

Ontology-Based User Guidance for Energy Efficiency Optimization Measures

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Abstract—Energy efficiency has grown to a critical competitive factor of production systems. Governmental and non-governmental organizations as well as commercial consultants provide solutions for energy management. However, these institutions only draw up standards and guidelines to increase efficiency and do not provide actual measures. Due to inconsistencies in the understanding of energy efficiency, solutions are hardly comparable. Moreover, enterprises focus on knowledge about cost-efficient production systems, whereas knowledge about energy efficiency is put in second place, as the objective of environmental sustainability commonly is induced extrinsically. This leads to inefficiencies in the selection and application of energy efficiency measures. In this paper we provide an approach for using ontologies for selecting energy efficiency optimization measures. Through the use of ontologies, a categorization of energy efficiency measures is facilitated. In addition, ontologies are capable to describe relations between the concepts of the knowledge base and thus allow reasoning. Hence, the given approach is able to guide a non-expert user through the process of energy efficiency measure selection and moreover provides benchmark data for eligible solutions. Within this paper, we illustrate the application of the approach based on the examples of electric drives and pump systems.

Keywords— *Energy Efficiency, Optimization, Information Retrieval, Ontology, Green Production, Knowledge Base, User Guidance*

I. INTRODUCTION

Energy efficiency optimization of production systems is crucial for competitiveness of enterprises. Many companies therefore strive for increasing the energy efficiency of their production facilities. Besides the economic impact, a green corporate strategy also has effects on the company's public image and at least saves the environment. In order to support industry in this issue, governmental as well as non-governmental organizations provide guidelines and directives as e.g. ISO 50001 [1]. Energy management systems seize on this standards and provide methodologies, e.g. Plan-Do-Check-Act cycles to continuously optimize energy efficiency [2].

However, there are several challenges to face when implementing energy efficiency measures. Before implementing optimization measures, inefficiencies in production systems and the environment have to be identified. In order to reveal inefficiency within a production system, there has to be a profound understanding of the system to be optimized as well as the knowledge about optimization approaches. Hence, the person responsible for optimization has to be familiar with both the production system as well as available energy efficient measures. Particularly small enterprises do not have the resources to cover both domains of knowledge. Therefore many optimization potentials kept unrevealed and production is only partly energy efficient. Another challenge poses the definition of energy efficiency itself. According to ISO 50001, energy efficiency can be understood as the ratio or another quantitative relation between the output respectively the return on services, goods or energy and the energy deployed [1]. This leads to an inconsistent understanding of energy efficiency as companies are able to create their own KPIs to measure the energy efficiency. As a consequence, several optimization targets are conceivable, as for example the reduction of allover energy consumption or peak load as well as the enhancement of the carbon footprint. Hence, efficiency optimization measures can hardly be compared without considering the prevailing optimization targets. Moreover, there is a large knowledge pool about energy optimization measures. Even if the knowledge of a specific measure is accessible, the measure has to be retrieved. In order to identify the optimal measure for a specific system, there is a necessity to know all relevant and applicable solutions. However, machine users, who commonly have a broad comprehension of the system they are operating, mostly are no experts in the domain of energy efficiency. Even dedicated energy experts are not able to know every single optimization measure due to the large amount of knowledge on this issue. This poses a major challenge when selecting and applying measures to optimize the energy efficiency of production systems.

In this paper we present the approach to guide the user, in a company generally the person responsible for energy efficiency, through the process of selection and implementation of energy optimization measures. The given approach is based on the utilization of ontologies to describe both the status quo, i.e. the system to be optimized, as well as the knowledge about optimization measures. In section 2 we discuss the general use of ontologies for representing knowledge about energy efficiency. Section 3 is dedicated to the Knowledge-based Energy Optimization for Production Systems (KEOPS) approach and describes the methodology of user guidance within this approach. Section 4 eventually evaluates the approach with two exemplarily applications: the evaluation of electric drives and the selection of pump systems.

II. THE USE OF ONTOLOGIES FOR DESCRIPTION OF ENERGY EFFICIENCY MEASURES

A. *Ontologies as a means to represent knowledge*

The discipline of knowledge representation provides various approaches to structure data, information and knowledge. A possible way to represent knowledge is the use of lists or databases. However, when a hierarchy and relations among the parts of knowledge are necessary, these means easily come to their limits. Modern information retrieval systems thus utilize ontologies for knowledge representation [3]. According to [4], an ontology is ‘a formal, explicit specification of a shared conceptualization’. Ontologies thereby are capable not only to describe concepts, and thus relevant parts of reality, but to model relations among concepts and hence put the represented knowledge into context [5, 6].

Besides the ability to represent relations, ontologies are also able to handle incomplete or inconsistent information [7]. This feature allows the extension of the knowledge base with knowledge that is only partly available. Thus, information that may be spread over the company can be accumulated and joined to valuable knowledge. Moreover, ontologies allow to use case-based reasoning, as shown in [8]. Hence, not only existing knowledge can be represented but also new knowledge can be created. Using a comparison of solutions or input data, the resemblance of concepts can be derived. Out of this, the applicability of measures for specific problems is determined. By setting a threshold value, all available measures within this value can be applied for the problem, even if they are not explicitly assigned as a solution.

Another advantage of ontologies is the extendibility of the knowledge. Through the use of several levels of ontologies, specific knowledge about an application can be added without changing the general concepts of a domain. Furthermore, ontologies provide the advantage to represent knowledge in a formal way, i.e. the stored knowledge is machine-readable. Unlike databases, ontologies therefore provide a context that can be computed with a machine. This facilitates a human-machine-communication and reduces data necessary for machine-to-machine communication, as the context does not have to be calculated from a data mass. Therefore, ontologies have become a standard for knowledge representation and are utilized for a multitude of application fields. Exemplarily domains are agriculture, medicine or software engineering.

There are several methodologies to model ontologies. In this paper we utilize an iterative strategy based on [9] and [10]. The developed ontologies are evolved in three phases: the planning phase with a domain definition and determination of requirements, the modeling phase with the creation of classes and the setting of relations as well as the implementation phase with the choice of the representational language and the actual implementation of the models. These iterative steps are accompanied by continuous knowledge acquisition and evaluation and testing of the model.

A variety of representational languages can be used for the development of ontologies, such as RDF(S), DAML or KIF. In our work we draw on the Web Ontology Language (OWL). Compared to other description languages, OWL represents a quasi-standard and is supported by most developing environments [3]. Furthermore, a specific part of OWL, namely OWL-DL is capable to describe logic expressions. Thus, also more complex relations among concepts can be represented and inferences are facilitated. The modeling of the developed ontologies is realized with the software tool Protégé, a Stanford University development environment that can handle all common types of description languages [9].

B. *Ontologies in the energy efficiency domain*

In the domain of energy efficiency, ontologies mainly apply in the context of building technology. Shah et al. [11] show the use of ontologies for a classification of home appliances based on their energy consumption. Wicaksono et al. [12] describe the application of ontologies to control household devices and monitor their states. Another approach for the use of ontologies for eco-efficient building design is discussed in [13]. The authors propose the application of semantic web technology in the design process of buildings in order to provide a performance based design optimization environment.

The idea of an ontology-based description of automated manufacturing plants in order to enable the evaluation of energy efficiency is discussed in [14]. Using the lightweight ontology OntoENERGY, the proposed approach enables a continuous monitoring of energy efficiency of technical systems throughout their lifecycle. The authors show the validation of the ontology with a simulation model based on an actual test bed. The approach, in combination with the simulation model is capable of identifying and assessing optimization potentials. The approach provided in [15] uses an ontology as knowledge base for the implementation of energy management systems. The ontology represents concepts such as products, processes and resources as well as the relation among these energy-relevant elements. Hence, a holistic energy performance evaluation is enabled and can be conducted by both the employees and the management. Therefore, knowledge gaps about energy efficiency within a company can be overcome. Nevertheless, domain experts that develop specific measures for specific energy inefficiencies still are necessary and a knowledge transfer among companies or industries is hardly possible. For this purpose, in this paper we discuss the approach of the use of ontologies for the description of explicit energy efficiency measures for production systems. The next section demonstrates the general methodology that can be used for the process of energy efficiency optimization of a production facility.

III. KEOPS APPROACH FOR USER GUIDANCE

In [16] we firstly discuss the idea of describing energy efficiency optimization measures with ontologies. The proposed KEOPS approach is based on a problem-solving methodology, discussed in [17] with the aim to ensure an overview and practicability in use. The intention is to use elaborated problem-solving competences and to apply them to industrial problem solving and particularly to the field of retrieval of most suitable approaches for realizing energy efficiency in production systems. For this purpose we transfer the existing methodology and include the process steps in the KEOPS approach.

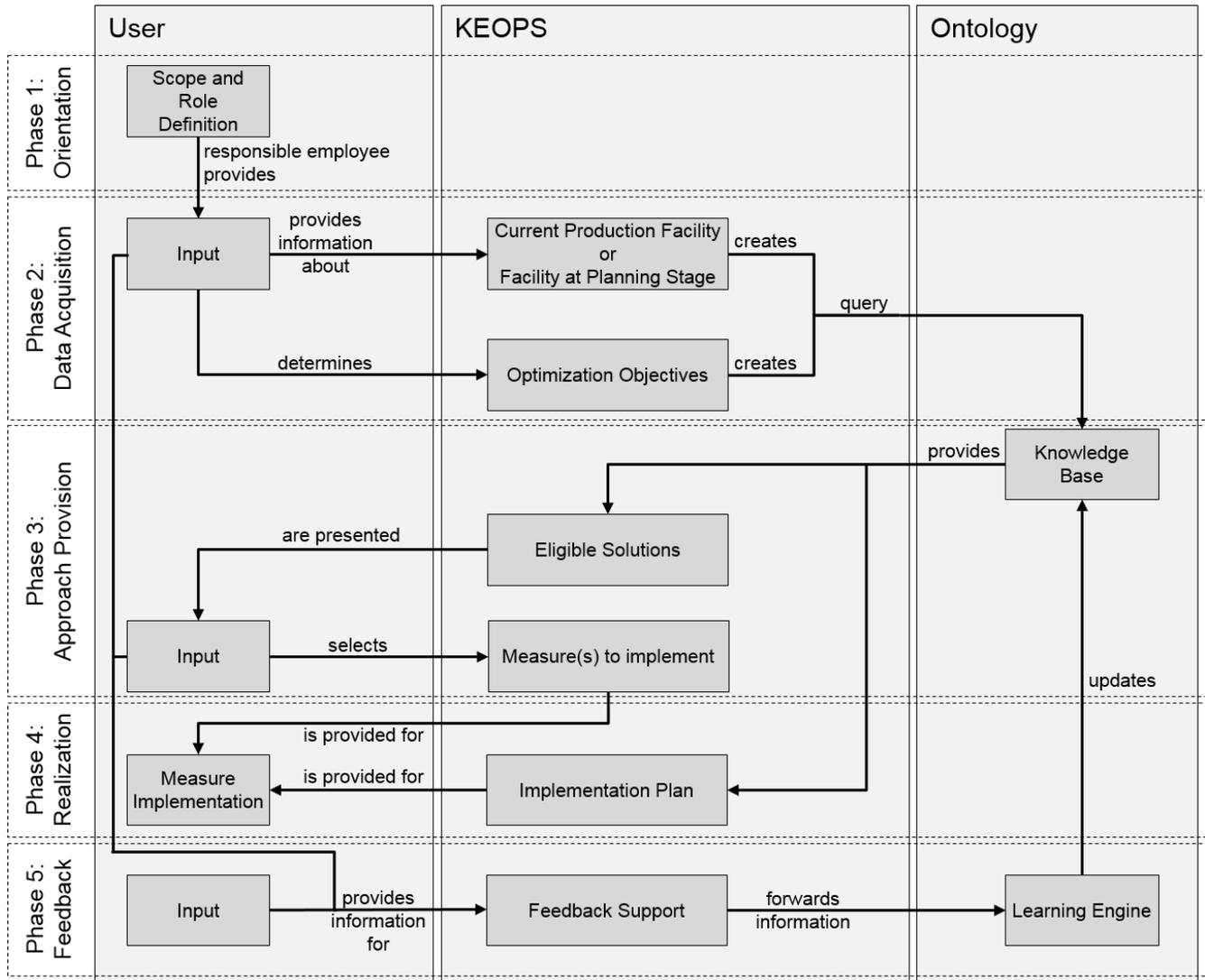


Fig. 1: The KEOPS approach provides user guidance within the process of selection and application of efficiency measures according to [16].

The approach shown in Fig. 1 consists of five phases that guide the user through the process of energy optimization: the orientation phase, the data acquisition phase, the approach provision phase, the realization phase and finally a feedback phase. At this, the sub-processes and information flows are assigned to three roles:

- The user who wants to conduct the energy efficiency optimization process, e.g. the energy manager or a process specialist,
- the KEOPS system, which provides GUIs and handles the communication between the user and the ontology,
- the ontology, which acts as a knowledge base for optimization measures.

In the following, the single phases are illustrated in more detail:

A. Phase 1: Orientation and Prerequisites

The first step of the KEOPS approach considers the creation of the prerequisites for the process of energy efficiency optimization. Efficiency measures commonly consist of a mostly complex set of processes and actions. Hence, the scope of optimization, i.e. the processes and resources to be optimized, as well as the roles and responsibilities for the improvement process have to be defined in the first place. This step is mainly driven by the management, involving relevant employees in order to ensure a higher acceptance of the optimization process and thus to realize higher saving potential. Major tasks are to set up a corporate strategy for energy efficiency, to clarify responsibilities for later tasks and to provide the necessary resources, e.g. funds, human resources and competences. The process goes along with the recommendations of ISO 50001 [1], specific implementation guidelines are shown in [2].

B. Phase 2: Data acquisition, situation analysis, problem description and target analysis

Once the responsibilities are set up, the optimization task has to be defined. In the phase of data acquisition, the user has to input all relevant information for the process of efficiency improvement. This input data contains both information about the systems to be optimized as well as about the optimization objectives. For this purpose, KEOPS offers tools to support the user in providing the relevant information. Initially, the current setup of the production system, or a system at planning stage, respectively, is required. This includes relevant parameters of processes, machines and the environment. As can be seen from that, the user previously has to know which parameters are relevant. At this issue, KEOPS provides a meta-ontology, containing the structure of an abstract production system and all relevant issues that can be taken into consideration for optimization tasks. The ontology can be understood as an empty blueprint of the real system which the user has to fill out. The meta-ontology is based on the ontology proposed in [18] and is adapted and extended by concepts of functions of system parts or processes as well as by knowledge about energy efficiency. The top-level concepts of the meta-ontology can be seen in Fig. 2. With this inquiry the user is able to describe the situation that is to be optimized, e.g. the power consumption of a machine, the built-in electric engines, the cutting parameters, etc. The communication model between the user and the ontologies is shown in Fig. 3.

- characteristic
- characteristicAttribute
- component
- function
- handlingDevice
- levelOfComplexity
- manufacturingTechnique
- material
- optimizationPurpose
- physicalVariable
- process
- subsystem

Fig. 2: Top-level concepts of the meta-ontology.

A second precondition for the search for optimization measures is the definition of optimization objectives. As aforementioned, energy efficiency is not an established terminology but can be understood in manifold ways. Examples are the reduction of the total energy consumption, the leveling of peak loads or the improvement of the carbon footprint. Hence, before selecting actual measures, the user has to determine the objectives he is pursuing with the optimization process. In order to support this task, KEOPS provides a list of common optimization targets in the field of energy efficiency. Nevertheless, the user can add his or her own objectives, if the actual target is not provided. A prioritization of optimization goals is supported using the analytic hierarchy process (AHP). For this purpose, we provide a special software tool that contains common optimization targets and that can be utilized for clarifying and determining the criteria for the search which is conducted in the next step.

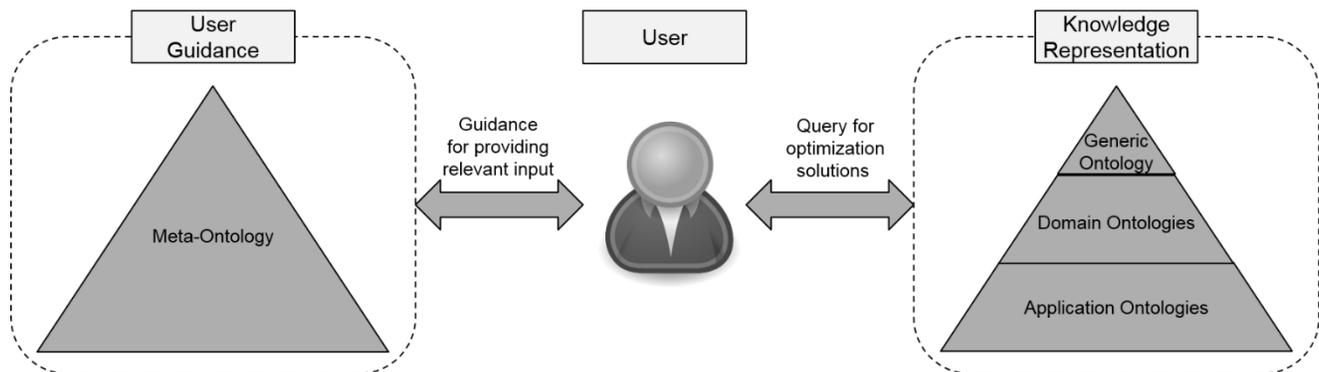


Fig. 3: User interaction with meta-ontology and knowledge base.

C. Phase 3: Provision of energy efficiency measures

Within this phase relevant and applicable energy efficiency measures, matching the search query defined in phase 2, are presented to the user. The user subsequently can choose one or several measures that are to be implemented. In the following we describe how the search query is conducted and how eligible solutions can be evaluated.

The first part of this phase comprises the search for applicable energy efficiency solution and the provision of the associated measures. With the information provided by the user, namely a thorough description of the optimization object in form of an ontology and the intended optimization objectives, a search query can be created and applied to the knowledge base. For this purpose, concepts of the status-quo ontology are compared to concepts in the knowledge pool regarding the predefined criteria. A concept, representing a specific energy efficiency measure, is returned, if it matches the boundary conditions of the production system described in the status-quo ontology and if it represents an improvement of energy efficiency. Subsequently, the relevant measures are presented to the user. In order to ensure that the solutions meet all requirements, the user has to evaluate the suggested results. The possible solutions have to be double-checked regarding their conformity with the stated goals. After confirming the applicability and the effectiveness of the measures, one solution or a combination of multiple solutions has to be selected.

D. Phase 4: Realization of energy optimization potentials

After an efficiency measure is selected, the solution can be implemented in the production system. For this purpose, an implementation plan has to be developed. At that the user can choose whether to use an implementation plan provided through the knowledge bases, when available, or to develop a distinct realization plan. The newly created implementation plan can be uploaded to the knowledge base in order to improve the existing data. The actual implementation of an energy efficiency measure is the completing part of the realization phase. At this process stage the user implements the solution in his production system and documents the implementation process. Thereby the realization plans can be evaluated and the existing knowledge about the applicability of energy efficiency measures can be updated. This ensures the knowledge base to be kept up to date and the data to be increased in quality.

E. Phase 5: Success monitoring and feedback

The final process step considers the knowledge feedback to the knowledge base. The user is able to provide experience of the implementation process and the effectiveness of the provided measure to KEOPS via an input mask. The input data is transferred to a learn engine that evaluates the effectiveness of the chosen solution for reaching the particular goal and eventually updates the knowledge base. Therefore, preferred and effective solutions are bookmarked, the knowledge pool can be personalized and improved.

IV. APPLICATION OF THE KEOPS APPROACH

In this chapter we demonstrate the application of the approach on two exemplarily domains. The first scenario covers energy efficiency with electric drives. The second scenario considers energy efficiency of pump systems. As the status quo of an existing production system is very specific and hardly transferable, and thus, not generalizable, we focus on the representation of the energy efficiency knowledge with an ontology and the selection of a specific measure.

A. Selection of electric drives

Electric drives have a great impact on industrial energy consumption. They account for 70 % of the overall energy consumption of manufacturing industry [19]. Moreover, 90 % of the lifecycle costs of electric motors are caused by energy, only 10 % emerge from purchase [20]. Energy efficiency measures for electric drives thus not only save the environment but almost always save costs. An effective way to reduce energy consumption is to apply the correct drive for the specific purpose. Garbrecht [21] proposes a methodology for selecting a motor for a specific application. The approach considers parameters such as required motor power, rotation speed or acceleration. For modeling the knowledge about drive selection, the given parameters are implemented as classes. Relations among these classes are modeled as object properties, characteristics that hold values are modeled as data properties. The top classes of the ontology as well as object and data properties can be seen in Fig. 4. The ontology covers common types of electric drives, such as:

- AC-asynchronous motors, optionally with starting capacitor and operating capacitor
- AC-synchronous motors, optionally with starting capacitor
- asynchronous motors, optionally with frequency converter in four-quadrant operation, position controller and speed controller
- commutator motors
- DC-permanent magnet motors, optionally with H-bridge, position controller and speed controller
- electric drives with H-bridge, optionally with position controller and speed controller
- stepper motors, optionally with DC-link
- synchronous motors, optionally with frequency converter in four-quadrant operation, position controller and speed controller.

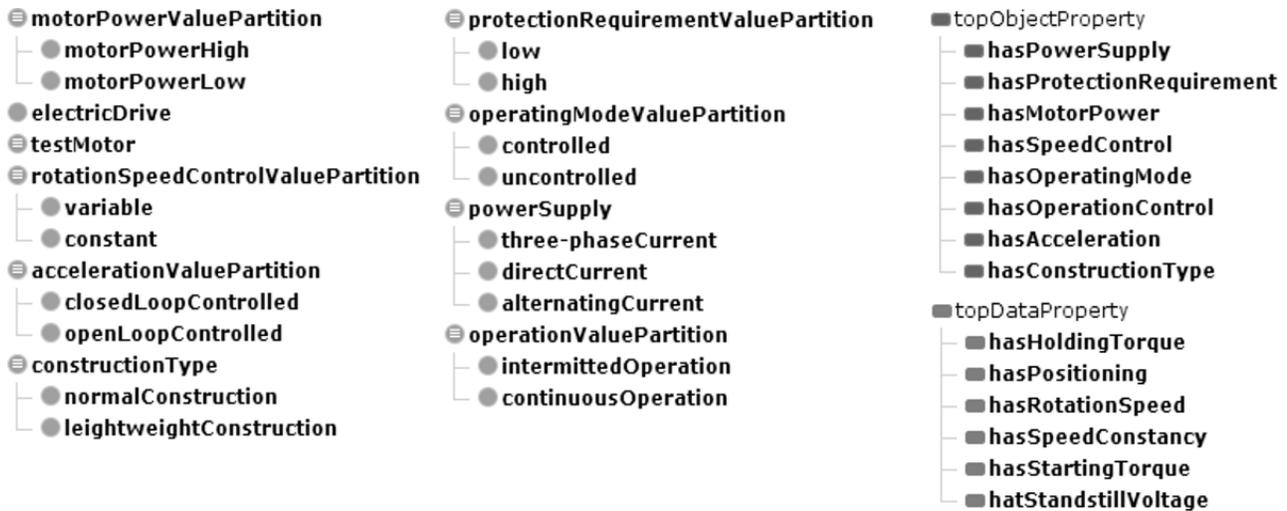


Fig. 4: Modeling of the knowledge about electric drives with classes (left and middle), object properties and data type properties.

Within the KEOPS process, the user creates a search query, according to his or her requirements, which can be applied to the knowledge base. For instance, the user requires an electric drive with a three-phase current power supply, or alternatively, an alternating current power supply and a closed-loop controlled acceleration. Positioning is not required. The query for this example is:

```
(hasPowerSupply some three-phaseCurrent
or hasPowerSupply some alternatingCurrent)
and hasAcceleration some closedLoopControlled
and hasPositioning value false
```

The query returns four possible types of electric drives: electric drives with H-bridge and speed controller, DC-permanent magnet motors with H-bridge and speed controller as well as synchronous and asynchronous motors with frequency converter in four-quadrant operation and speed controller. The results are shown in Fig. 5.

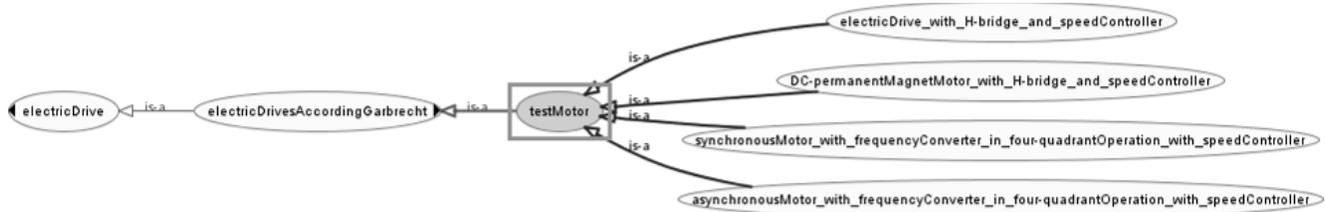


Fig. 5: Results of the query for selecting an electric drive.

In productive utilization, the user states his or her optimization objectives. The instances of the returned classes are filtered and sorted concerning these objectives. Hence, to the user a list of electric drives that are relevant for the specific application is returned. Subsequently, the user can evaluate the provided drives concerning additional criteria, such as investment costs or payoff time. A possible implementation plan that can be added in the knowledge base is an order form or the link to a web-based ordering system of the producer of the specific drive.

B. Pump systems

Equivalently to electric drives, also pump systems account for a notable share of industrial energy consumption. And as well, the energy efficiency of pump systems is dependent on correct selection of the pump system. When applied with incorrect parameters, a pump system can cause immense power consumption and the system even can be damaged. Typical parameters for the selection of pump systems are the lift head and the flow rate as well as the maximum switching frequency, which points

out the operation mode of the pump. Moreover, the field of application is a crucial criterion, as pumps are limited in the media, they can convey. The parameters are transferred to an ontology that can be seen in Fig. 6.

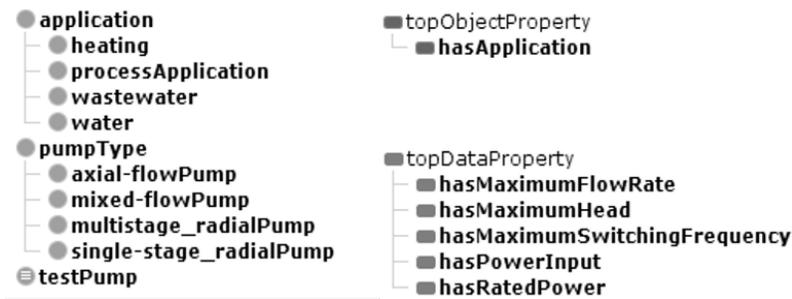


Fig. 6: Modelling of the pump system ontology

In order to demonstrate the selection of a pump system, we create six instances of pump systems with different pump types, different application fields and diverse characteristics. The created pumps cover a wide range within the field of pumps and are shown in Table I.

TABLE I. INDIVIDUALS OF PUMP SYSTEMS

Pump Feature	Pump Systems					
	Pump 1	Pump 2	Pump 3	Pump 4	Pump 5	Pump 6
Pump Type	Axial-Flow	Axial-Flow	Mixed-Flow	Mixed-Flow	Single-stage Radial Pump	Multi-stage Radial Pump
Application	Water, Wastewater	Water, Wastewater	Heating, Water	Heating, Water	Process Application	Water, Wastewater
Maximum Flow Rate in m^3/h	1×10^5	1×10^5	1×10^4	1×10^4	1×10^3	2×10^3
Maximum Head in m	15	15	20	20	150	4×10^3
Maximum Switching Frequency in $1/h$	15	40	15	15	15	15
Power Input in kW	1.01	1.15	2.69	3.21	7.06	10.17
Rated Power in kW	1.30	1.10	3.75	3.85	7.50	15.50

Given the situation that a user requires a pump system for conveying water, the lift head is 20 meters and the power input has to be 3.0 kW or less. With the description of the optimization objectives and the initial state, a search query can be created. The eventuating search query is:

```
(hasApplication some water)
and (hasMaximumHead some double[>= 20.0])
and (hasPowerInput some double[< 3.0])
```

The query results in pump 3 to be selected, as also can be seen in Table I. As there is only one result matching the requirements, the user only can choose whether to implement the pump system or not. For this purpose, further characteristics can be added. Within the knowledge base, there is also the possibility to attach information on implementation and usage, such as producer information, blueprints and manuals, if available.

C. Limitations of the approach

The KEOPS approach provides user guidance for the selection and implementation of energy efficiency measures. Due to the representation of both knowledge about optimization measures as well as meta-ontologies for the creation of queries, even users with no profound expertise on energy efficiency are able to optimize a production system. However, there are several issues to consider when using the approach.

A general issue of the knowledge description with ontologies is the structure of the knowledge base. A wide range within the represented knowledge is to be modeled with different application ontologies instead of one comprehensive ontology [9]. As there is a large variety in the knowledge about energy efficiency – there is knowledge about buildings, machines, processes, energy generation and much else – also a variety of ontologies is required. The quantity of ontologies is crucial for the performance of the system. Both a too large ontology as well as too many ontologies lead to a not optimal performance. Fig. 3 shows the general structure of the knowledge base. Both ontologies presented in this paper can be categorized as application ontologies. With the implementation of a wider range of efficiency optimization measures, the relevant domains and their interdependencies have to be identified and modeled. At this, a top ontology according to the one presented in section III is appropriate. The structure as well as the exact number of required ontologies is subject of further research.

Another challenge poses the maintenance of the knowledge base when the system is in use. In order to build-up or maintain a complex ontology system, both competences in the domain of knowledge representation and ontology design as well as a profound technical expertise are required. Especially knowledge about ontology design can hardly be provided by companies. On the one hand, this necessitates a standardized approach for modeling additional ontologies, e.g. through the use of a modeling meta-ontology. On the other hand, an automated method for maintaining existing knowledge is required. An algorithm for knowledge base maintenance regarding consistency is necessary, as well as a methodology for assuring the topicality of the implemented knowledge.

The major challenge when implementing the ontologies poses the large amount of knowledge within the domain of energy efficiency. A manual implementation of the entirety of knowledge neither is economic nor feasible. The transfer of knowledge into ontologies only is economically reasonable with the use of automated algorithms. An option is merging ontologies when available. The approach of inserting an existing ontology into another is discussed in [7]. However, this covers only a small part of the available knowledge. The major part of knowledge is available in form of natural language, i.e. texts such as books, papers, reports, etc. For this purpose, [22] discusses the approach of text mining. This approach allows the extraction of concepts and relations from natural texts and the automated generation of an ontology. Text mining already shows up adequate results for the English language. For other languages, e.g. German, however, the approach necessitates further dedication [3].

V. CONCLUSION

In this paper we discuss the approach of representing knowledge about energy efficiency measures in production environments with the use of ontologies. Due to the large amount of knowledge within this domain and the hurdle of insufficient knowledge of persons in response for energy efficiency, optimization processes in companies often are inefficient and insufficient. For this purpose we provide the KEOPS methodology for user guidance within the process of efficiency optimization. The approach enables the user interaction using a meta-ontology and AHP to create structured queries for information retrieval. Moreover, we show the applicability of the approach with two exemplarily applications. However, the use of ontologies for knowledge representation still is challenging and has its limitations. A major issue that should be addressed in further research is the automated generation of ontologies. At this, the approaches of ontology merging and text-mining offer a good potential. Moreover, various machine learning technologies offer opportunities to be discussed in the context of ontology validation and extension.

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BIOGRAPHY

Markus Brandmeier, born in 1987, is currently a research assistant at the Institute for Factory Automation and Production Systems (FAPS) at Friedrich-Alexander University Erlangen-Nürnberg, Germany. He holds a Master of Science degree in Industrial Engineering. His work in the research sector system engineering focuses on knowledge management regarding energy efficient productions systems. At that a special issue is the design of ontologies for describing energy efficiency measures.

Prof. Dr.-Ing. Jörg Franke, born in 1964, received his doctorate after studying production technologies in Erlangen with a thesis on the "Integrated development of new products and production technologies for space-molded interconnect devices (3-D MID)" at Friedrich-Alexander University Erlangen-Nürnberg. Since March 2009 he has been leading the Institute for Factory Automation and Production Systems (FAPS) at the University of Erlangen-Nürnberg. His research focus includes the development of new manufacturing processes for mechatronic products, in particular for electronic components, assembly of electric motors, as well as planning and simulation of complex mechatronic systems.