INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

MANAGEMENT OF ENERGY RELATED KNOWLEDGE IN INTEGRATED PRODUCT DEVELOPMENT – CONCEPT AND SELECTED INSTRUMENTS

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ABSTRACT
Beside functionality, cost, quality, and so on, design engineers are facing a new challenge – the development of energy efficient products. Since especially in the early phases only few solid knowledge about the impacts of design alternatives on energy related figures like consumption, savings, or efficiency is available, the need for a systematic management of energy related knowledge is evident. For this purpose and on the basis of an integrated product development framework, the paper emphasizes the variety of energy related knowledge in product development, presents a concept for an energy related knowledge management and exemplifies its systematic identification, use, and development with help of development-concurrent energy calculations and a target energy management approach.

Keywords: energy related knowledge, integrated product development, knowledge management, development-concurrent energy calculation, target energy management

1 INTRODUCTION
It is not new that a consideration of requirements like functionality, quality, cost, manufacturability, and eco-friendliness in early phases of product development is highly efficient. The designers' strong responsibility for the realization of such requirements results from the high impact of their decisions on the product design related with small degrees of freedom in decision making remaining in later steps of the product creation process and the following life cycle stages [1], [2]. To address the challenges arising from these requirements, various DfX/DtX strategies and tools have been developed.
For some years now, attention focuses on a further challenge, *design to energy* and *design to energy efficiency* (DtEE), respectively (i. a., Directive for energy-using products (EuP), methodology for the assessment of the environmental impact of EuP's [3], [4]). DtEE can be taken as part of a design for environment strategy aiming at ensuring that products meet the customers' needs for energy efficiency over their entire life cycle [5], and/or at improving the energy productivity of a company's manufacturing processes [6]. The goals of DtEE arise from the fact that products and the processes to manufacture them take energy inputs to transform material inputs into products and wastes, and therefore predominantly influence not only the company's energy consumption and environmental outcome, but also the emerging cost of the products and their manufacturing. On the one hand, passed opportunities to optimize energy efficiency or productivity during product development would increase a product's energy use and cost as well as energy wastes and waste disposal costs. On the other hand, efforts for improving energy efficiency will have positive or negative effects on manufacturing, operation, maintenance, and recycling costs and thus will influence a company's earnings in different ways [6].
As a result, pursuing a DtEE strategy, the design engineers have to pay attention to both energy consumption/conservation and their effects on various types of cost (beside aspects like functionality and quality which are not covered here). Therefore, energy and cost related knowledge is a prerequisite for a goal-oriented development of energy and cost efficient products. In contrast to this importance, in the early stages, the available energy related knowledge is usually insecure, fuzzy or incomplete. This leads to the need for a systematic structuring of *energy related knowledge* and a *knowledge management* that enables the effective and efficient handling and development of this knowledge. To date, however, this need remains unmet given that the literature hardly deals with these topics.
To address this problem, based on an integrated product development (IPD) framework (section 2) the paper describes the scope and complexity of energy related knowledge in IPD and introduces an ap-

proach for its structured management (section 3). After that, development concurrent energy calculation methods and a target energy management approach are described as means to support the systematic identification, use, and development of energy related knowledge (section 4). The summary and conclusions of the paper are presented in the fifth section.

2 A FRAMEWORK FOR INTEGRATED PRODUCT DEVELOPMENT

The term "integrated product development" (IPD) is often used in theory and practice [1], [7], [8]. Nevertheless, there is no common understanding about its definition, elements and contents. In this paper, it will be understood as a systematic approach that employs a teaming of different functional disciplines (e. g., design, marketing, cost management, manufacturing) to integrate and concurrently apply all necessary product development activities as well as organizational and technical resources to produce competitive products that satisfy the customers' needs at a high level [8]. Within this scope, the product life cycle and the life cycle related knowledge are taken into account, in order to develop products that fulfill the intended requirements, especially functionality, quality, suitability for production, market need, cost, energy efficiency. According to this and on the basis of a concept by Vajna and Burchardt [7], a general "IPD framework" has been proposed by Köhler and Götze [9] (Figure 1).

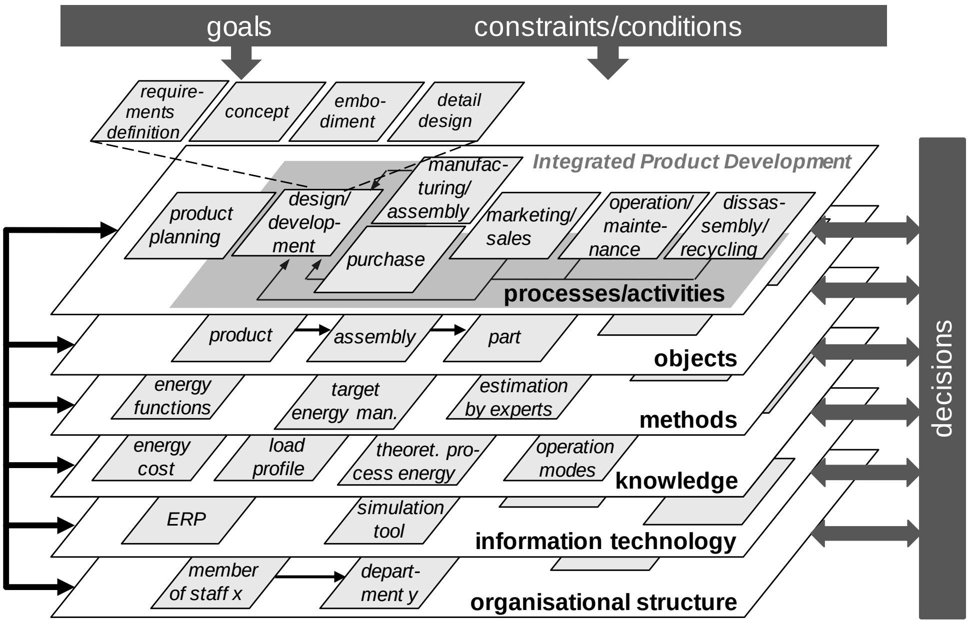

Figure 1. Framework for integrated product development [9]

This framework comprises different dimensions of IPD: The relevant *processes* of a product's life are organized at the *process level*. Beside the use and recycling stage, the product creation process is one important process of the product life cycle including all activities from product planning up to the point when the products are sold to the customers. The design process, focused in this paper, is a subprocess of the product creation process. As visualized for this process (Figure 1), all processes can be divided into subordinate processes up to individual activities [1], [2]. In the most cases, the processes and activities result from decisions about individual objects. Therefore, these objects are differentiated at the *object level*. Using hierarchical structures, objects can be individual products, assemblies, parts, features, etc., but also groups of objects like size ranges and modular products [2]. The *methods level* gathers a pool of methods to support the goal-oriented development of effective and efficient products [2]. With respect to the paper's focus, these are methods supporting the strategies design to energy efficiency and design to cost. Since product development is a process of knowledge generation and engineering, a *knowledge level* is introduced, containing existing relevant factual and methodological knowledge as well as new knowledge that is generated during the application of the existing knowledge [10]. The *information technology level* comprises IT components to support the method application as well as information integration [11], [12]. At the last level, the *organizational structure level*, the IPD relevant departments as well as the according staff of the company are contained.

The items in the dimensions are influenced by the superordinate *objecti*ves of the company as well as internal and external *constraints/conditions* (e. g., legal or financial restrictions). As also indicated in

Figure 1, the items of an individual level are interconnected with other items of the same level and items of other levels by manifold interdependencies, also including *decisions* that have to be taken when developing new products, product variants, or components etc., in order to achieve the objectives under consideration of the constraints/conditions.

3 ENERGY RELATED KNOWLEDGE AND ITS MANAGEMENT

3.1 Energy related knowledge within the IPD framework

As already mentioned the product development process is a knowledge generation and engineering process. This also refers to the energy related knowledge that is necessary for product development. It comprises factual as well as methodological knowledge about technical and economical aspects, like

- general basics of energy conversion and its physical and thermodynamic principles,
- measurement, calculation, and simulation of different energies and their consumptions,
- energy costs and the impacts of energy related design decisions on other types of cost (e. g., manufacturing costs, costs of operation and maintenance, etc.),
- drivers of energy use and energy related cost drivers and their effects.

The first basic category of knowledge is the *energy related factual knowledge*. It is needed in the different steps of the design processes and comprises *general* energy related knowledge (e. g., resistance coefficients, fluid viscosities, friction coefficients, stiffnesses) and *specific* knowledge from completed designs (e. g., power input of already designed machine tools, estimated energy consumption for draft alternatives), involved departments (e. g., information about effects of energy saving components on the manufacturing costs from the accounting department), and – with respect to a particular object – from previous design steps (e. g., the definition of a certain working principle determines the components that can be used to realize it). The second basic category is the *energy related methodological knowledge* (e. g., equations for the calculation of the theoretical process energy in machining processes and constraints for their application in a given design context). On the one hand, the knowledge in this category is an important basis for the application of methods and factual knowledge in every step of the design process. On the other hand, due to the application of existing methods and knowledge, new energy related methodological knowledge (e. g., the constraints of the application of equations mentioned above) is generated in every design step (Figure 2).

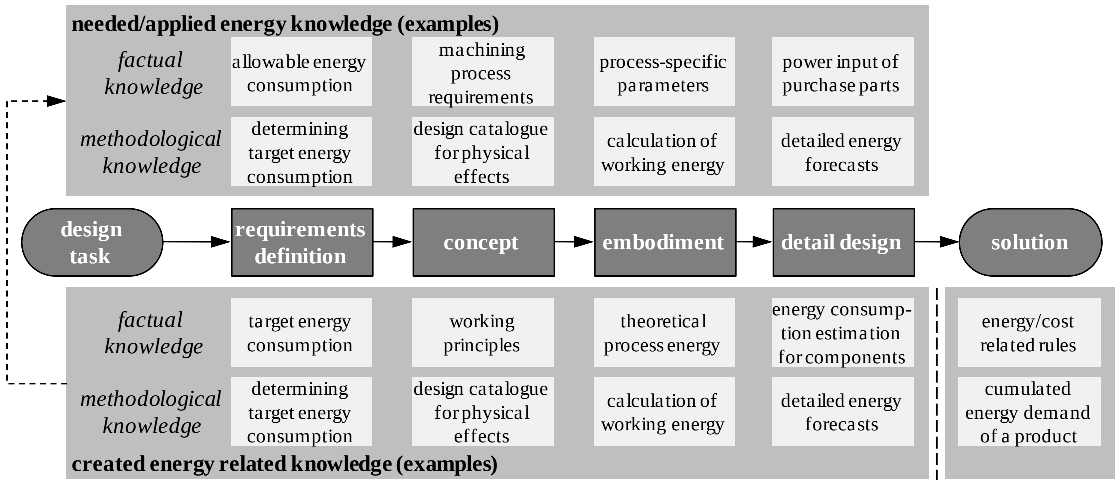

Figure 2. Energy related knowledge in the design process

However, engineering literature (in particular in electrical engineering, physics, thermodynamics), engineer standards (e. g., DIN EN 60034-30) and ecodesign literature (e. g., [12], [13]), are full of technical and methodological knowledge items that could be taken as potentially useful in design processes (e. g., thermodynamic state equations, diagrams and laws, nomograms to visualize sets of thermodynamic equations, design equations for heat exchangers). While the available energy related technical knowledge focusing on specific issues can be called considerably, there are only little contributions which deal with a systematic management of energy related knowledge in design processes (e. g., load profiles of machine tools during their operation and maintenance phase, total compressed air consumption for the manufacturing of one piece of a certain product) [14], [15], [16].

All this factual and methodological energy related knowledge is primarily included in the IPD framework's knowledge level. Beyond that, there are relationships to the other levels. For instance, energy related knowledge is applied in the particular activities of the design processes or it is generated in these processes/activities (Figure 2) as well as in later stages of the product life cycle (separated box in Figure 2). The inclusion of the methodological knowledge shows that there also exists a close relationship to the methods level (e. g., methods for measurements, calculations, simulations, and estimations of energy related figures like consumption, conservation, and cost). Specific parts of the knowledge are related to particular objects that are organized in the object level (e.g., energy use of individual parts, laws of energy dependent cost growth for size ranges). Furthermore, the energy related knowledge will be stored, located, developed, and distributed within the company with the help of information technologies. Last, the knowledge is also reflected by the organizational structure and its human resources (i. e., a company is organized as a matrix with a functional structure for day-to-day business and project-oriented structure for new product design projects).
In order to successfully handle these various and complex energy related knowledge required in the IPD, a systematic approach is needed for its management. That can be realized on the basis of process models and instruments of general knowledge management concepts.

3.2 Approach for the management of energy related knowledge

Knowledge management is an intentional and goal-oriented process to identify, develop/enhance, distribute, use, preserve, and update knowledge [10], [17]. The approach for a management of energy related knowledge in the design process will be composed of a theoretical framework with different knowledge management building blocks and recommendations for their design. The definition of the building blocks bases on the knowledge management approach by Probst, Raub and Romhardt [17], [18] (Figure 3).

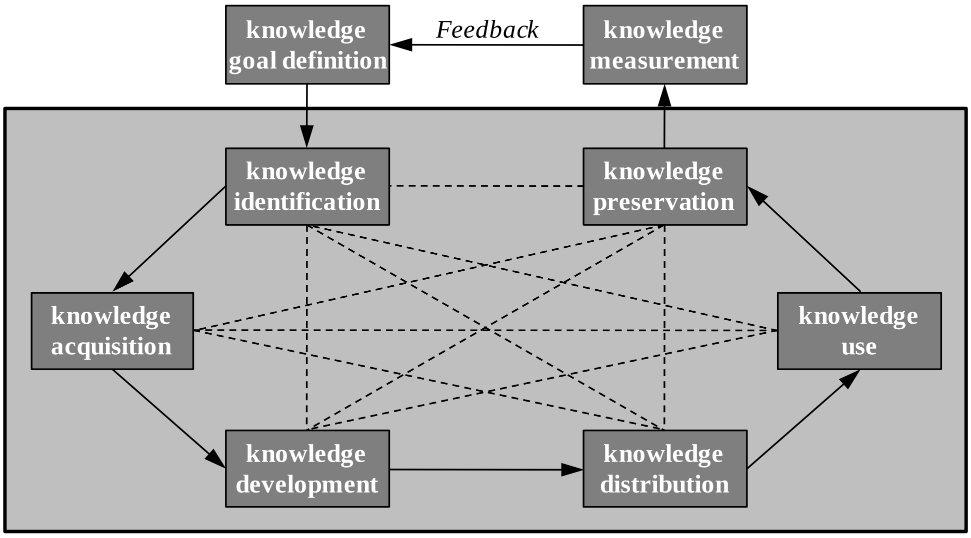

Figure 3. Building blocks of knowledge management by [17]

The grey box in Figure 3 contains the "operational" building blocks knowledge identification, acquisition, development, distribution, use, and preservation. They are the core processes of energy related knowledge management. Because, individual knowledge management "activities should never be conducted in isolation from one another" ([18], p. 20), the blocks are interrelated (dashed lines). In addition, the content and activities in the operational blocks need a direction. As this depends on the goals a company pursues with an energy related knowledge management, the framework is enhanced by two "strategic" building blocks, knowledge goal definition and knowledge measurement. Together with these additional blocks a superordinate management cycle is constituted [10], [15] which is similar to the PDCA cycle (plan, do, check, act) by Deming [19].
First, the proposed concept for energy related knowledge management in design processes will include the framework with specified building blocks for every step of the design process. Second, it should comprise a literature-based composition of recommendations for the specification of the blocks within the particular design steps.

Table 1. Management of energy related knowledge in the design process – examples from machine tool design

<table>
<tr><th>design steps / building blocks</th><th>requirements definition</th><th>concept</th><th>embodiment</th><th>detail design</th></tr>
<tr><td>knowledge goal definition</td><td colspan="4">normative: establishing a knowledge conscious corporate culture; developing a corporate knowledge philosophy with statements about the importance of knowledge within the company
strategic: decisions about the energy related knowledge that will be relevant in the future and has therefore to be preserved and developed
operational: deduction of individual sub-goals for the implementation of energy related knowledge management activities</td></tr>
<tr><td rowspan="2">knowledge identification</td><td colspan="4">identification of the existing internal and external energy related knowledge, e. g.,</td></tr>
<tr><td>market requirements like reduced carbon output</td><td>required machining processes, relevant working principles</td><td>needed active/passive, primary/secondary components</td><td>energy optimized time-dependent modes of operation</td></tr>
<tr><td rowspan="3">knowledge development/ acquisition</td><td colspan="4">acquisition and development of energy related knowledge, e. g.,</td></tr>
<tr><td>derived target energy values for processes, components</td><td>energy saving machining technology, working principles</td><td>calculation of theoretical process energy</td><td>detailed energy consumption estimations</td></tr>
<tr><td colspan="4">transformation of tacit into explicit energy related knowledge</td></tr>
<tr><td rowspan="3">knowledge distribution</td><td colspan="4">distributing of energy related knowledge, e. g.,</td></tr>
<tr><td>specifications for target energy values from the marketing department</td><td>machining process related drivers for energy consumption or conservation</td><td>energy efficient design guidelines</td><td>power input of purchase parts from the supplier</td></tr>
<tr><td colspan="4">multiplication of energy related knowledge; increasing the communication among the staff to improve the availability of energy related knowledge</td></tr>
<tr><td>knowledge use</td><td colspan="4">promoting the willingness to use existing and available energy related knowledge, e.g., by relieving psychological barriers of use</td></tr>
<tr><td rowspan="2">knowledge preservation</td><td colspan="4">storage and updating of internal energy related knowledge, e. g.,</td></tr>
<tr><td>experience with respect to the energy related customer requirements</td><td>results from process energy calculations for certain product functions</td><td>energy consumption (estimations) for similar machine tools, components</td><td>simulation results for a certain product configuration</td></tr>
<tr><td>knowledge measurement</td><td colspan="4">measuring the changes in the energy related knowledge base, review and evaluation of the achievement of the normative, strategic, and operational knowledge goals</td></tr>
</table>

On the one hand, a literature review concerning “energy related knowledge management in product development and/or design processes” yields the result, that authors do not raise issues like options to identify, develop, use, distribute or preserve energy related knowledge explicitly and in a structured way. On the other hand, the identified variety of energy related knowledge in the literature mentioned in the previous subsection can be used as a basis for the identification, development/acquisition, and preservation of energy related knowledge and the development of methodological support in the particular building blocks. Table 1 illustrates examples of possible activities of an energy related knowledge management concerning either one design step or the whole design process (analog to [9], [10] who arranged such activities with respect to cost knowledge). Such knowledge and respective methods to identify, use, and develop energy related knowledge are presented in the next section.

4 SELECTED METHODS FOR THE IDENTIFICATION, USE, AND DEVELOPMENT OF ENERGY RELATED KNOWLEDGE

In this section, two categories of methods are considered that are able to support the identification, use, and development of energy related knowledge in design processes. (Please note that these methods could also be discussed beyond the scope of knowledge management, i. e., simply as methods in design to energy efficiency.) First, methods are considered that can be applied to estimate, calculate, and/or simulate energy related output figures like consumption, conservation, efficiency, power losses, thermal dissipation etc. These methods are partly transferred from the domain of cost-oriented product development. In the following, they are called – according to the development-concurrent cost calculation methods of cost-efficient design – development-concurrent energy calculation methods. These methods map the relationships between technical parameters and energy related output figures using heuristic rules, statistically or analytically derived functions, equations, systems of equations as well as qualified estimations by domain experts and/or corresponding measurements according to the amount and accuracy of existing knowledge (see also [14]). Knowledge related aspects of these methods are described in section 4.1.

However, concerning the overall design process, these methods can only provide selective decision support. For a more comprehensive view and the realization of a continual knowledge engineering and generation process along the design process (and for the entire life cycle) more holistic concepts are needed. Target energy management is such a holistic approach supporting the management and controlling of design specifications and corresponding knowledge with respect to given design targets like minimum energy consumption or maximum energy conservation. Thus, in section 4.2 this approach and its contribution to knowledge identification, use and development are introduced.

4.1 Development-concurrent energy calculations

Methods for development-concurrent energy calculations support the identification, use and development of energy related factual and methodological knowledge which is necessary to evaluate and compare certain energy related output figure values for different design alternatives (and they are objects of methodological knowledge by themselves). Similar to the classification of methods for cost-efficient design [1] they can be categorized as shown in Figure 4:

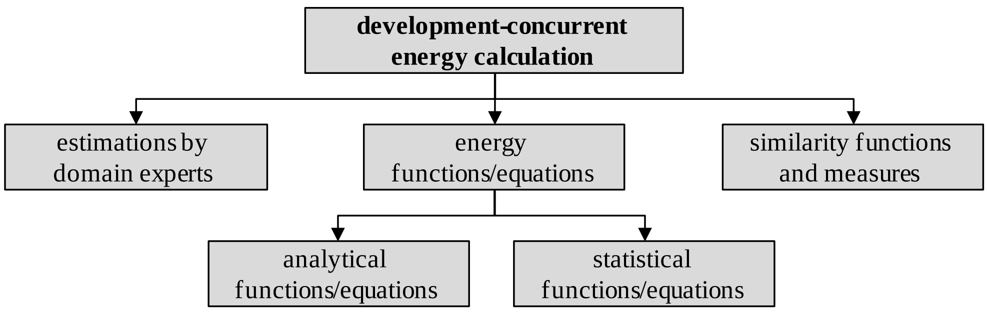

Figure 4. Classification of development-concurrent energy calculation methods

The methods can be understood as specific ways of knowledge engineering and generation that create energy related factual and methodological knowledge from corresponding ingoing knowledge items using one or more “conversion rules” (Figure 5).

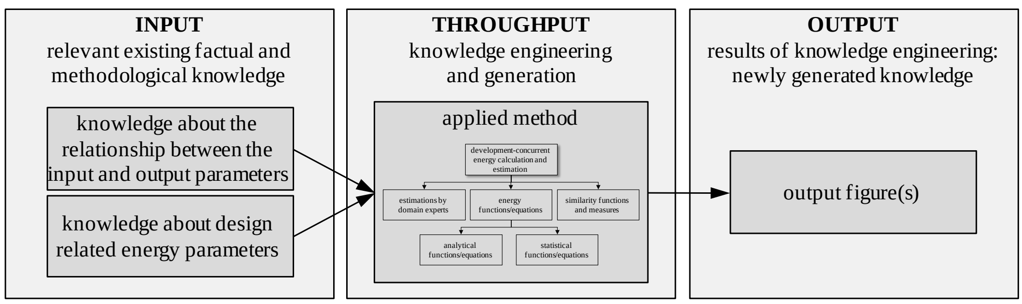

Figure 5. Input-throughput-output-representation for energy related knowledge engineering and generation

While estimations by domain experts usually base on a high part of tacit knowledge, energy functions (or equations) represent explicit knowledge that is result of analytical or statistical calculations to identify the relationships between energy related input parameters and output figures. Beyond that, energy forecasts could be made using product and company specific similarities of already existing products that must not necessarily base on analytical or statistical relationships. In the following, method specific characteristics of the ingoing and outgoing knowledge items are presented.

Estimation by domain experts

Estimations by domain experts are the partly or totally intuitive prediction of energy consumption and other energy related output figures for products, assemblies or individual parts on the basis of their experience. This requires a broad knowledge about the object of estimation (product, assembly, and part), its manufacturing and/or the potential operating conditions as well as its behavior during the use at the customer. But, due to the application of primarily tacit knowledge, estimations are always tightly connected to the expert and its expertise. Therefore, the estimation results as well as their origination are often not completely traceable for third parties and highly error-prone.

Energy functions/equations

In terms of the differentiation used in this paper, energy functions or equations are all mathematically formulated relationships usable to determine the values of energy related output figures (e. g., energy consumption, energy losses) as subject to one or more energy related input parameters. The functions/equations can be formed on the basis of deterministic/analytical or statistical relationships. They are applied to estimate, to calculate, and to simulate the values of certain energy output figures. Depending on the complexity of the object and the purpose of energy evaluation, deterministic energy functions could require simple factual and methodological knowledge about physical/thermodynamic relationships over more complex knowledge (Table 2) up to highly complex knowledge about how to set up dynamic simulation models on the basis of non-linear differential equations to evaluate the energy consumption of a whole complex product like a machine tool.

Table 2. Example for (relatively simple) energy related knowledge

Example	Determining the necessary power input (P_i) into a power line to get a certain power output (P_0) [20]
methodological knowledge	$P_i = P_0 + \left(\frac{P_0}{E_0 \cos\phi}\right)^2 \frac{2L\rho}{A}$
factual knowledge	E_0 root-mean square voltage at which the energy should be delivered $\cos\varphi$ power factor of the consumer's load L length of the power line ρ coefficient of resistivity A cross-sectional area of the cable

When designing new products, certain energy related figures could perhaps not be computed on the basis of deterministic functions/equations or the systems of equations are too complex to set them up for every new product. An example for knowledge belonging to this category is information about the effects of operating conditions on the daily energy consumption of a product and its components. Such information may be derived from statistical evaluations of series of measurements of consumption flows and the respective operating conditions. The resulting knowledge about the product's consumption behavior (e. g., load profiles for electricity use) can be input in new design processes where it allows to identify main energy consuming components and to direct energy saving actions.

Similarity functions and measures

Similarity functions and measures are used to forecast the energy outputs (e. g., consumption, conservation, losses, emissions) of particular products on the basis of comparisons with already existing similar products. Here, the term "similarity" expresses the degree to which design objects (e. g., products, assemblies, parts) are equal or not with respect to certain values of energy related product characteristics that can be influenced by design engineers. For example, measured load profiles for existing products could be used to form such similarity functions and measures. This enables a design engineer to retrieve the potential energy consumption of a new product in a certain operational environment from the load profiles and consumption of similar products in similar environments. Due to the divergence between similarity and equality, the consumption of the new and the reference product(s) is generally not the same. Thus, an adaptation has to be made for which again functions/equations can be applied.

In conclusion, it should be pointed out that the energy related input knowledge as well as the results derived with the described methods can be compiled in *energy tables* (analog to the well-known cost tables [1]). Energy tables contain structured information about energy consumption and/or other relevant energy related figures according to technical parameters. Thus, they help to identify the energy related impacts of design alternatives and production technologies. With respect to a knowledge management in design processes they contribute to nearly all operational building blocks (Figure 3).

4.2 Knowledge in a target energy management

The methods described in 4.1 only support the solution of subproblems. But they do not provide sufficient information for the management and controlling of design processes and the relevant energy related knowledge with respect to given design targets like minimum energy consumption or maximum energy conservation. Because of this, a *target energy management* approach is proposed that – analog to the target costing concept (see e. g., [21], [22]) – can be applied to control energy-oriented product design. Therefor, the systematic use and development of energy-related knowledge is a necessary prerequisite. Beside the stringent use of existing energy related factual and methodological knowledge as well as the creation of new knowledge, the target energy management procedure (for a detailed description see [23]) itself can be seen as part of the corporate knowledge (Figure 6).

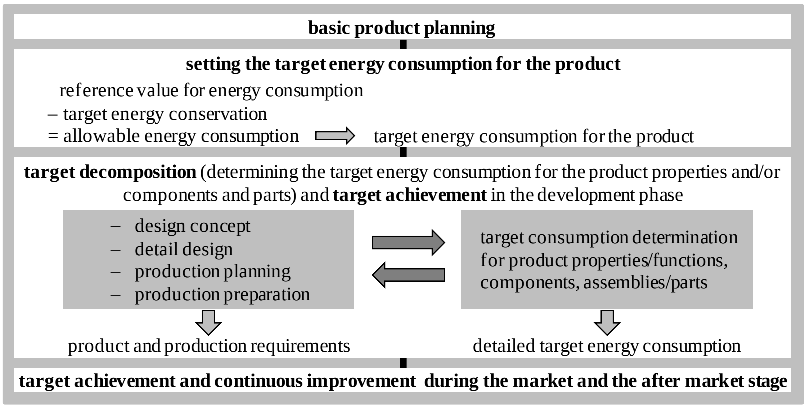

Figure 6. Process of target energy management

In general, the target energy management process consists of four steps (Figure 6): basic product planning, target determination, decomposition and achievement in the development phase, and achievement and continuous improvement in the market and after market stage. In particular, the detailed procedures depend on different factors as the product to be developed, its complexity, the determined target(s), etc. Therefore, for the following explanations a specified target is used: *design of a product with customized functionality and minimum energy use during its operation and maintenance phase.*
First, a *basic plan* for the new product on the basis of the company's product and corporate strategy and with a specific focus on energy consumption is defined. After that, the energy consumption target is established. Depending on the source of target determination (market, customer, intra-company), an allowable *target energy consumption is given* or *it is determined* by subtracting an energy conservation potential from a reference value (Figure 6). The energy related knowledge required to determine the energy target can be gathered from outside the company (e. g., conservation requirements, allowable levels of energy consumption, energy related benchmarks from competitors), but also identified inside the company (e. g., energy related figures of already existing products of the company).
In the next step, the established *target energy consumption is decomposed* up to the component, subassembly and part level. Following the conventional target costing procedure, the target is allocated on the basis of components benefit ratios (and analog assemblies and parts benefit ratios). The process starts with the identification of the product properties and their relevance (weighting) as perceived by the customers. Then, the product components and their contributions to property fulfillment are deter-

mined. Based on this, benefit ratios for the components are computed by summarizing the products of the components contribution to property fulfillment and the properties' weights. After that, the target energy consumption of every component is calculated by multiplying the respective benefit ratio with the total target energy consumption. To prove or to improve the results of this rather market-oriented decomposition, a component-allocation method may be used additionally [22]. Then, the target energy consumption will be directly allocated to the components, etc. This requires authoritative knowledge about energy consumption, consumption drivers, and conservation potentials from already manufactured and operating products and components of the company, component suppliers or competitors.

During *target achievement in the development phase*, methods for energy conservation of already existing components and the design of new low-energy components can be applied. Corresponding knowledge comprise among others

- when and how to use the above classified methods to estimate, calculate or simulate the energy consumption of different product components and the whole product,
- where (process, component, product level) and how energy usage could be eliminated/reduced (product specialization, component dimensioning, adjusted-to-needs energy usage [15]).

To control design specifications with respect to the fulfillment of customer requirements and consumption targets, a target energy consumption index, similar to the target cost index [1] can be used.

Especially with respect to an energy related knowledge management in connection with IPD, it is important to note that the target energy management process should not stop after the consumption target has been achieved in the design process. In particular for capital goods, without systematic maintenance of the energy consuming components the consumption would increase with time. Thus, *target energy consumption achievement and continuous improvement during the market and after market stage* as well as respective knowledge from these phases (e. g., about the effective energy use, load profiles, operating environment, and recycling alternatives) should be an integral part of a target energy management and subject of the company's energy related knowledge management.

5 CONCLUDING REMARKS

In summary, the paper showed an approach for the management of energy related knowledge which is, on the one hand, based on a framework for integrated product development, and on the other hand, on the general knowledge management concept by Probst et al. [17]. Then, this approach is specified by transferring methods for the handling of knowledge from the field of cost-oriented product development and cost management, respectively. First, development-concurrent energy calculations are proposed for the calculation, estimation and/or simulation of energy related output figures. Second, target energy management is introduced as a holistic approach for the management and controlling of design specifications and corresponding knowledge with respect to energy related design targets.

We would like to point out that the paper should be perceived as a conceptual basis. With respect to the proposed concept of knowledge management it has to be admitted that for some of the step-specific building blocks appropriate methodological support could neither be found in the literature nor be developed in the article. In particular, in relation to *energy-related cost knowledge* is only available to a limited extent, because it is company-specific and often restricted to the delivery cost of electricity, gas, etc. Thus, further research is necessary in the corresponding fundamental fields: (1) identification and classification of design specific energy related knowledge and methods for its efficient management including tasks as context sensitive retrieval, storage etc., and (2) more detailed methodological elaboration of interdependencies of energy related technical and cost knowledge (management), such as the extension of the described target energy management by cost aspects.

ACKNOWLEDGEMENT

The paper presents results from our research within the Cluster of Excellence 'Energy-Efficient Product and Process Innovation in Production Engineering' (eniPROD®) that is funded by the European Union (European Regional Development Fund) and the Free State of Saxony.

Europa fördert Sachsen. EFRE Europäischer Fonds für regionale Entwicklung

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