systems instead of using pure mathematical models [Siler and Buckley 2004]. Fuzzy logic employs the concept of the degree of membership, leading to high flexibility. Fuzzy systems can be developed based on experience and expertise of system suppliers and systems operators. These aspects are translated as inputs to the fuzzy system. Such systems apply linguistic variables, which are comparatively easy to handle. In some instances, models of reality can be better expressed by fuzzy models, as there are no dead/discontinuous zones in reality. A fuzzy model development can be viewed as comprising of the three important steps of fuzzification, rule evaluation and defuzzification [Börcsök 2000]:

- **Fuzzification** is the process of fuzzifying the inputs. It is the transformation of crisp sets into fuzzy sets with blurred boundaries. This is done by evaluating a membership function. The numerical values are transformed into degree of membership. They are associated to a particular fuzzy set by means of a membership function.
- **Rule evaluation** is the step of generating a black box of the model. The evaluation of the mathematical model and control logic in a crisp set is replaced by fuzzy evaluation. This involves 3 phases – applying the fuzzy operator, implication and aggregation. The term “applying the Fuzzy operator” refers to the application of the logical operators over the fuzzy sets. The selection of the operator is based on the need of the application. The core elements of the implementations are the membership functions. The membership functions define the degree of truth or activation of a certain rule. This is also influenced by the weightage provided to each rule. The input to the implication operator is the antecedent which is a single number from each membership function and the output is single fuzzy set termed as consequent. This output represents the operator applied to each fuzzy set.
- **Defuzzification** is a method of mapping from a space of fuzzy entities over an output universe of discourse into a space of non fuzzy (crisp) entities. Nearly all applications need crisp inputs in order to function or to make decisions. The final aggregated output has to be defuzzified for subsequent operations or process steps. The various types of defuzzification determine which value is selected from a fuzzy aggregated output as crisp value. The most commonly used methods of defuzzification are “Centroid”, “Bisector”, “Middle of maximum”, “Smallest of maximum” and “Largest of maximum”.

### 3. Conventional Approaches

In order to fully understand the objectives of applying fuzzy logic to the prognosis of production energy consumption, the conventional approach is briefly described in this section. It is important to note that this approach is sensible as well; however, the application may be hindered by product complexity and the necessary operations to prepare the geometrical model.

Calculations of the energy consumption in 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 to determine the energy necessary for the milling operation. Current research in production technology can provide the necessary tables and equations to determine this energy, but only if 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; it is therefore very promising to couple future systems with CAD systems. Figure 2 shows a view of the conventional system to be developed in the scope of this research project.



**Figure 2. Vision of the conventional system**

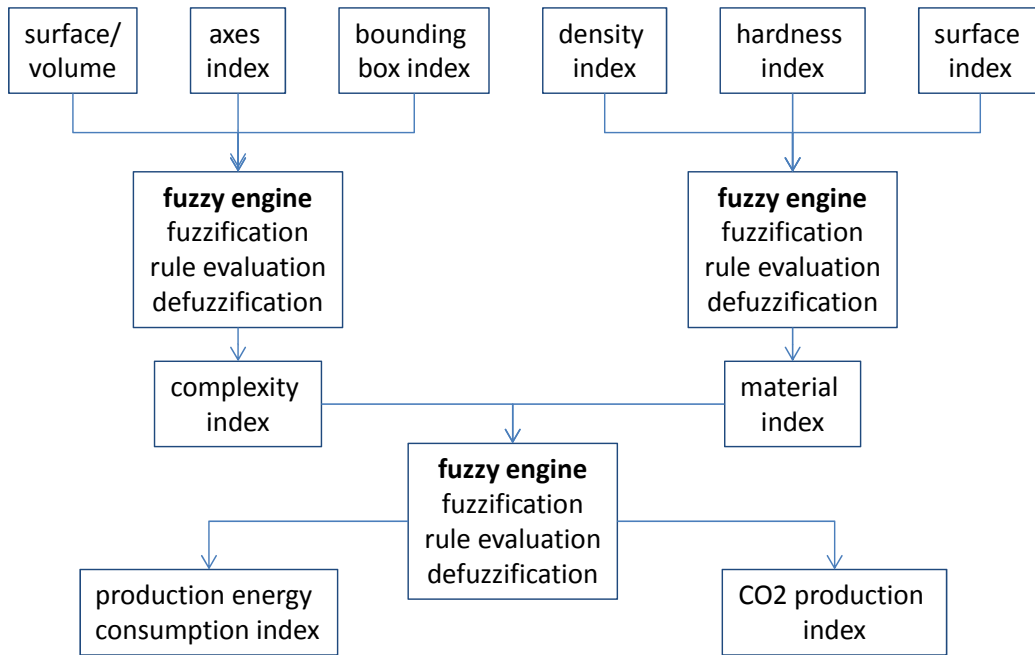
However, in the overall scope of the project, it is to be expected that not all influences can exactly be quantified due to reasons of complexity and time pressure in product development. Therefore additional methods which use some kind of artificial intelligence, such as fuzzy methods, are to be investigated and their suitability is to be tested. It is hypothesized that these methods will possibly achieve less accurate estimates of the production energy consumption, but also with much lower requirements for the input information.

## 4. Application of Fuzzy Logic

This section explains the application of fuzzy logic for estimating production energy consumption. Firstly, the proposed procedure scheme is explained. Secondly, the proposed input product characteristics are described. Thirdly, the relevant indices are listed and elucidated. The fourth subsection describes the rules applied in the project. Finally, the fifth subsection gives the results of a sample application.

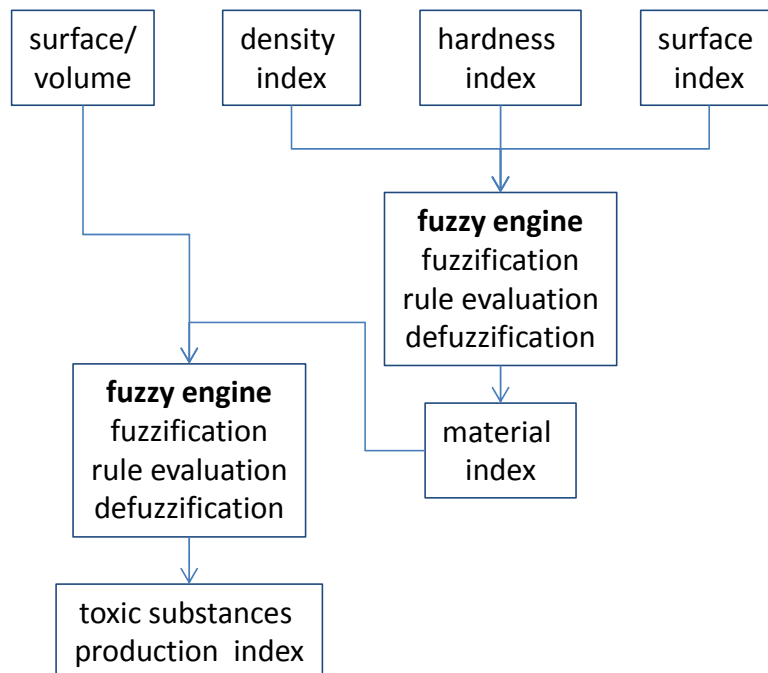
### 4.1 Proposed procedure scheme

The inputs of a fuzzy logic system are the fuzzy variables. For the given system, six sensible fuzzy variables were found (compare section 4.2). In the main part of the system, these fuzzy variables are first used in two fuzzy engines in order to determine the first indices (compare section 4.3). The results, which are once again crisp values after defuzzification, are then given to a third fuzzy engine in order to find two important indices – the “production energy consumption index” and the “CO2 production index”. Figure 3 depicts the proposed procedure scheme.



**Figure 3. Main procedure scheme**

A second procedure is proposed in order to generate the toxic substances production index (Figure 4).



**Figure 4. Additional procedure scheme**

The two procedure schemes are depicted in order to give an overview for the later subsections of this section.

#### 4.2 Definition of fuzzy variables

The defining of the input variables is a very demanding task. In this case, an extensive survey of production engineering was carried out. The main idea behind the fuzzy variables stems from research works by Achiche and Ahmed [2009]. In this research, comparable indices were used in a fuzzy engine in order to investigate 3D shapes and how they are perceived.

#### 4.2.1 Surface/volume ratio

The first main indicator for the complexity of a product is the ratio between surface and volume. Simple forms which can be produced with a small amount of energy such as simple cylinders, are characterized by a small surface/volume ratio. This ratio is defined as follows:

$$\frac{\text{surface}}{\text{volume}} \text{ ratio} = s/v = \frac{\text{component surface} \left[ \text{mm}^2 \right]}{\text{component volume} \left[ \text{mm}^3 \right]} \quad (1)$$

#### 4.2.2 Density index

In general, products which have a higher density also require more energy, for instance, in order to be machined, or transported. In order to quantify this influence, the density index is proposed, which results from the ratio between the mean density of the component under consideration and the density of platin, which is the material with the highest density which still has practical functionality in industrial products:

$$\text{density index} = di = \frac{\text{component density} \left[ \text{g/dm}^3 \right]}{\text{density of platin} \left[ 21,45 \text{ g/dm}^3 \right]} \quad (2)$$

#### 4.2.3 Hardness index

The energy for machining or drilling product components is furthermore influenced by the hardness of the respective component. This influence is considered in the hardness index which describes the ratio between the surface hardness of a certain product component and the highest hardness which is usually observed in technical products (*830 in Vickers hardness HV*).

$$\text{hardness index} = hi = \frac{\text{component hardness} \left[ \text{HV} \right]}{\text{very high hardness} \left[ 830 \text{ HV} \right]} \quad (3)$$

#### 4.2.4 Axes index

Most modern products these days are designed with the help of 3D CAD systems such as Creo, Catia or NX. In this project, the models of such systems were analysed in order to identify possibilities for gathering abstract, quantitative information about the geometry. One possibility which was identified is to count the number of axes. An axis is generated with many component entities, such as holes or protrusions. It can be hypothesized that a high number of axes in the relation to the size of the product indicates a product with many production steps and, therefore, a high production energy consumption. Consequently, the axes index is defined as the ratio of the number of axes in the CAD model of a product component and the component volume as an indicator of the size of the component:

$$\text{axes index} = ai = \frac{\text{number of axes}}{\text{component volume} \left[ \text{mm}^3 \right] \cdot 1000} \quad (4)$$

#### 4.2.5 Surface index

Rather high energy consumption in production can result from surface treatment processes such as painting. The surface index addresses this influence. The surface index is the ratio between the surface treatment (which is a number between 0 and 1; for instance 0.3 means painted, 0.5 coated with metallic material, 0.7 coated with ceramic material) multiplied by the surface and the component volume as an indicator of the size of the component:

$$\text{surface index} = si = \frac{\text{surface treatment} \cdot \text{surface} [\text{mm}^2]}{\text{component volume} [\text{mm}^3]} \quad (5)$$

The numbers for certain treatments are, in this phase of the research, based on estimations by experienced designers and will be further clarified in the course of the project on the basis of an in-depth literature analysis and discussions with production companies.

#### 4.2.6 Bounding box index

Modern CAD systems, such as Creo, allow relatively easy determination of a bounding box which completely encloses a product component. Similar to the surface/volume ratio, a large bounding box length in combination with a rather small volume indicates a complex shape, including, for instance, many holes or a hollow structure. The production energy consumption for such shapes is usually higher; the magnitude is captured by the bounding box index, which is defined by the ratio of the bounding box length and the component volume multiplied by a constant factor:

$$\text{bounding box index} = bi = \frac{\text{bounding box length} [\text{mm}]}{\left( \frac{\text{component volume}}{[\text{mm}^3] \cdot 1000} \right)} \quad (6)$$

### 4.3 Definition of output indices

Two main influences characterize the energy consumption in production:

- the complexity of the component, leading to many subsequent energy-consuming production and transportation processes and
- the material of the component – the density, hardness and other material properties can lead to an multiplication of energy expenditure for the production of the respective component.

On the one hand, the **complexity index** summarizes the influences of other indices, which indicate the complexity of a product's component. This index describes the intricacy of manufacturing (thus indicating the energy consumption) based on influences from the geometry. On the other hand, the influences of indices which indicate the production complexity arising from the material of a component are summarized in the **material index**. This index describes the difficulty of manufacturing based on influences from the material.

Both influences need to be combined in order to assess the energy necessary for production – thus forming the **production energy consumption index**. In a similar manner, the **CO<sub>2</sub> production index** can also be generated. A major influence of toxic substances in the production process is from surface treatment; therefore the size of the surface in comparison with the size of the component is a major indicator. A further indicator is the material index, which indicates the difficulty of production of the material. Both indicators together form the toxic substances production index.

### 4.4 Definition of output indices

The general idea of the application of fuzzy logic to this assessment of product components is based on the scientific work of Achiche and Ahmed [2009]. Also, the general formulation of the rules was adopted from this research work. Table 1 shows an example for fuzzy rules – the list of rules to determine the complexity index. In this phase of the research, the rules are based on the judgment of experienced designers and first investigations with sample parts.

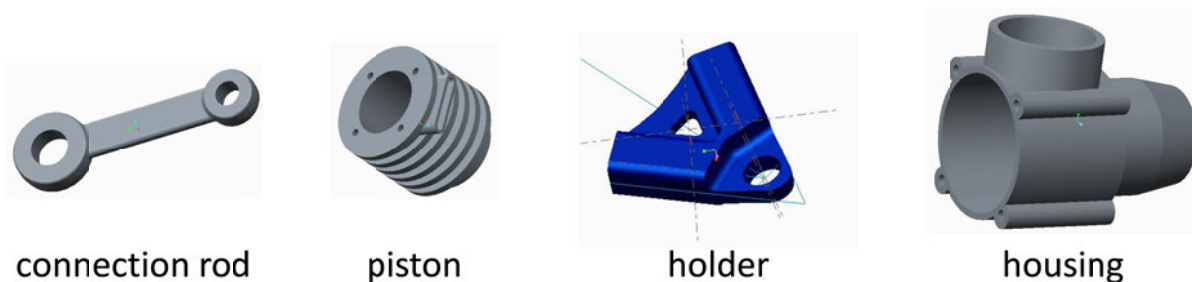
**Table 1. Fuzzy rules (example: complexity index)**

s/v	ai	Bbi	conclusion
low	low	low	not
medium	low	low	not
low	medium	low	not

low	low	medium	not
low	low	high	slightly
low	high	low	slightly
high	low	low	slightly
low	medium	medium	slightly
medium	low	medium	slightly
medium	medium	low	slightly
medium	medium	medium	moderately
low	medium	high	moderately
low	high	medium	moderately
medium	low	high	moderately
medium	high	low	moderately
high	low	medium	moderately
high	medium	low	moderately
low	high	high	quite
high	high	low	quite
high	low	high	quite
high	medium	medium	quite
medium	high	medium	quite
medium	medium	high	quite
high	high	medium	very
high	medium	high	very
high	medium	medium	very
high	high	high	very

#### 4.5 Exemplary application and results

For an exemplary application, four different parts which result from the CAD training and developments for a formula student race car were chosen. The data was taken from the CAD model. For some of the entities, sensible estimation were made. Figure 5 shows the four analyzed parts.

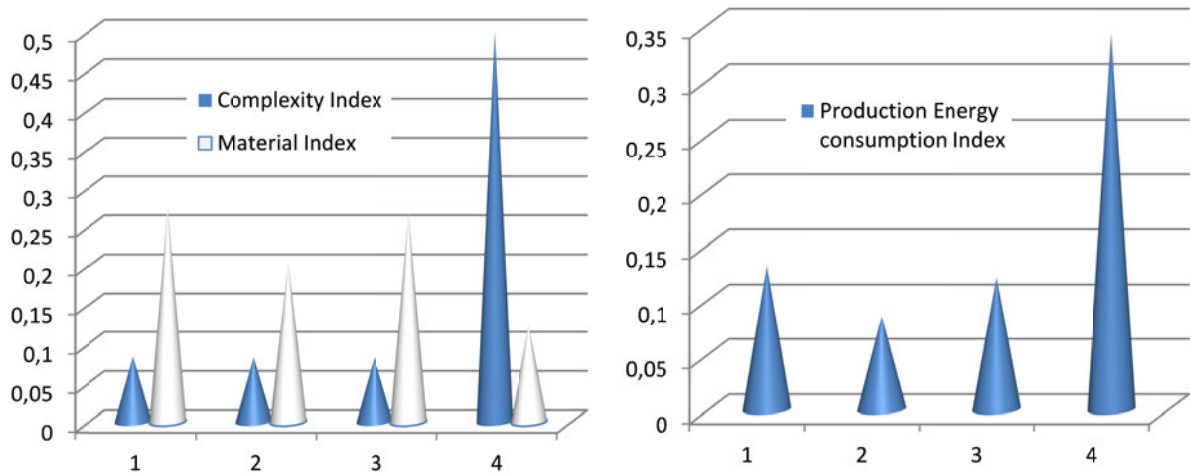


**Figure 5. Analysed parts**

The main parameters of the four parts were given to the initial two fuzzy engines and the first two indices were determined. The results in Figure 6 (left side) show clear distinctions. The high complexity index of the housing is definitely a consequence of the hollow structure. Such structures are relatively light and have a small volume but require a lot of energy to produce. On the other hand, the low material index of the housing is influenced by the rather small hardness of this part and no necessity of surface treatment – in contrast, for instance, to the piston with elaborate surface treatment for the running socket.

In the second fuzzy engine, these results were combined leading to two indices. One example is the production energy consumption index (Figure 6 – right side).





**Figure 6. Results for analysed parts**

## 5. Outlook

The results presented above show a general feasibility of fuzzy logic in order to support an estimation of production energy consumption. Further steps are necessary in order to support the evidence. A combination of two different possibilities will be applied in the further course of the project:

- The energy consumption for the production of certain product components will be estimated by applying conventional approaches as described in Section 3. These results will then be compared with the results from the application of fuzzy logic.
- The actual energy consumed for the production of certain product components will be gathered by means of analysing the energy consumption of the manufacturing and assembly systems of production companies. These results will be compared with the results from the application of fuzzy logic.

It is also important to note that the indices which result from the application of fuzzy logic do not yet reflect results in terms of units of energy such as Kilowatthours (kWh). This was done intentionally in order to be independent from the specific characteristics of certain industries. Still, for the final application of the developed tools, correlation tables for the conversion of the results to concrete units of energy and CO<sub>2</sub>-emission are needed.

## 6. Summary

The objective of this paper was the presentation of an explorative study concerning the use of Fuzzy Logic to predict the production energy consumption early in the product development process. Today, the energy necessary for the production of goods is very often not analysed in detail. The energy consumption in production and disposal is determined very early in the product development process by designers and engineers, for example by decisions concerning the product architecture. Nowadays tools with the objective to predict the energy consumption in production and disposal are nearly non-existent. The information available in early phases is often rough, indistinct and incomplete. This gives rise to fuzzy systems for their unique capability to deal with such problems. In the presented research, a fuzzy system was applied in order to estimate the production energy consumption of four product examples. Six fuzzy variables were proposed which can be used to determine indices which indicate the energy consumption. Initial results are promising. Further work will include a systematic comparison of these results with conventionally determined production energy consumption.

## Acknowledgement

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