OntoENERGY – A Lightweight Ontology for Supporting Energy-efficiency Tasks

Enabling Generic Evaluation of Energy Efficiency in the Engineering Phase of Automated Manufacturing Plants

Tobias Linnenberg[1], Andreas W. Mueller[2], Lars Christiansen[1], Christian Seitz[2] and Alexander Fay[1]

[1]*Helmut Schmidt University, Department of Mechanical Engineering, Hamburg, Germany*

[2]*Siemens AG, Industry Sector, Advanced Technologies & Standards, Nuremberg, Germany*

Keywords: Energy Domain Knowledge, Energy Efficiency, Energy Conservation, Knowledge Acquisition, Energy Management, Ontology, Energy Engineering.

Abstract: To facilitate the automated evaluation of energy-efficiency aspects of a system in the early lifecycle phase of engineering, a consistent semantic definition of the relevant terminology as well as the interrelations between those terms is required. For this purpose, a lightweight ontology named OntoENERGY has been developed, which allows for continuous handling of energy-efficiency issues in technical systems throughout their entire lifecycle. To verify OntoENERGY, a simulation model based on a real test bed of an automated plant process was modeled, analyzed, and assessed, with a focus on energy consumption and the related information. This allows optimization potential to be identified and enables a direct assessment, with the aid of a simulation model.

1 INTRODUCTION

Resource efficiency and energy efficiency are both intensely discussed topics today, important not only in the context of the impending climate change, but also with regard to the turnaround in energy policy promoted by the German government. This topic requires new and enhanced methods to support the development of efficient systems (DECHEMA, 2009).

Energy is a special resource, occurring in different forms and quantities, and required throughout industrial systems. In general, energy efficiency therefore represents a special kind of resource efficiency. Technical systems, such as electrical installations, hydraulic systems, air compressors, and thermal systems all feature domain-specific characteristics requiring differentiated approaches in design and analysis to permit efficient operation. In this paper, we focus on the area of energy efficiency.

Energy-efficient tasks can be integrated into all phases of the product lifecycle. In the design and planning phase of a product, simulation tools are already used. These tools enable the most appropriate automation equipment to be selected and the optimal production process to be defined. In the operation phase, service tools for diagnostics and predictive maintenance could reduce the dissipation of energy and resources. Unfortunately, these tools are not coordinated with each other. To achieve this, a common understanding of data is necessary.

When it comes to capturing the required energy-related information, the fields of energy (management) systems and automation systems offer a wide spectrum of perspectives and glossaries with a great variety of possible interpretations. An explicit definition of the terms common to these fields of application as well as the formalization of their correlations is therefore essential in order to facilitate a sound analysis and understanding of the energy efficiency of a system design. It is also necessary for the identification of optimization potentials and precise communication about these aspects. With a view to the field of digital engineering and the tasks taking place within the digital factory context (Chryssolouris et al., 2009), we consider it advisable to enable the required software tools to handle these aspects in an automated and integrated way. This becomes even more important when it comes to the ongoing

Linnenberg T., W. Mueller A., Christiansen L., Seitz C. and Fay A..
OntoENERGY – A Lightweight Ontology for Supporting Energy-efficiency Tasks - Enabling Generic Evaluation of Energy Efficiency in the Engineering Phase of Automated Manufacturing Plants.
DOI: 10.5220/0004622903370344
In *Proceedings of the International Conference on Knowledge Engineering and Ontology Development* (KEOD-2013), pages 337-344
ISBN: 978-989-8565-81-5

demand for the integration of plant IT systems based on a homogeneous syntax and semantics (Sauer, 2010).

Here, ontologies depict a suitable tool for achieving this objective. Using ontologies, it is possible to structure knowledge in a manner that can be read by both machines and humans. This allows automated and distributed processing and analysis of energy-related information. Thus, defining and providing the required vocabulary is the first step toward facilitating engineering tools to perform automated reasoning on the soundness of system engineering measures. We therefore developed OntoENERGY as an easy-to-use vocabulary for the field of energy efficiency.

Although motivated by industrial needs in the field of automation systems in the manufacturing industry, OntoENERGY will be applicable to any domain with the need for the evaluation of energy-efficiency issues.

The structure of the paper is as follows. Section 2 provides an overview of related work. Section 3 presents the relevant fundamentals of the energy domain. In Section 4, the design of OntoENERGY is introduced, and Section 5 describes a first application scenario. A short synopsis in Section 6 concludes the paper.

2 RELATED WORK

When approaching knowledge formalization in the field of energy efficiency, it is essential to consider existing standards in this domain, especially since our work is motivated by industrial needs. The EU directive 2006/32/EG "Energy Service Directive" (European Parliament, 2006) and, derived from that, the German energy conservation law ("Energieeinsparungsgesetz"), as well as the German energy conservation regulations ("Energiesparverordnung"), based on the latter, can be considered as the most important. These provide mandatory minimum energy-efficiency requirements for real estate and property owners and other energy aspects. They apply to residential buildings, office buildings, and certain industrial facilities, taking into account not only the installed equipment but the entire balance of energy creation, storage, and handling. The energy flows are evaluated using primary energy factors.

The VDI directive 4661 "Energetic characteristics" (VDI, 2003) is designed to provide a broad and fundamental, uniform definition of the terminology encountered in the energy economy.

In order to capture and process energy-related information fully automatically, a semantic definition of the required terminology of the energy domain is required. However, from the perspective of the authors, there is no distinct ontological formalization of the fundamental terminology that is required for consideration of energy efficiency in general, and that can be directly applied to both automation and non-automation application domains. Nevertheless, several previous works can be used as reference to energy-related ontologies. (Borst et al., 1995) defined an extensive ontology for the modeling of physical systems. Here, energy is covered as an integral part in a generic but purely physical view, which does not suffice for capturing the information in the energy-efficiency context. On the other hand, (Zeiler et al., 2009) limited their approach to problems related to energy conversion processes in the building and infrastructure domains. Coming from this domain as well, the more extensive ontology by (Wicaksono et al., 2012) offers the possibility of capturing knowledge about (discrete) manufacturing processes as they relate to energy management. However, their work is on the level of domain ontology. Thus, these approaches have two drawbacks in common: They are only scalable within the designated range of applications, and their generalization, i.e. transfer and application to other domains, is difficult.

Comprehensive upper ontologies like SUMO (Niles and Pease, 2001) or SWEET (NASA, 2012) also define energy-related terms. Although their definitions are intended for generic use, both lack important aspects required in the energy-efficiency context. Also, their implementations do not permit easy subsetting for special application purposes.

3 FUNDAMENTALS OF THE ENERGY DOMAIN

Regardless of the respective field of application, there are many recurring aspects within the energy domain, which are considered as equal for all basic use cases, e.g. analyses. Therefore, the understanding of the fundamental terminology in the context of power engineering and energy economy, required for energy-efficiency support, forms the basis of OntoENERGY. Hence, this section provides the most important definitions, extending the industry-related VDI directive (VDI, 2003), which was chosen because of its maturity. Furthermore, these definitions can be based on fundamental mathematical relations.

3.1 Basic Definitions

Energy constitutes a fundamental physical variable, denoted by the SI unit of Joule [J] or alternatively Watt seconds [Ws]. According to the first law of thermodynamics – the law of energy conversion – energy can neither be created nor annihilated. Thus, energy cannot be "consumed" but only converted. Furthermore, a complete conversion of one form of energy into another is impossible according to the second law of thermodynamics. It states that energy conversion processes are always connected with thermal losses and the generation of entropy. In this context, we distinguish between three major interpretations of the term energy.

- The *physical* interpretation, which serves as a generic clause for the *electrical*, *chemical*, *thermal,* and *mechanical* forms of energy.
- The *industrial* interpretation, which categorizes the different forms of energy according to their appearance as primary energy and secondary energy.
- The *automation*-related interpretation, which aids in the understanding of manufacturing processes and hence requires a qualitative differentiation of the energy involved. Thus, we distinguish between the following four forms of energy:
  - *Product energy*, which is contained in the product itself. In a production process, it describes the energy contained in a work piece, e.g. thermal energy after a heating period or potential energy in high-rise storage.
  - *Process energy*, which is brought into the process and therefore affects the work piece. The energy content of a thermodynamic or mechanical system is controlled through process energy. Hence, any instance of process energy is accompanied by a change in product energy.
  - *Resource energy*, which depicts the "base load" of all consumers involved in the process. Such consumers support the process at least through subsidiary actions or the supply of energy. Examples are air compressors, transformers, automatic control systems, lighting systems, ancillary units, and heating, ventilation, and air conditioning systems (HVAC).
  - *System energy*, which represents the overall amount of energy of the entire automated system considered in the analysis. It embodies the total of all energy amounts and energy flows in the system.

Energy demand is a goal, based on the possibilities to satisfy it. Thus, it is defined as the amount of energy required to satisfy a goal or to produce a good with the aid of an appropriate technology under defined circumstances. For purposes of comparison, this is the quantification of an energy demand projected onto forms of primary energy carriers like coal, oil, or gas – the so-called primary energy factor.

The *cumulated total energy demand* of a system is determined by the total of all energy demands as required by all elements of the system (resource energy) and the process-related energy demand (process energy) (Verl et al., 2011). A detailed analysis of the total energy demand allows for the distinction between the steady use of resource energy and the fluctuating consumption of process energy, and consequently for the differentiation of fixed and variable elements of the energy demand. Additionally, processes and components that are not directly related to the main process, e.g. air compressors, lighting, or HVAC systems (Dietmair and Verl, 2008), still contribute to the total energy demand. Such energy-consuming processes cannot be allocated to a single process and thus need to be treated as a common energy demand. Finally, the actual energy demand is determined by the respective mode of plant operation (Dietmair and Verl, 2008).

Since energy cannot actually be consumed in the first place, there is no consistent definition for the commonly used term *energy consumption* in general literature. In (VDI, 2003), the term "delivered energy" is used, which describes the total energy content of primary and secondary energy carriers delivered to the consumer. From an external point of view, the "energy consumption" can thus be regarded as the energy delivered to a system. Aside from that, (VDI, 2003) also defines *energy consumption* as the "quantity of particular forms of energy consumed in order to cover energy demands under real conditions." Essentially, energy consumption refers to the amount of actually converted energy that has to be applied in order to reach a given goal. This depends heavily on different external and internal factors. According to (Dietmair and Verl, 2008), the current system state (e.g. idle, active, shut-down, etc.) can be regarded as the most important influence. Thus we can differentiate between fixed and variable parts of the amount of consumed energy – similarly to the energy demand.

3.2 Mathematical Correlations

In the following, the basic definitions depicted above are extended by fundamental mathematical correlations. These illustrate physical and economical correlations necessary to understand and analyze system performance with regard to energy efficiency.

Anergy represents the operationally unusable part of the energy, which may therefore be called “lost energy.” At the other end of the spectrum is *exergy*, which is the usable part of energy because it is convertible to usable work (Rudolph and Wagner, 2008). Exergy and anergy together form the total amount of energy, describing the working capacity of a system.

$$energy = exergy + anergy \tag{1}$$

The term efficiency, especially *energy efficiency*, is defined by various norms and directives (VDI, 2003), (European Parliament, 2006), which can be subsumed by equation (2).

$$efficiency = \frac{revenue}{effort} \tag{2}$$

Efficiency is the ratio of an energy-equivalent system output (the revenue) to the supplied energy input (effort) within a discrete time- or state space. Obeying the first and second law of thermodynamics, stating that technical processes are always subject to energy losses, this ratio ranges between [0, 1[. Efficiency is the most important factor when evaluating the performance of a system in terms of energy. This means that energy efficiency is the realization of an energy-related (conservation) goal met by a predefined effort.

Consequently, *energy dissipation* can be expressed as the difference between the actual demand and the target demand in the current system state.

$$dissipation = actual\ demand - target\ demand \tag{3}$$

Regarding the use of the value of dissipation for simulation purposes, for example, it is important to note that deviations of these two values may be induced by modeling errors or required simplifications. These abstractions must be regarded in detail when faults need to be identified by means of simulation.

4 DESIGN OF THE OntoENERGY ONTOLOGY

Having presented the terminological prerequisites, we will now describe the basic requirements for OntoENERGY, followed by the design decisions and their implementation.

4.1 Requirements

The main objective of OntoENERGY is to define semantics of the fundamental physical quantities and their interrelations as found in the energy domain. Although the use case initially addressed was the energy-efficiency evaluation of automated processes in order to identify related potential shortcomings and pitfalls already in the early plant engineering phase, we envision that it is applicable to any application or domain in which such energy analyses are needed. From this, we derived the following basic requirements, each of which has equal importance:

- Applicability: It must be possible to directly apply the ontology to energy-efficiency related analyses on factory automation machinery and their operation.
- Extensibility: It must be possible to consistently upgrade the ontology in subsequent usage scenarios.
- Portability: It must be possible to directly apply the ontology to different domains or port it into proprietary software tools with various use cases and conditions in the field of energy efficiency.

Hence, our requirement was that OntoENERGY must act as a lightweight upper ontology that application- or domain-specific ontologies can easily build upon. Furthermore, it must be easily integratable into various software tools, such as plant design tools or energy management systems.

4.2 Design Decisions

With the goal of creating an upper ontology, the focus of our work was on the TBox level, reaching a high degree of abstraction and support of domain-independent use cases. Several basic decisions were made in order to achieve a clear and understandable hierarchization of the terminology introduced in Section 3.

First, OntoENERGY should, insofar as possible, be usable as a single, small, stand-alone ontology without external dependencies, in order to be easily portable and integratable. The resulting hierarchization can be found in Figure 1.

Second, the distinction of the three main interpretations of energy (physical, industrial, and automation) should be retained. These are used to sub-classify the associated forms of energy.

Third, emphasizing OntoENERGY’s objective of supporting energy-efficiency analysis, the quantity of energy dissipation is regarded in this context as the most important result of a s ystem’s

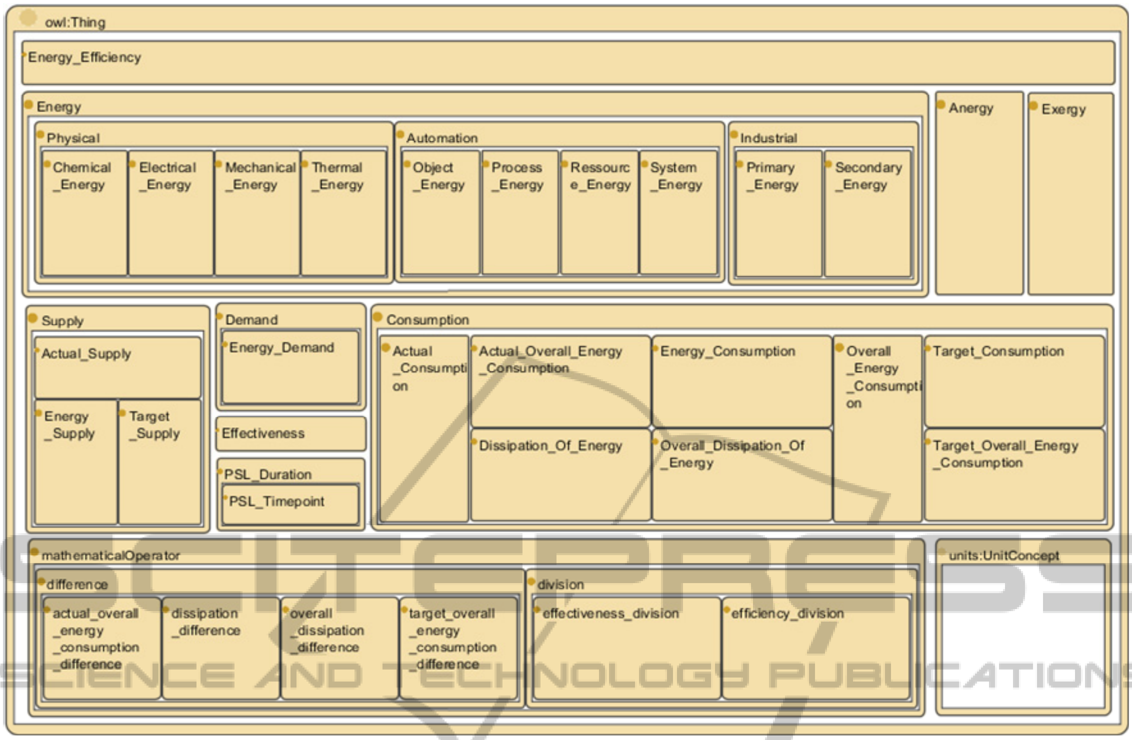

Figure 1: Concept hierarchy of OntoENERGY.

energy- efficiency evaluation. In OntoENERGY, it shall be classified as "non-productive consumption" of energy. This is due to the nature of energy dissipation, which stands for "consumption" of energy without increasing the value of the absorbing system.

Fourth, mathematical correlations are treated as terminological and modeled in the ontology in a way similar to that in SWEET (NASA, 2012), but in a compact and simplified form using explicitly defined roles, for example divisor and dividend as allocated operands of a division. The elaborated mathematical operations may be found on the bottom of Figure 1. Although full-fledged representations of mathematical concepts that allow for arbitrarily complex expressions exist, for example MathML (Carlisle et al., 2010), using these was considered unsuitable, since it would not meet the goal of easy applicability, and furthermore would exceed the scope of this work.

For implementing OntoENERGY, the Web Ontology Language (OWL) (Bechhofer et al., 2004) was chosen for practical reasons, especially because of its inherent support for automated reasoning and the tools available for coupling to third-party software.

4.3 Implementation

The definition of the overall structural and conceptual hierarchy of OntoENERGY followed the terminology and its relational structure as described in Section 3 (see Figure 1).

The concept *Energy* subsumes the subconcepts *Physical*, *Industrial* and *Automation*, representing the three interpretations of energy. These in turn subsume concepts representing the respective forms of energy. With their aid, tools can perform detailed energy analyses. Additionally, the concepts of *Exergy* and *Anergy* allow for assessments of energy quality.

The concepts *Supply* (as the "effort"), *Demand*, and *Consumption* (as the "claim") are used for describing the different processes of energy exchange and for subsuming various quantities while providing key performance indicators. Here, *Supply* is of particular importance in order to identify and categorize the sources and sinks of energy. Further, *Dissipation_Of_Energy*, as stated previously, is allocated to the *Consumption* superconcept.

Mathematical correlations involved in calculating different target values are subsumed under the *mathematicalOperator* concept. Due to the missing support of ternary relations in OWL (W3C, 2006), their respective semantics have been modeled using a hierarchy of object properties (see Figure 2), with adequately defined domains and ranges, for representing the roles the operands play in applying the operators.

Figure 2: Object property hierarchy for explicit mathematical correlations.

Hence, for instance, the calculation of energy efficiency is represented as

```
efficiency_division μ division *
  (=1 efficiency_has_dividend.Consumption) *
  (=1 efficiency_has_divisor.Supply)
Energy_Efficiency μ (=1
  efficiency_is_division_of.
    efficiency_division)
```

with the roles of all entities and also the formula involved being specified.

In order to analyze courses of energy consumption that occur for example during plant operation in general or execution of certain processes in particular, it is necessary to capture basic temporal information about the occurrences of values. Therefore, the basic concepts of *Duration* and *Timepoint* were borrowed from the Process Specification Language (PSL) (ISO, 2006).

For representing the quantities' units, `units.owl` of SWEET V1.1 (NASA, 2006) was included as the sole external dependency. This is justifiable, since this was also designed as a stand-alone ontology, and thus no further external references would be needed (in contrast to newer SWEET versions).

5 APPLICATION OF OntoENERGY

For application and proof of concept of OntoENERGY, the authors used a Siemens research facility in Nuremberg (see Figure 3), providing detailed energy usage information and employing a hybrid process in combination with a discrete simulation model, and for which a semantic model describing the plant structure and the process exists.

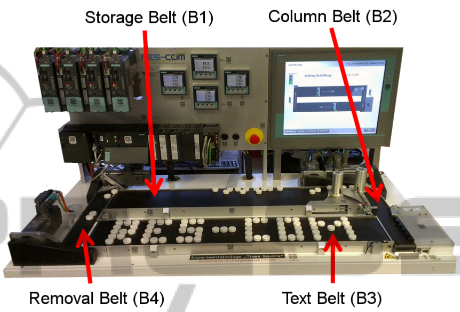

Figure 3: Siemens research facility.

The facility consists of four modules B1-B4, each consisting of a conveyer belt, a drive system (electrical engine and frequency converter), and various sensors. It is controlled by one Programmable Logic Controller (PLC). Moreover, there are energy meters for measuring the actual energy consumption of each module. The purpose of this facility is to generate an arbitrary left-to-right text, produced from small plastic disks, comparable to an electronic continuous text. Therefore, this process employs combinations of moving and stopping the electrical engines of B1 and B2 to create columns, resulting in the desired letters. By transporting the columns from B2 to B3 and discrete movement of B3, the letters are generated, which eventually results in a complete text.

As described in Section 3, the actual energy consumption depends on the modules' different modes and corresponding states during operation. Here, the demonstrator defines three different states.

First, the state *stand-by* denotes the fact that the whole system is supplied with energy but no actual process is carried out. The second state, *idle*, represents that only the cooling system of the frequency converter is running; again no process is carried out. The third state describes the actual execution of the *process* that properly moves the conveyer belts. For assigning the states of the demonstrator to the energy concepts of OntoENERGY, both the *stand-by* and the *idle* states refer to the concept *Resource Energy*. The concept *Process Energy* is assigned to the state *process*.

For energy evaluation, a reference process was examined in which all three states are addressed and the values described by OntoENERGY are delivered. If the reference process is started, the evaluation module in the simulation tool identifies the currently active energy state and the energy consumption associated with this state. The evaluation system can determine the upper and lower bounds for the energy states. The information is then passed on to consumer applications with energy-related tasks.

Figure 4: Detail of TBox extension with OntoENERGY.

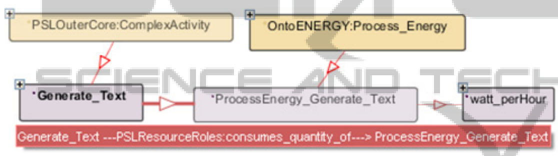

Figure 5: Detail of process knowledge annotation.

Since the reference process was executed several times with different rates, a corresponding power consumption curve exists for each velocity. With this evaluation mechanism, a complete energy report can be created that contains all information about the energetic behavior of each supervised component. This can be used to optimize or configure the system.

Because the primary intended use of OntoENERGY is the integration of different software tools within the field of industrial applications, a system setup with OntoENERGY resembles that in Figure 6. The arrows denote information flow (black: "raw" energy information, grey: semantically enriched information, which can be utilized for information interchange and also directly used by tools already based on semantic technologies), while the grey boxes denote components realized by the authors and the white box depicting an outlook for use of OntoENERGY-based information.

Using such setup, OntoENERGY enables the vertical integration of measured energy data, while at the same time permitting energy-related interactions between applications (horizontal integration).

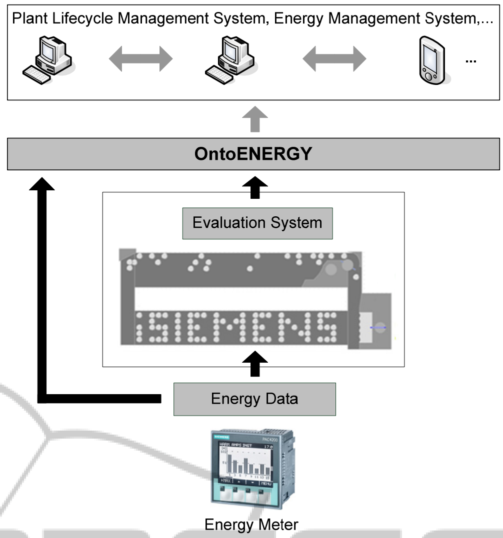

Figure 6: General system setup using OntoENERGY as common vocabulary (outline).

6 CONCLUSIONS AND OUTLOOK

The application of a simulation model in the engineering phase features two distinct advantages: In the context of long-term simulations, it can be used to predict future energy usage scenarios of single processes or entire plants on the one hand, and to evaluate planned process updates or the deployment of energy-efficient components and drives on the other hand. These energy-efficiency related analyses can be performed without changing the real-life test bed or disturbing the manufacturing process. Furthermore, the simulation model, reflecting the facility and process, helps to identify potentials for optimization and for developing and testing new engineering concepts as they relate to energetic aspects.

To facilitate the integration of process simulation tools and their energy-related results into the digital factory as well as a differentiated analysis and communication of energy consumption processes therein, a distinct terminological foundation and a definition of the energy-engineering related coherences is needed.

Requirements derived from these use cases were taken as the basic objectives when designing OntoENERGY. Thus, it features a precise semantic definition of the terminology as found in the energy domain. This allows for qualitative and quantitative allocation of different forms of energy throughout all engineering phases, using a consistent information model.

In order to cover a wide spectrum of different domains, the following three goals were regarded as equally important: 1. Applicability on factory automation machinery and its operation. 2. Extensibility and upgradeability in subsequent usage scenarios. 3. Portability and applicability to different domains or proprietary software tools.

Consequently, OntoENERGY has been realized as a universal lightweight upper ontology, allowing for individual adaptations while providing all necessary means for deploying it right out of the box. It can be easily integrated into future software tools and methodologies. The applicability of OntoENERGY to a process has been demonstrated on a real-life manufacturing domain test bed. Further steps will include the linking to third-party software tools and adaptations to specific domain requirements.

REFERENCES

Bechhofer, S., Van Harmelen, F., Hendler, J., Horrocks, I., McGuiness, D. L., Patel-Schneider, P. F., Stein, L. A., 2004: *OWL Web Ontology Language Reference*. URL http://www.w3.org/TR/2004/REC-owl-ref-20040210/. – accessed 19.04.2013.

Borst, P., Akkermans, J.M., Pos, A., Top, J., 1995. The PhysSys ontology for physical systems. In *Working Papers of the Ninth International Workshop on Qualitative Reasoning QR*, pp. 11–21.

Carlisle, D., Ion, P., Miner, R., 2010. *Mathematical Markup Language (MathML) Version 3.0*. URL http://www.w3.org/TR/MathML3/. - accessed 23.04.2013.

Chryssolouris, G., Mavrikios, D., Papakostas, N., Mourtzis, D., Michalos, G., Georgoulias, K., 2009. Digital manufacturing: history, perspectives, and outlook. In *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. Vol. 223, pp. 451–462.

DECHEMA e.V., 2009. *Chemieanlagen: ‚Operational Excellence' ist das Ziel: Trendbericht Nr. 3: Chemieanlagen-Konzepte.*

Dietmair, A., Verl, A., 2008. Energy Consumption Modeling and Optimization for Production Machines. In *Proceedings "International Conference on Sustainable Energy Technologies (ICSET)",* pp. 574-579.

European Parliament, 2006. *Directive 2006/32/EC on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC.*

ISO, 2006. *ISO 18629: Industrial automation systems and integration - Process specification language - Part 1: Overview and basic principles*.

NASA, 2012. *Semantic Web for Earth and Environmental Terminology (SWEET)*. URL http://sweet.jpl.nasa.gov. - accessed 21.04.2013.

NASA, 2006. *Semantic Web for Earth and Environmental Terminology (SWEET) V1.1: units.owl*. URL http://sweet.jpl.nasa.gov/1.1/units.owl. - accessed 21.04.2013.

Niles, I., and Pease, A., 2001. Towards a Standard Upper Ontology. In *Proceedings of the 2nd International Conference on Formal Ontology in Information Systems (FOIS-2001)*. Ogunquit, Maine, October 17-19, 2001.

Rudolph, M. and Wagner, U., 2008. *Energieanwendungstechnik. Wege und Möglichkeiten zur Optimierung der Energietechnik*. Springer. Berlin. Berlin 2008

Sauer, O., 2010. Trends in manufacturing execution systems. In *Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology,* pp. 685–693.

VDI, 2003. *VDI-Directive 4661: Energetic characteristics Definitions – terms – methodology*.

Wicaksono, H., Rogalski, S., Ovtcharova, J., 2012. Ontology Driven Approach for Intelligent Energy Management in Discrete Manufacturing. In *Proceedings of 4th International Conference on Knowledge Engineering and Ontology Development*. Barcelona, Spain, pp. 108-114.

World Wide Web Consortium (W3C), 2006. Defining N-ary Relations on the Semantic Web. URL http://www.w3.org/TR/swbp-n-aryRelations/. - accessed 05.03.2013.

Verl, A., Westkämper, E., Abele, E., Dietmair, A., Schlechtendahl, J. F.: Architecture for Multilevel Monitoring and Control of Energy Consumption. In Hesselbach, J., Hermann, C. (ed.): Glocalized Solutions for Sustainability in Manufacturing. Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd - 4th, 2011, pp. 347-352.

Zeiler, W., van Houten, R., Boxem, G., Savanovic, P., van der Velden, J., Wortel, W., Haan, J.-F., Kamphuis, R., Hommelberg, M., Broekhuizen, H., 2009. Flexergy. An ontology to couple decentralised sustainable comfort systems with centralized energy infrastructure. In *Proceedings of 3rd International Conference on Smart and Sustainable Built Environments (SASBE)*.