Towards an Energy Information System Reference Architecture for Energy-Aware Industrial Manufacturers on the Equipment-Level

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ABBREVATIONS

ARIS	Architecture of Integrated Information Systems
DG	Design Goal
DSRM	Design Science Research Methodology
EG	Epistemic Goal
EIS	Energy Information System
RQ	Research Question
TOGAF	The Open Group Architectural Framework
UML	Unified Modeling Language

CHAPTER I:

SEPARATE DISCOURSE

(GESONDERTE ABHANDLUNG)

1 MOTIVATION

"Acquire new knowledge whilst thinking over the old, and you may become a teacher of others."

Confucius (551 BC–479 BC)

This section is divided into three sub sections. Section 1.1 begins by briefly reviewing the concepts of energy, information, energy information, and their importance in industrial manufacturing. Section 1.2 then moves on to consider the aspect of energy information systems (**EIS**). In addition, the used terminology is clarified. Finally, the research goal and the structure of the dissertation are defined in section 1.3.

1.1 FROM ENERGY TO ENERGY INFORMATION

The concepts of energy and information have several meanings and scopes, depending on the subject of discussion. In this thesis, the concept of energy is seen as a representation of *"(…) physical cost of action in the real world"* (Hu and Zeigler 2011). The concept of information can be described with four aspects: *information-as-process, information-as-knowledge, information-as-thing,* and *information processing* (Buckland 1991).

The thought experiment of Maxwell's Demon suggests a link between energy and information (Knott 1911). On the one hand, *information-as-knowledge* can be used to improve the usage of energy (**energy efficiency**) (Knott 1911). One the other hand, obtaining information (*information processing and information-as-process*) requires the usage of energy (Hu and Zeigler 2011). Therefore, information about energy (**energy information**) combines the concepts of energy and information.

Since energy is limited, responsible use of energy is desirable. The energy information can be enriched with the financial, political, social, environmental, and technological factors that influence the energy usage (Pillmann et al. 2006; Bunse et al. 2011; Seidel et al. 2013; Effenberger and Hilbert 2018).

As the collection of energy information consumes energy, the outlined key challenge should be primarily addressed in domains that have a great potential for improving the energy efficiency. Industrial manufacturing is one of these domains. This can be seen in several industrial branches (Matsuda et al. 2012; Wu et al. 2012; Han et al. 2015; Effenberger and Hilbert 2018). In this thesis, the industrial manufacturers that are aware of this key challenge are called **energy-aware industrial manufacturers**.

For energy-aware industrial manufacturers, the financial and political factors (e.g. subsidies, laws, or the ISO 50001) are particularly relevant, since they must pay attention to profitability and compliance. Therefore, the measures for increasing the energy efficiency should make economic sense. This aim can be achieved with information systems that support the industrial manufacturers in their decision-making process (Watson et al. 2010; Goebel et al. 2013).

The research area of energy informatics, defined as a new subfield of information system research in 2010, *"(...) is concerned with analyzing, designing, and implementing systems to increase the efficiency of energy demand and supply systems"* (Watson et al. 2010). One of the general aims of energy informatics researchers is therefore the development of information systems that are capable of increasing the energy efficiency. To differentiate information systems with this specific aim from other information systems, the term energy information system (EIS) is used.

1.2 ENERGY INFORMATION SYSTEMS

The term EIS can be used as a hypernym for a variety of different systems. In the recent literature of the scientific community, EIS may include terms like *energy-aware information system, environmental decision support system, environmental* *management information system,* or *energy and carbon management system* (El-Gayar and Fritz 2006; Watson et al. 2010; Melville and Whisnant 2014). However, every of these EIS include the same principle: energy information (*information-as-thing)* is collected, transformed (information processing) and then prepared for analysis, resulting in *information-as-process* and *information-as-knowledge* for the user. Therefore, the term EIS is sufficient.

In the context of industrial manufacturing, EIS have been used to analyze the energy consumption in a larger scale, e. g. the energy consumption of the whole plant. However, the potentials for increasing the energy efficiency related to this level are exhausted and the equipment-level receives a growing attention. This is due to today’s increasing availability of cost-effective sensors that are used to obtain energy information from different equipment of the plant. The energy information can and should be enriched by machine information of the equipment. In the context of this thesis, machine information is defined as every production-relevant information with time reference for the observed equipment (Effenberger and Hilbert 2017). Regarding the aspect of *information-as-thing* and *information processing*, the time reference links machine and energy data.

The research area of industrial EIS is still very young. A recent and intense study of the literature on this topic concludes that the development of industrial EIS is being neglected (Effenberger and Hilbert 2018). The research is dominated by the use of case studies and mathematical modeling; in most of these case studies, the EIS are developed individually (Effenberger and Hilbert 2018). The lack of results regarding the development of EIS is unsatisfactory (Watson et al. 2010). However, there is a strong need for supporting the development of EIS to enable the effective improvement of the energy efficiency (El-Gayar and Fritz 2006; Goebel et al. 2013; Melville and Saldanha 2013; Melville and Whisnant 2014; Effenberger and Hilbert 2016).

1.3 RESEARCH GOAL AND STRUCTURE OF THE DISSERTATION

In summary, it can be stated that there is a need for improvement of the energy efficiency, especially for energy-aware industrial manufacturers. This problem can be addressed with EIS; however, these are still developed individually and lack support in the development process. Therefore, the research goal of this thesis is *to support the development of energy information systems for energy-aware industrial manufacturers in the form of reusable artifacts.*

This work is a cumulative dissertation. Therefore, this thesis is divided into two chapters: *Separate Discourse (Chapter I)* and *Publications (Chapter II).* The individual publications have their own structure and can be found in *Appendix A-D*. This section explains the structure of the separate discourse.

As can be seen from **Fig. 1**, the separate discourse is divided into three main sections: *Motivation, Research Design,* and *Results*. The section *Motivation* defines basic concepts and leads to the concept of energy information. Based on this concept, energy information systems are introduced. Their current challenges are briefly outlined in order to present the research goal.

Based on the research goal, the section *Research Design* approaches the research questions (**RQ**), epistemic goals (**EG**), and design goals (**DG**) from two angles. On the one hand, the basic scientific position is clarified. On the other hand, based on this position, the role of design science for reaching the research goal is examined. The RQ, EG, and DG are explained in section 2.3. The article then moves on to discuss the chosen methodology by assigning the RQ, EG, DG, and the articles into the separate steps of the research process.

Based on the chosen methodology, the section *Results* answers the RQ and discusses the epistemic achievements first, followed by the components of an EIS architecture which can be seen as the reached DG. Finally, the limitations and an outlook for future research are discussed.

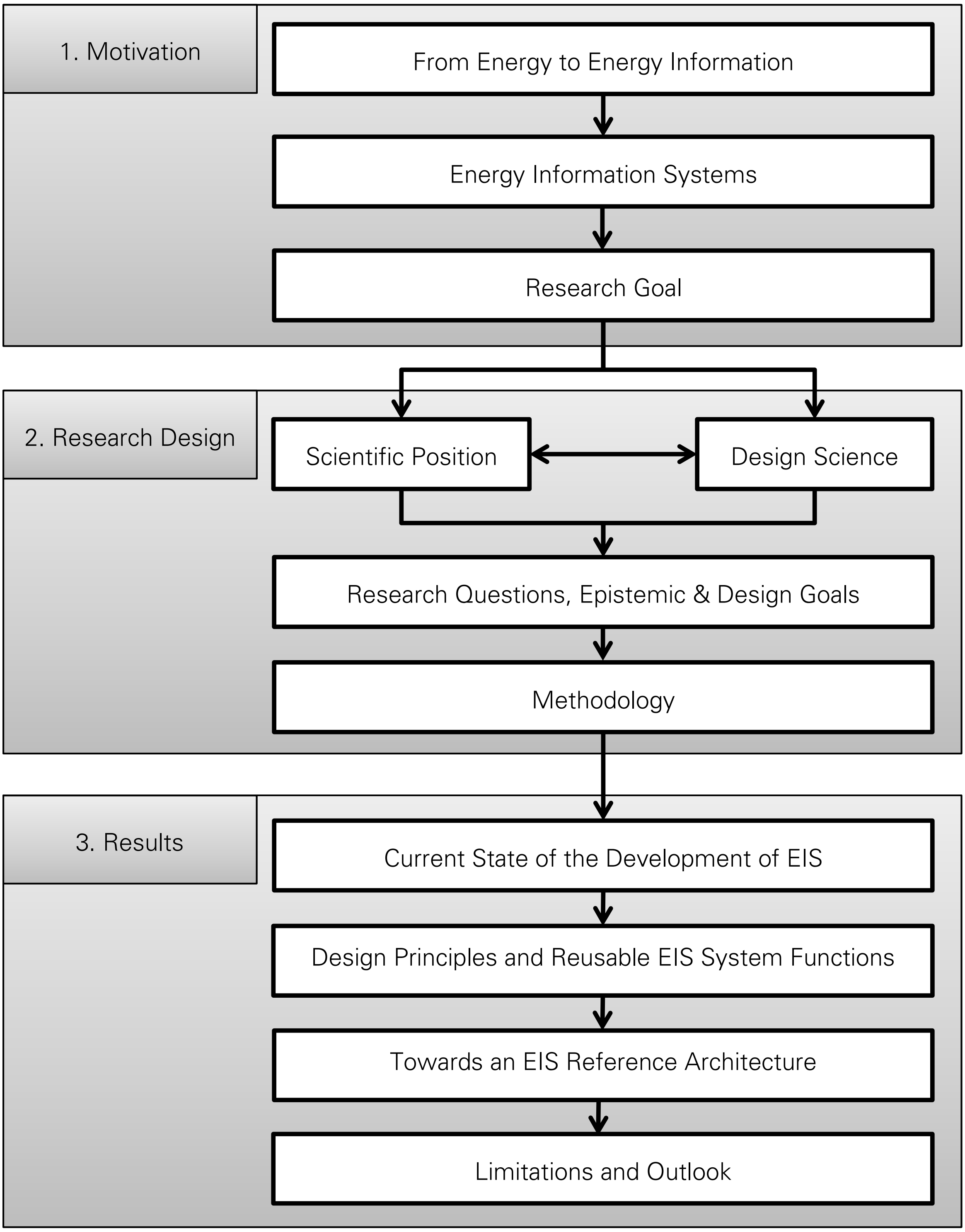

Figure 1. Structure of the separate discourse

2 RESEARCH DESIGN

"Have the course to use your own understanding!"

Immanuel Kant (1724-1804)

This section is divided into four sub sections. Section 2.1 begins by determining the scientific position of the thesis. Section 2.2 then moves on to discuss the position regarding design science. Section 2.3 presents the research questions as well as the epistemic and design goals of this thesis, followed by an explanation of the applied methodologies in section 2.4.

2.1 SCIENTIFIC POSITION

In order to be able to reach the research goal, the basic scientific position must first be defined and explained. The selection of the main criteria for the following argumentation is based on the frame of reference for the epistemological positioning of reference modeling (Becker, J. Niehaves, B. Knackstedt 2004).

In the opinion of the author, there must be an objective reality that we perceive subjectively. With regard to this ontological realism, we construct our own subjective reality through our sensory inputs and thoughts. Knowledge of objective reality arises from our intellect, mind, and experience. Therefore, knowledge and truth can be obtained inductively and deductively. In addition, the author follows the consensus theory of truth. To summarize, the author assigns this doctoral thesis to the context of moderate constructivism.

2.2 DESIGN SCIENCE

Based on the scientific positioning, the question arises as to how the research goal can be achieved. With the help of design science, it is possible to solve problems with simultaneous consideration of rigor and relevance (Hevner et al. 2004). The practical and scientific relevance of the given problem makes design science particularly suitable. Furthermore, design science supports both the moderate constructivism from the scientific position and the development of reusable artifacts from the research goal (Becker, J. Niehaves, B. Knackstedt 2004; Hevner et al. 2004). The resulting artifacts can be *"constructs, models, methods, and instantiations"* (Hevner et al. 2004).

Based on a construction-/design-oriented model understanding, a basic way to achieve the research goal is the use of modeling, especially reference modeling. "*A reference model is a representation of different sections of the real world that are ordered according to specific criteria and belong to a specific category (e.g. an industry) or to a specific task (e. g. architecture modeling)*" (definition is based on Fettke and Loos 2004a; the quote is translated from Baumöl 2018). In the context of reference modeling and design science, there are *methods* (methods for reference modeling), *constructs* (languages for reference modeling), models (reference models) and instantiations (models) (Fettke and Loos 2004b).

Furthermore, a reference model can be characterized by the fact that a reuse in the development of models is desired (Becker et al. 2004). However, economic advantages, for example in time and thus cost savings, only arise when reference models are actually used (Fettke and Loos 2004b). Therefore, well-designed and used reference models might be able *to support the development of energy information systems for energy-aware industrial manufacturers in the form of reusable artifacts.*

In addition, a reference model might be seen as a component of a reusable architecture description. The term architecture is defined by the ISO/IEC/IEEE 42010:2011 as "*fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution*", whereas the architecture description is the "*work product used to express an architecture*" (ISO/IEC/IEEE 2011). At this point, it should be mentioned that there are several architecture models, e.g. the Architecture of Integrated Information

Systems (**ARIS**) or The Open Group Architectural Framework (**TOGAF**). However, the ISO/IEC/IEEE 42010:2011 follows a more generic approach with the construct of an architecture description. At this point, a specific architectural model like ARIS or TOGAF is not needed; such an action might limit the consideration of all necessary aspects of an EIS.

An architectural description encourages the development of different viewpoints and views for an EIS. Viewpoints are needed due to the fact that an energy manager has a different set of requirements than a maintainer of an EIS. The usage of viewpoints enables the system architect to frame different sets of requirements, whereas the view is a model that is assigned to a viewpoint.

Taking into account the research objective and a practical relevance, it is helpful not just to develop reference models, but to classify them into an architecture description. This would allow system architects to use all of the corresponding models together and to develop EIS more efficiently and effectively. Therefore, a reusable architecture description that consists of reference models (**reference architecture**) might provide the needed standardization and reusability to support scientists and practitioners in developing EIS in the future.

Furthermore, the used models, constructs, and methods in this thesis can be assigned to the components of a theory (**design theory**) (Gregor and Jones 2007). Within the field of design science research there is a dissent about the role of the classic kernel theory in design theory processes and design science research methodologies. Basically, a distinction can be made between three views:

- *kernel theory fundamentalists* need *a* kernel theory for grounding and a design theory as a result
- *kernel theory pragmatists* need no kernel theory for grounding and a design theory as a result
- *design theory opponents* need no kernel theory for grounding and no design theory as a result (Fischer et al. 2010)

On the one hand, a kernel theory for grounding is not necessarily needed, as can be seen from the pure existence of insightful and successful results of design theory opponents and kernel theory pragmatists. On the other hand, the fundamental problem of the (possible) missing reusability of the results of design science cannot be ignored. This research therefore seeks to bridge the gap from the design theory opponents to the kernel theory pragmatists and structures the results of this thesis along the components of a design theory.

This aim in the context of design science research might be achieved with the usage of **design principles**. Even if the exact definition of the term is still under discussion, design principles allow the capturing and communication of essential design knowledge (see Chandra et al. 2015 for an in-depth consideration of the term).

In addition, the *"concept of design principles aims to ensure a guided creativity for developers and architects that use them for the development of design science artifacts"* (Effenberger 2018) and enables researchers to accumulate new and reusable knowledge and therefore support purposeful design science theories (Gregor and Jones 2007; Chandra Kruse et al. 2016).

2.3 RESEARCH QUESTIONS, EPISTEMIC & DESIGN GOALS

As stated in section 2.2, the research goal of *supporting the development of energy information systems for energy-aware industrial manufacturers in the form of reusable artifacts* should be addressed in the context of design science. Therefore, it is useful to further differentiate the research questions (RQ) that are resulting from the research goal into epistemic goals (EG) and design goals (DG). First of all, it must be examined whether the assumption that the development of EIS is neglected is tenable. This leads to the first RQ and EG:

- **RQ1:** *What is the current state-of-the-art regarding the development of energy information systems?*
  EG1-1: Current state-of-the-art as well as research gaps and questions regarding the development of energy information systems.

To be able to answer RQ1, a systematic literature review was performed (Effenberger and Hilbert 2018). The state-of-the-art corroborated the assumption that the development of EIS is neglected and led to the current research gaps and RQ in this field of study. This was the starting point of the following RQ, EG, and DG:

- **RQ2:** *What are the informational requirements of energy-aware industrial manufacturers and which of them can be used for the development of reusable EIS system functions?*
  EG2-1: A catalog of reusable EIS system functions which are derived from the informational requirements.
  DG2-1: A reference function view for an energy information system reference architecture.

At this point it should be stated that an information requirement analysis is a useful method for the development of information systems and therefore for EIS (Stroh et al. 2011). However, at least a reference information view is necessary. Therefore, the following RQ, EG, and DG arise:

- **RQ3:** *What are the design-relevant abstractions of a reference information model focusing on the combination of energy and machine data for energy-aware industrial manufacturers?*
  EG3-1: A catalog of design principles that capture the knowledge for developing an information model for the combination of energy and machine data.
  DG3-1: A configurable reference information view for an energy information system reference architecture.
  DG3-2: A methodology for configuring the information view.

It can be discussed whether EG3-1 is not a design goal. However, by considering design principles as accumulable knowledge and therefore design-relevant abstractions, the epistemological character is in the foreground.

2.4 METHODOLOGY

As can be seen from section 2.3, a systematic literature review and an information requirement analysis have already been mentioned. Before discussing these methods in detail, the overall research methodology should first be explained. There is a variety of methods for developing reusable artifacts and several of them can be applied. To be more concise, a certain commonality can be found in the various methodologies (Ostrowski and Helfert 2011). Therefore, the thesis could be assigned to the steps of multiple methodologies. However, a methodology must be chosen. Therefore, the lines of thought that have led to a concrete decision are revealed below by discussing the two most promising methodology candidates.

There is a design science roadmap, which places value on intensive requirements analysis and conception (Alturki et al. 2011). This methodology can be seen as a consensus of multiple design science methods and is therefore particularly extensive (Ostrowski and Helfert 2011). However, in this methodology, it is written that - in the step "Explorer Knowledge Base Support of Alternatives" - a kernel theory is needed (Alturki et al. 2011). Even if the research fits well into the methodology for the most steps, the kernel theory contradicts the own scientific positioning (see section 2.2).

A similar method is the design science research methodology (**DSRM)** (Peffers et al. 2007). This methodology includes all the important processes and steps and is not as complex as the design science roadmap. There are several research entry points and an iterative process for artifact improvement is supported. Furthermore, no kernel theory is needed for this methodology. Regarding the RQ, EG, and DG, this methodology fits well (see **Fig. 2**).

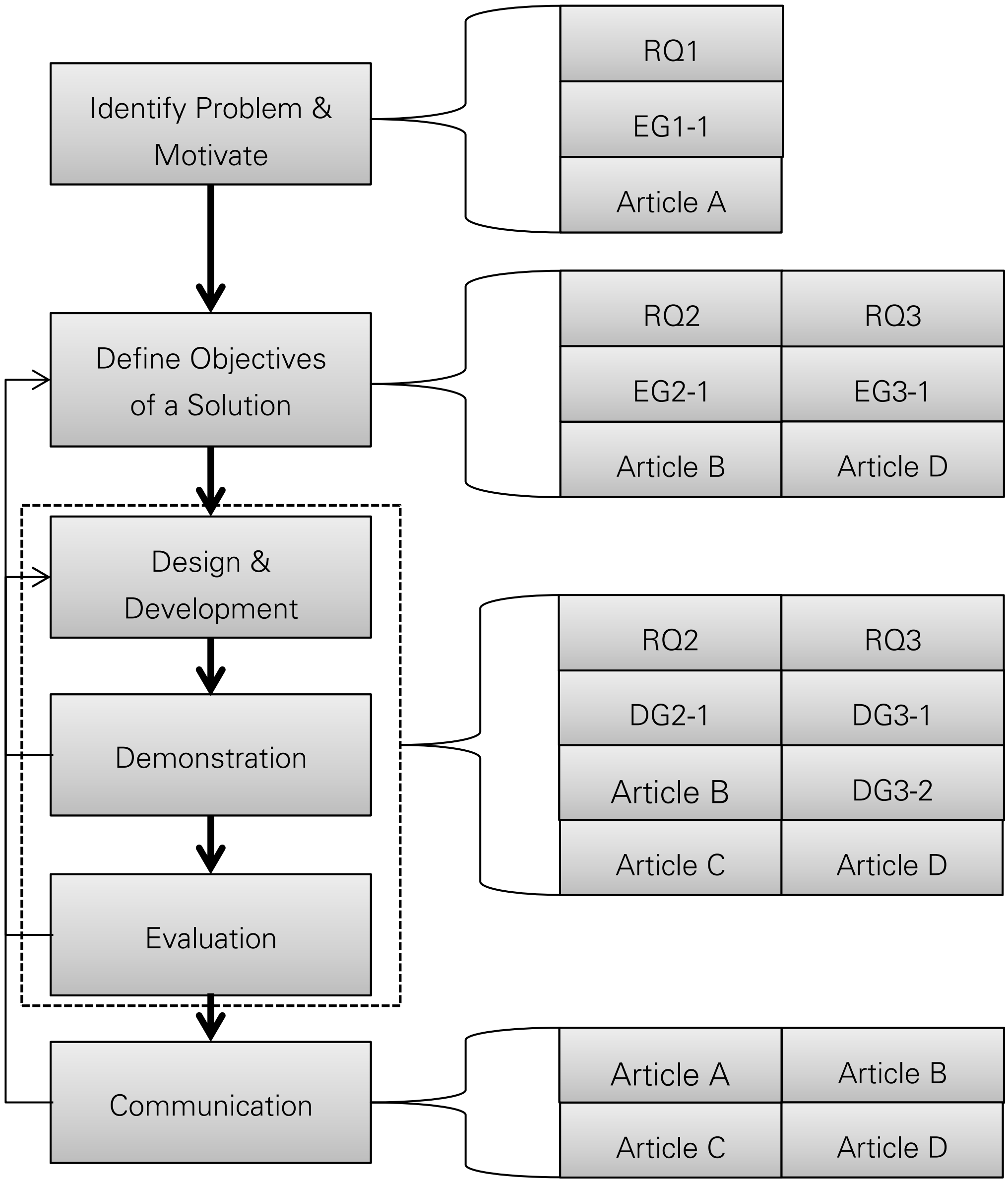

Figure 2. Assignment of articles, research questions, epistemic and design goals to the design science research methodology (Peffers et al. 2007)**.**

As can be seen from Fig. 2, the methodological approach is problem-centered (Peffers et al. 2007). For the phase *Identify Problem & Motivate* a systematic literature review, based on the methodology of Kitchenham and the guidelines of Webster and Watson, was performed (Webster and Watson 2002; Kitchenham 2004; see Effenberger and Hilbert 2018 for more details). This literature review was combined with an argumentative deductive approach and resulted in EG1-1, which led to the development of RQ2 and RQ3 and their corresponding EG and DG.

Regarding the phase *Define Objectives of a Solution*, two different methodological approaches, both based on case studies, were used. The basis for answering RQ2 and reaching EG2-1 was a document-based informational requirement analysis (Effenberger and Hilbert 2016). The key challenge was to identify the common informational needs based on several cases. Due to these circumstances, no prioritization was possible and similar informational requirements of multiple industrial manufacturers had to be summarized. In addition, a situational assignment of these information requirements was not possible (Stroh et al. 2011). These key challenges were addressed by focusing on the conceptual similarities of the informational requirements. This abstraction automatically led to a special formulation of informational requirements that resulted in functional system requirements and therefore system functions.

It is difficult to assign a methodology for the abstraction of design principles from multiple sources. Design principles were written down after the evaluation of the case studies and by thinking over and discussing the design-relevant abstractions with system architects. A mixture of one group and two individual interviews as well as extracted design principles from case studies is the exact description of the applied research process (see Effenberger 2018 for more details). The design principles had to ensure that reusable knowledge for the whole domain of EIS for energy-aware industrial manufacturers was captured.

The catalog of system functions and the design principles were the basis for DG2-1, DG3-1, and DG3-2. These DG were reached by applying the *Design & Development*, *Demonstration*, and *Evaluation* phases of the DSRM. The application of the system functions and design principles can be seen as a cycle which was reapplied in four case studies to refine the artifacts (Effenberger and Hilbert 2017; Effenberger 2018).

However, the artifacts affected the design principles and vice versa. Finally, the *Communication* can be seen as the publication of this and the other articles.

3 RESULTS

"The impediment to action advances action.

What stands in the way becomes the way."

Marcus Aurelius (121-180)

This section is divided into four sub sections. Section 3.1 begins by examining the current state of the development of EIS. Section 3.2 then moves on to discuss the reusable EIS system functions and the design principles. Section 3.3 examines the components of an EIS reference architecture. Furthermore, the results are structured along the components of a design theory. Finally, section 3.4 concludes with the limitations, and an outlook for future research is discussed. In this section, the results are outlined and explained in a concise manner to show their role in the overall doctoral thesis.

3.1 CURRENT STATE OF THE DEVELOPMENT OF EIS

> **RQ1:** *What is the current state-of-the-art regarding the development of energy information systems?*
> **EG1-1:** Current state-of-the-art as well as research gaps and questions regarding the development of energy information systems.

The referred article can be found in Appendix A. The aim of this article was to perform a systematic literature review for substantiating the initial assumption of this thesis that the software development aspect of EIS has been neglected. The initial assumption was substantiated with the results of the systematic literature review.

The methodology was based on Kitchenham and Webster & Watson (Webster and Watson 2002; Kitchenham 2004). The main result of this article is that the software development aspect of EIS for energy-aware industrial manufacturers is neglected. Therefore, RQ1 was answered and EG1-1 reached. This resulted in two new RQ (RQ2 and RQ3) and their corresponding EG and DG. Therefore, this article represents the basis for the identification of the problem of this thesis. There is a small, more general reformulation of the identified RQ in section 2.3. This has no substantial impact, because the reformulation was done for a better understanding on how the RQs support the research goal.

3.2 DESIGN PRINCIPLES AND REUSABLE EIS SYSTEM FUNCTIONS

This section is divided into two sub sections. In section 3.2.1, the development and role of the reusable EIS system functions are discussed. Finally, the development of the design principles is examined in section 3.2.2.

3.2.1 Reusable EIS System Functions

> **RQ2:** *What are the informational requirements of energy-aware industrial manufacturers and which of them can be used for the development of reusable EIS system functions?*
> **EG2-1:** A catalog of reusable EIS system functions which are derived from the informational requirements.

The referred article can be found in Appendix B. One aim of the article was to define a reusable catalog of system functions that supports system architects in their architecture rationales. In the first step, a document-based informational requirement analysis was performed. Regarding the ISO/IEC/IEEE 42010:2011, the main stakeholders were the energy managers and energy engineers (users, operators, acquirers, and suppliers of the system). The standard suggests adding even more types of stakeholders (owners and maintainers of the system); however, the aim of this research is not to design one specific architecture for one purpose. As described in section 2.4, the analysis of different cases limited the possibilities of performing a proper prioritization or situational determination. However, the omission of these two aspects is even beneficial in this case. Now, a system architect can use the catalog, independent of the situation and prioritization. To be more concise, the situational determination and prioritization takes place in the concrete planning of an instantiation. In order to transform the informational requirements into functional system requirements (system functions), the system requirements definition process based on the ISO/IEC/IEEE 15288:2015 was used (ISO/IEC/IEEE 2015).

To summarize, the main result of this article is a catalog of system functions that can be reused by system architects to support their architecture rationales. Therefore, RQ2 was answered and EG2-1 was reached. If a new EIS needs to be designed, system architects can use the list of the system functions for selecting and prioritizing the needed functions for their specific instantiation. This was a crucial benefit for the case studies that were performed in this thesis.

3.2.2 Design Principles

> **RQ3:** *What are the design-relevant abstractions of a reference information model focusing on the combination of energy and machine data for energy-aware industrial manufacturers?*
> **EG3-1:** A catalog of design principles that capture the knowledge for developing an information model for the combination of energy and machine data.

The referred article can be found in Appendix D. One aim of the article was to identify the design-relevant abstractions of an information model regarding the combination of energy and machine data. As explained in section 2.4, the concept of design principles was chosen to document the design-relevant abstractions.

One striking aspect is the formulation of the design principles. Since the DSRM has been chosen and the long-term goal is a configurable reference information model, the design principles focus on "*material properties and do[es] not say anything about action*" (Chandra et al. 2015, the note in brackets was changed by the author).

However, Chandra et al. (2015) suggest that the formulation of design principles should include more aspects by combining material properties with action properties and boundary conditions: "*Provide the system with* ***[material property—in terms of form and function]*** *in order for users to* ***[activity of user/group of users—in terms of action]****, given that* ***[boundary conditions—user group's characteristics or implementation settings]****.*" (Chandra et al. 2015).

In the context of this article, the formulation of design principles can achieve this suggestion by adding the reusable EIS system functions in order to define the possible actions and the boundaries of the system. Therefore, the design principles and system functions have to be considered together. Regarding the ISO/IEC/IEEE 42010:2011, this result frames the concerns of developers and system architects (developers and builders of the system) (ISO/IEC/IEEE 2011). In addition, the design principles encapsulate architecture rationales.

Therefore, the main result of this article is a catalog of design principles that describe the materiality aspect of a configurable reference information model for the combination of energy and machine data for energy-aware industrial manufacturers. These design principles can be combined with the system functions to be the foundation for components of a reference EIS architecture. Therefore, RQ3 was answered and EG3-1 was reached.

3.3 TOWARDS AN EIS REFERENCE ARCHITECTURE

This section is divided into three sub sections. In section 3.3.1, the decomposition & allocation view is further explained. The article then moves on to discuss the main result of the thesis: the configurable reference information model in section 3.3.2. Finally, in section 3.3.3 the results are structured along the components of a design theory.

3.3.1 Decomposition & Allocation View

> **RQ2:** *What are the informational requirements of energy-aware industrial manufacturers and which of them can be used for the development of reusable EIS system functions?*
> **DG2-1:** A reference function view for an energy information system reference architecture.

The referred article can be found in Appendix B and is based on the reusable EIS system functions from section 3.2.1. The aim of the article was to use the catalog of system functions and turn them into a component for an EIS reference architecture for energy-aware industrial manufacturers. Since the article is based on the description of an architecture from the ISO/IEC/IEEE 42010:2011, a decomposition & allocation view was used to reach the goal (ISO/IEC/IEEE 2011).

The aim of the decomposition & allocation view is to divide the EIS into sub components and assign these to the functional system requirements (system functions). This increases the usefulness of the system functions, since system architects obtain an additional classification and structuring option. Furthermore, since EIS are developed individually, this allows a certain degree of standardization. Regarding the naming conventions of the ISO/IEC/IEEE 42010:2011, this result is a decomposition & allocation view that is governed by the decomposition & allocation viewpoint. The view and viewpoint frame every of the identified concerns from the catalog of system functions (ISO/IEC/IEEE 2011). The architecture model governs the model kind; in this case, this is a component diagram from the unified modeling language (**UML**). The component diagram is instantiated by identifying the needed system functions and removing the components that are not needed from the catalog of reusable EIS system functions. Within the diagrams, the system functions were formulated in the active to ensure a better readability. The diagrams can be found in Appendix B-II.

Therefore, the result of the article is the allocation of system functions to reusable components. By using predefined and configurable components, a basic and reusable decision support is given to the system architects. Therefore, a further standardization is achieved. This standardization enables system architects to select and allocate system functions based on their requirements. The decomposition & allocation view is a component for the research goal of an EIS reference architecture. Therefore, DG2-1 was reached.

3.3.2 Configurable Reference Information Model

- **RQ3:** *What are the design-relevant abstractions of a reference information model focusing on the combination of energy and machine data for energy-aware industrial manufacturers?*
  DG3-1: A configurable reference information view for an energy information system reference architecture.
  DG3-2: A methodology for configuring the information view.

The referred article can be found in Appendix D. The aim of this article was to develop a configurable reference information model for energy-aware industrial manufacturers at the equipment-level. In addition, a methodology for configuring the information model had to be developed.

The goals have been reached and the results were evaluated within four case studies and within multiple discussion rounds with two system architects to ensure that the results were useful. Furthermore, it was shown that the usage of the reference information model leads to an improved quality (increased effectiveness) and savings in terms of costs and time (increased efficiency). Regarding the naming conventions of the ISO/IEC/IEEE 42010:2011 this result is an information view that is governed by the information viewpoint. The view and viewpoint frame every of the identified concerns from the design principles (ISO/IEC/IEEE 2011). The architecture model governs the model kind; in this case, this is an extension of the UML called CROM (Kühn et al. 2014).

3.3.3 An EIS Reference Architecture structured along the Components of a Design Theory

All the results can be structured along the components of a design theory. Gregor and Jones (2007) propose eight components (see Table 1). However, based on the prior positioning as a kernel theory pragmatist, the component *justificatory knowledge* is no necessity (based on the classification of Fischer et al. 2010, see section 2.2). However, it is possible to argue that the construction-/design-oriented model theory behind the DSRM and the ISO/IEC/IEEE 42010:2011 is an influencing kernel theory for this thesis. Furthermore, the insights from the interviews with the system architects are based on the consensus theory of truth.

Table 1. An energy information system reference architecture structured along the components of a design theory, based on (Gregor and Jones 2007).

Number	Type	Description
1	Purpose and Scope	The aim is to support the development of energy information systems for energy-aware industrial manufacturers (see section 1.3).
2	Constructs	*System-of-Interest, Stakeholder, Concern, Architecture Viewpoint, Model Kind, Architecture View, Architecture Model, Architecture Description, Architecture, Correspondence Rule, Correspondence,* and *Architecture Rationale* as defined in (ISO/IEC/IEEE 2011), *Design Principle, System Function, Constructs of the UML, and CROM* (Kühn et al. 2014).
3	Principles of Form and Function	A decomposition & allocation viewpoint and view, and an information viewpoint and view are developed in order to support the development (see section 3.3.1 and 3.3.2). These architecture viewpoints and views are based on the stakeholders and concerns of the system of interest (energy information system, see section

		3.2.). Architecture rationales are presented as design principles (see section 3.2.2).
4	Artifact Mutability	4.1.) The architecture description can be changed by adding, deleting, or altering stakeholders and concerns. 4.2.) Based on 4.1.), the decomposition & allocation viewpoint and view can be changed by adding, deleting or altering system functions and components of the diagram or by adding new component diagram views to the viewpoint. 4.3.) Based on 4.1.), the information viewpoint and view can be changed by adding, deleting, or altering design principles and changing the configuration methodology and the configurable reference information model. In addition, new CROM views can be added to the viewpoint. 4.4.) The informational viewpoint, view, and the configuration methodology might be used in other scenarios where energy and machine data have to be combined, e.g. energy procurement (Effenberger 2018). 4.5.) New architecture viewpoints, architecture views, model kinds, architecture models, architecture rationales or correspondence rules and correspondence can be added to the architecture description.

5	Testable Propositions	5.1.) If a system architect follows the principles of form and function, he will be more efficient and effective in the development of energy information systems than by other systems or methods. The criteria are: savings in terms of cost and time for efficiency and an improved quality for effectiveness. 5.2.) The instantiation of the decomposition & allocation view is consistent with the catalog of reusable EIS system functions. 5.3) The instantiation of the configurable reference information view is consistent with the design principles.
6	Justificatory Knowledge	6.1.) No necessity for kernel theory pragmatists; see the beginning of section 3.3.3 for a discussion regarding this subject.
7	Principles of Implementation	7.1.) Identify the needed system functions and delete the components that are not needed from the decomposition & allocation view (see section 3.3.1). 7.2.) Follow the methodology for configuring the configurable reference information model (Effenberger 2018).
8	Expository Instantiation	See the four case studies (Effenberger 2018)

3.4 LIMITATIONS AND OUTLOOK

This reference architecture is a first basis and can be extended. However, the used constructs and the artifact mutability allow such an extension with many possibilities. For example, new information views as a foundation for energy prognosis or the integration with other information system might be possible due to correspondence rules, architecture viewpoints and views. In particular, a collection of methods might be helpful for a process viewpoint and view which then prepares for integration into other architectural models.

Furthermore, this reference architecture must critically be examined by case studies that combine a much higher variety of different system functions; in the four case studies many similarities can be found. On the one hand, this is reasonable and supports the possibility of design-relevant abstractions. On the other hand, there might are some counter-examples that would help in expanding the reference architecture. Such an extension would begin with new (reusable) information requirements, which either lead to system functions or design principles and finally find their influence in existing or new views or viewpoints.

To summarize, crucial contributions for the design of an energy information system reference architecture for energy-aware industrial manufacturers at the equipment-level have been made. In complex case studies that have been conducted over multiple years for semiconductor and automotive producers, it has been shown that these contributions are not just of a theoretical nature, but really provide value and support the architecture rationales. Furthermore, all of the identified research gaps were closed.

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Effenberger F, Hilbert A (2018) A Literature Review on Energy Information System Software Development: Research Gaps and Questions in Industrial Manufacturing. In: Drews P, Funk B, Niemeyer P, Xie L (eds) Multikonferenz Wirtschaftsinformatik 2018. Lüneburg, pp 1–7

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CHAPTER II:
PUBLICATIONS

OVERVIEW

Table 2. List of publications

ID	Author(s)	Title	Source
A	Effenberger, Hilbert	A Literature Review on Energy Information System Software Development: Research Gaps and Questions in Industrial Manufacturing	(Effenberger and Hilbert 2018)
B	Effenberger, Hilbert	Towards an energy information system architecture description for industrial manufacturers: Decomposition & allocation view	(Effenberger and Hilbert 2016)
C	Effenberger, Hilbert	Energie- und Maschinendaten im Verbund: Unterstützung von Analysen auf Anlagenebene durch Energieinformationssysteme industrieller Hersteller	(Effenberger and Hilbert 2017)
D	Effenberger	Linking Energy and Machine Data: From Design Principles to a Configurable Information Model	(Effenberger 2018)

APPENDIX A: A LITERATURE REVIEW ON ENERGY INFORMATION SYSTEM SOFTWARE DEVELOPMENT: RESEARCH GAPS AND QUESTIONS IN INDUSTRIAL MANUFACTURING

Table 3. Information regarding Appendix A

Title	A Literature Review on Energy Information System Software Development: Research Gaps and Questions in Industrial Manufacturing	
Author(s)	Frank Effenberger (FE), Andreas Hilbert (AH)	
Status	Published	
Source	Effenberger F, Hilbert A (2018) A Literature Review on Energy Information System Software Development: Research Gaps and Questions in Industrial Manufacturing. In: Drews P, Funk B, Niemeyer P, Xie L (eds) Multikonferenz Wirtschaftsinformatik 2018. Lüneburg, pp 1–7	
Contribution of the Authors	Concept of the Manuscript (80%, 20%)	FE, AH
	Analysis of the State of the Art (90%, 10%)	FE, AH
	Selection and Application of Methodologies (90%, 10%)	FE, AH
	Wording and Review of the Manuscript (80%, 20%)	FE, AH

APPENDIX A-I: ACCEPTED MANUSCRIPT OF THE ARTICLE

This is the accepted manuscript of the article "*A Literature Review on Energy Information System Software Development: Research Gaps and Questions in Industrial Manufacturing*". Please use the published version of the article:

http://mkwi2018.leuphana.de/wp-content/uploads/MKWI_43.pdf

APPENDIX A-II: EXCLUSION CRITERIA

The methodology was based on Kitchenham and Webster & Watson (Webster and Watson 2002; Kitchenham 2004). Since the methodology of Kitchenham requires the definition of exclusion criteria, which are not described in detail in the article, they are briefly outlined here.

The exclusion criteria are based on content and the existence of a research methodology in the article. Articles were excluded when they focused on the following topics: *energy consumption of households, green information technologies, the management of the energy plant industry for net stability, the building industry, energy transmission, urban wastewater management*, and *energy geo information systems*. Furthermore, the design of the meta-analysis in this article is rather statistically oriented and leads to no direct meta-findings. Since this area of research is still rather young, the focus was not placed on this part of the review.

APPENDIX B: TOWARDS AN ENERGY INFORMATION SYSTEM ARCHITECTURE DESCRIPTION FOR INDUSTRIAL MANUFACTURERS: DECOMPOSITION & ALLOCATION VIEW

Table 4. Information regarding Appendix B

Title	Towards an energy information system architecture description for industrial manufacturers: Decomposition & allocation view	
Author(s)	Frank Effenberger (FE), Andreas Hilbert (AH)	
Status	Published	
Source	Effenberger F, Hilbert A (2016) Towards an energy information system architecture description for industrial manufacturers: Decomposition & allocation view. Energy 112:599–605. doi: 10.1016/j.energy.2016.06.106	
Contribution of the Authors	Concept of the Manuscript (80%, 20%)	FE, AH
	Analysis of the State of the Art (90%, 10%)	FE, AH
	Selection and Application of Methodologies (90%, 10%)	FE, AH
	Wording and Review of the Manuscript (80%, 20%)	FE, AH

APPENDIX B-I: ACCEPTED MANUSCRIPT OF THE ARTICLE

This is the accepted manuscript of the article "*Towards an Energy Information System Architecture Description for Industrial Manufacturers: Decomposition & Allocation View*". Please refer to the published version of the article with this doi:

https://doi.org/10.1016/j.energy.2016.06.106

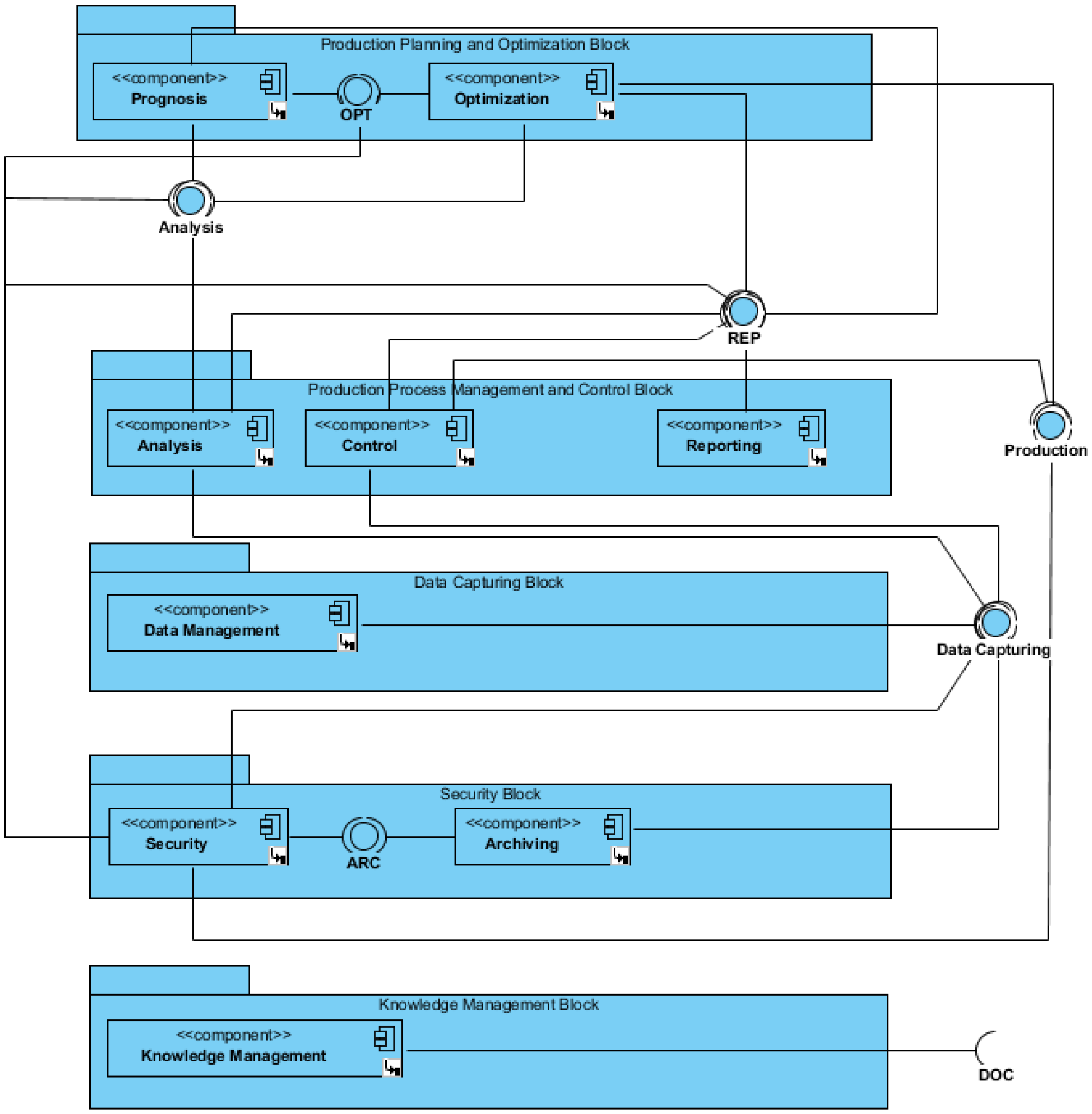
APPENDIX B-II: APPENDIX OF THE ACCEPTED MANUSCRIPT

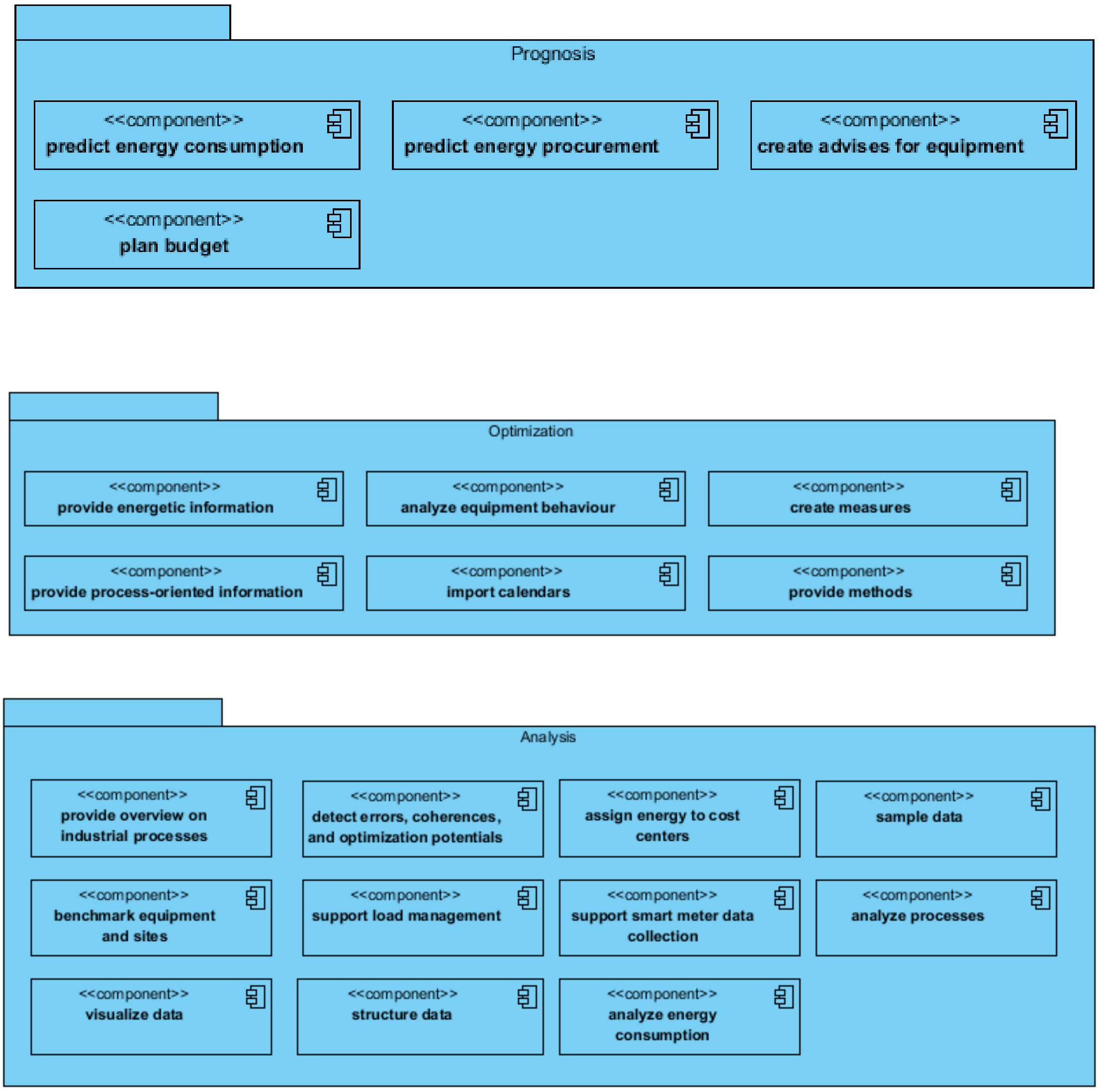
Please refer to the published version of the article with this doi:

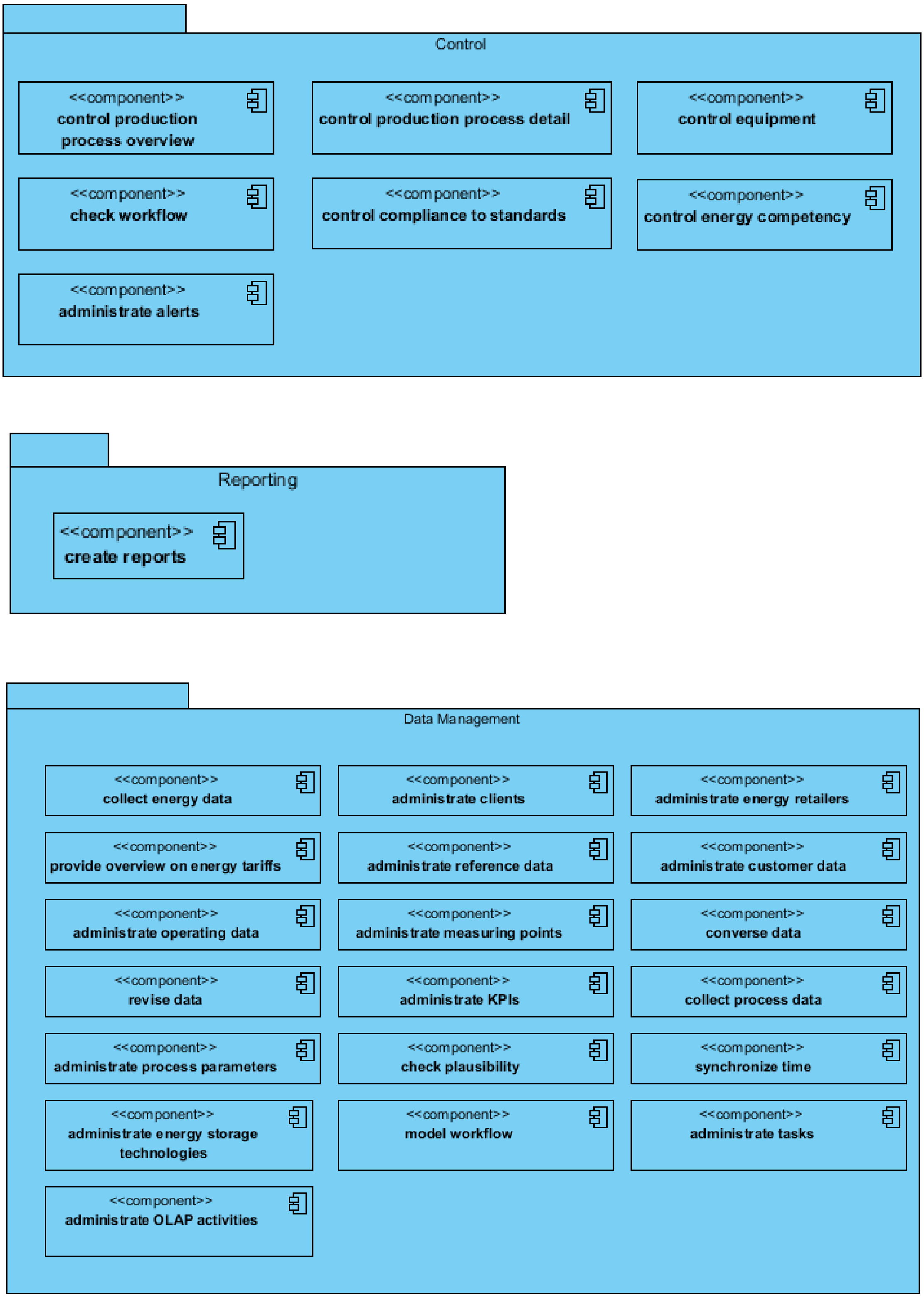
https://doi.org/10.1016/j.energy.2016.06.106

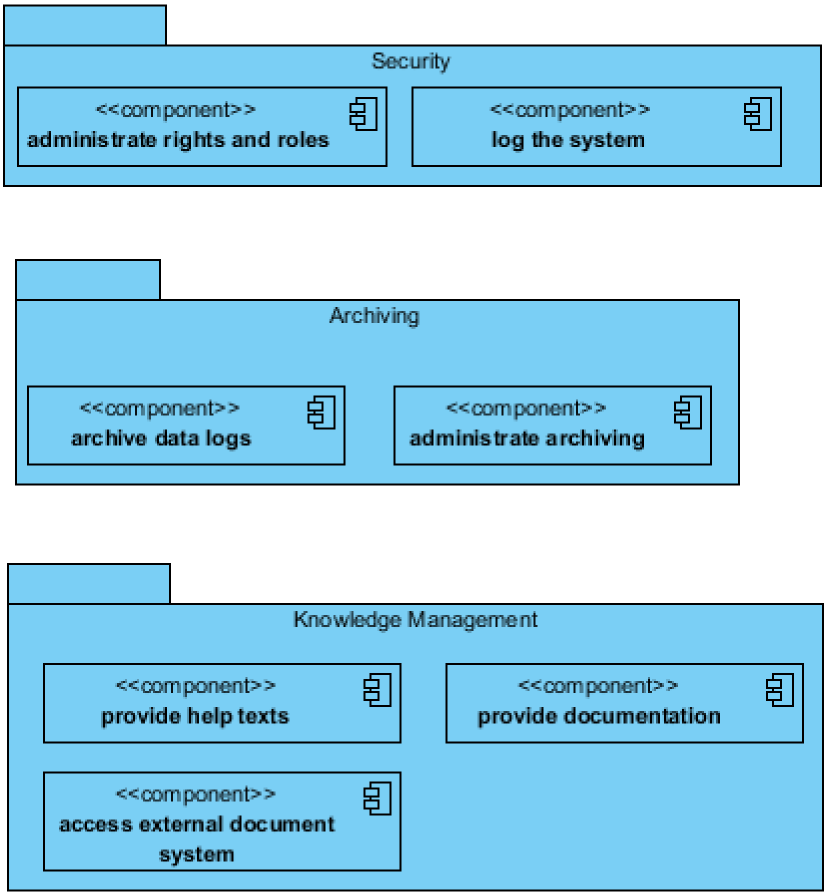
APPENDIX B-III: COMPONENT DIAGRAMS

These are the component diagrams for the decomposition & allocation view, based on Zampou et al. (Zampou et al. 2014; Effenberger and Hilbert 2016).




Prognosis
<<component>>
predict energy consumption
<<component>>
predict energy procurement
<<component>>
create advises for equipment
<<component>>
plan budget
Optimization
<<component>>
provide energetic information
<<component>>
analyze equipment behaviour
<<component>>
create measures
<<component>>
provide process-oriented information
<<component>>
import calendars
<<component>>
provide methods
Analysis
<<component>>
provide overview on industrial processes
<<component>>
detect errors, coherences, and optimization potentials
<<component>>
assign energy to cost centers
<<component>>
sample data
<<component>>
benchmark equipment and sites
<<component>>
support load management
<<component>>
support smart meter data collection
<<component>>
analyze processes
<<component>>
visualize data
<<component>>
structure data
<<component>>
analyze energy consumption


Control
<<component>> control production process overview
<<component>> control production process detail
<<component>> control equipment
<<component>> check workflow
<<component>> control compliance to standards
<<component>> control energy competency
<<component>> administrate alerts
Reporting
<<component>> create reports
Data Management
<<component>> collect energy data
<<component>> administrate clients
<<component>> administrate energy retailers
<<component>> provide overview on energy tariffs
<<component>> administrate reference data
<<component>> administrate customer data
<<component>> administrate operating data
<<component>> administrate measuring points
<<component>> converse data
<<component>> revise data
<<component>> administrate KPIs
<<component>> collect process data
<<component>> administrate process parameters
<<component>> check plausibility
<<component>> synchronize time
<<component>> administrate energy storage technologies
<<component>> model workflow
<<component>> administrate tasks
<<component>> administrate OLAP activities



In order to transform the informational requirements into functional system requirements (system functions), the system requirements definition process based on the ISO/IEC/IEEE 15288:2015 was used (ISO/IEC/IEEE 2015). In the article, some aspects of the steps were not explained in detail. Therefore, they are briefly explained here.

Regarding step a.), the functional boundary was defined by the information requirements. The overall strategy was to identify commonalities in the requirements after duplicates were eliminated. This enabled the classification of information requirements to function or system blocks. The sub steps 3.) and 4.) were not needed due to the fact that the process was performed via a text and table editors which were already available.

Regarding step b.), the functions were defined as required. However, due to the architectural aspect of this thesis, the implementation of constraints and risks were not needed. This can be seen as a relevant step in for the instantiation, but not for this level of detail. The functional system requirements were analyzed as required in step c.). The sub steps 2.)-4.) as well as step d.) were performed through the case studies that were performed in this thesis.

APPENDIX C: ENERGIE- UND MASCHINENDATEN IM VERBUND: UNTERSTÜTZUNG VON ANALYSEN AUF ANLAGENEBENE DURCH ENERGIEINFORMATIONSSYSTEME INDUSTRIELLER HERSTELLER

Table 5. Information regarding Appendix C

Title	Energie- und Maschinendaten im Verbund: Unterstützung von Analysen auf Anlagenebene durch Energieinformationssysteme industrieller Hersteller	
Author(s)	Frank Effenberger (FE), Andreas Hilbert (AH)	
Status	Published	
Source	Energie- und Maschinendaten im Verbund: Unterstützung von Analysen auf Anlagenebene durch Energieinformationssysteme industrieller Hersteller. HMD Prax der Wirtschaftsinformatik 319:1–13. doi: 10.1365/s40702-017-0375-5	
Contribution of the Authors	Concept of the Manuscript (80%, 20%)	FE, AH
	Analysis of the State of the Art (90%, 10%)	FE, AH
	Selection and Application of Methodologies (90%, 10%)	FE, AH
	Wording and Review of the Manuscript (80%, 20%)	FE, AH

APPENDIX C-I: ACCEPTED MANUSCRIPT OF THE ARTICLE

This is the accepted manuscript of the article "*Energie- und Maschinendaten im Verbund: Unterstützung von Analysen auf Anlagenebene durch Energieinformationssysteme industrieller Hersteller*".

Please refer to the published version of the article with this doi: https://doi.org/10.1365/s40702-017-0375-5

APPENDIX D: LINKING ENERGY AND MACHINE DATA: FROM DESIGN PRINCIPLES TO A CONFIGURABLE INFORMATION MODEL

Table 6. Information regarding Appendix D

Title	Linking Energy and Machine Data: From Design Principles to a Configurable Information Model	
Author(s)	Frank Effenberger (FE)	
Status	Not Published	
Source	Effenberger F (2018) Linking Energy and Machine Data: From Design Principles to a Configurable Information Model. In: Towards an Energy Information System Reference Architecture for Energy-Aware Industrial Manufacturers on the Equipment-Level. p 1–27, Appendix D	
Contribution of the Authors	Concept of the Manuscript (100%)	FE
	Analysis of the State of the Art (100%)	FE
	Selection and Application of Methodologies (100%)	FE
	Wording and Review of the Manuscript (100%)	FE

APPENDIX D-I: THE ARTICLE

Linking Energy and Machine Data: From Design Principles to a Configurable Information Model

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Abstract. The key challenge of energy-aware industrial manufacturers is the improvement of energy efficiency. This challenge might be addressed with measures at the equipment-level of an industrial plant. I was able to show that there is currently no appropriate and reusable information model that provides a solid basis for improving the energy efficiency at the equipment-level. Therefore, I developed information models in three case studies and identified 12 reusable design principles. These design principles were evaluated within three evaluations rounds with two system architects. Based on these design principles, a configurable reference information model for the combination of energy and machine data as well as a configuration methodology were developed and then evaluated in a fourth case study. In addition, the reference model was reapplied to the three previous case studies.

Keywords: energy information system, design principles, information model, industrial manufacturing, machine data.

1 Introduction

The key challenge of energy-aware industrial manufacturers is the improvement of energy efficiency (Chen et al. 2013). In addition, the reduction of energy consumption enables the saving of costs and an efficient, sustainable production (Thollander et al. 2015). However, there is not only an economic factor. There are political, social, and environmental drivers (Bunse et al. 2011; Fekete et al. 2014). These drivers are increasing the importance of energy efficiency.

To be able to improve this key performance indicator, measures at the equipment-level can be taken. These measures require a transparent decision-making basis. This basis can and should be provided by data of the industrial plant. On the one side, time series based energy data can be obtained from various sensors of the industrial equipment. On the other side, event-driven machine data can be obtained from various sources, e. g. manufacturing executions systems or programmable logic controllers. The combination of machine and energy data in information models can provide the needed transparent decision-making basis for the equipment.

Design science provides methodologies for research on the development of reusable information models (Peffers et al. 2007). In this paper, I decided to capture knowledge in design principles. I then used these design principles to develop a reusable information model that qualifies as a reference model.

In addition, the concept of energy informatics, defined as a subset of information systems research in the MIS Quarterly, can address this subject with energy information systems (EIS) (Watson et al. 2010). However, I will show that current research in this area seems to focus on other subjects. Therefore, I contribute to energy informatics by:

- identifying 12 design principles that describe an information model for the combination of energy and machine data based on information models from three case studies
- developing a configurable information model and a configuration methodology which are applied in a fourth case study and reapplied to the previous case studies

In the next section, the related work is presented, followed by the methodology for the development of the design principles and the configurable information model. The paper then moves on to describe and discuss the results. Finally, the paper concludes with an outlook for future research.

2 Related Work

A previous and intensive study of the scientific literature from 2003 to 2016 analyzed the current research gaps and questions for energy information system software development in the context of energy-aware industrial manufacturing (Effenberger and Hilbert 2018). In this literature review, over 3680 articles were examined and the results concluded that the research subject of information models for the combination of energy and machine data is being neglected (Effenberger and Hilbert 2018). I used the results of this literature review and searched for information models in the context of EIS.

A study from 2013 identified the lack of “(…) energy management at the organization, factory or process level” (Vikhorev et al. 2013). Therefore, it was not surprising that there were almost no information model articles that focused on the equipment-level. I identified only one article that focused on this problem (Zampou et al. 2014).

Zampou et al. provided a framework for energy-aware industrial manufacturers that can and should be reused when considering the combination of energy and machine data. However, the described information model was only an instantiation and there were no possibilities for changes or configurations (Zampou et al. 2014).

Therefore, the next logic step was to make the existing knowledge abstract and reusable. Based on these results, I decided to focus on the development of a reference information model for the combination of energy and machine data. The methodology for this development is presented next.

3 Methodology

Design science is suitable for this type of research. Design science aims to develop artifacts that might be methods, constructs, models, or instantiations (March and Smith 1995). These artifacts have to ensure relevance and rigor (Hevner et al. 2004a). The goal of this research is the development of a configurable reference information model and the corresponding methodology for configuring it.

In the first step, I aim to describe the artifact with design principles. The concept of design principles aims to ensure a guided creativity for developers and architects that use them for the development of design science artifacts. To be more concise, a recent study shows that design principles are no fixed set of tasks; developers and architects interpret and combine them with their domain knowledge (Chandra Kruse et al. 2016). For this reason, design principles are a crucial extension of the knowledge base.

To ensure relevance, rigor, and a reusability of the results, I use the well-established design science research methodology to guide the research process (Peffers et al. 2007). For the development of this artifact, I use a problem-centered initiation. The identification of the problem is the introduction of this paper. Regarding the objectives of the solution, these are the key requirements:

1. The information model structures all relevant energy and machine data in an industrial plant on the equipment-level.
2. The information model provides a reusable decision-making basis.

For every evaluation phase, I distinguished between a prototype and a full evaluation. In a prototype evaluation, only the achievement of the objectives of the specific case study was relevant. In a full evaluation, the evaluation partners rated the reusability, completeness, applicability and understandability of the results. The completeness indicates that the information model is able to structure all relevant energy and machine data, whereas the other criteria evaluate the decision-making basis for the industrial manufacturer.

For the design, development, and demonstration & evaluation phases, I performed four case studies (two with an automotive and two with a semiconductor producer). In the design phase of the first case study, I developed a prototype that should be able to fulfill the key requirements. I then tried to extract the knowledge of this prototype by writing down the design principles that were describing this model. The prototype model was then instantiated and evaluated. In the next step, the design principles were used for the design phase in the second case study. After another implementation and evaluation phase, the third case study followed.

In addition to this, I was aware of the fact that the design principles could benefit from another evaluation. Therefore, I showed two experts (system architects) the design principles after the third case study and discussed them in three separate design principle evaluation rounds (the first and second round with every system architects separately, the third round with both system architects). In these discussions I proceeded as follows: At the beginning, an explanation of the aim of this study as well as a further explanation of design principles was provided to the system architects. In the next step, I explained that every of the design principles could be rejected and deleted, rejected and changed, or accepted. In addition, new design principles could be added. I then showed every design principle and read them as a whole. Finally, all design principles were discussed separately and the system architects made one of the four possible decisions. The resulting design principles are therefore able to serve as a reusable decision-making basis.

Based on the evaluated design principles, a configurable information model could be developed. I chose *configuration* as the reference modeling style because it has a high potential for future automation. However, this implies an anticipation of model adjustments (Becker and Knackstedt 2004).

I used the design principles as rules and guidelines that can be used as a methodology to configure the information model. In this case, the steps of the methodology have to ensure that the information model satisfies every design principle. In the end, the methodology was applied to the fourth case study to show the relevance of the artifact. In addition, the methodology was reapplied to the previous three case studies. This enables the explanation of the specific decisions regarding the configuration of the information model and supports the integration of attributes that are needed for system functions of the EIS (I use a well-defined basis for system functions for EIS that were extracted in a previous study (Effenberger and Hilbert 2016)).

4 Results and Discussion

In this section, the design principles and the results of the evaluations are shown. The presented design principles are the consensus of the three evaluation phases with the system architects as well as the first three case studies. The case studies (including the fourth) are presented first, followed by the design principles.

4.1 Case Studies

In the first case study, an energy-intense heating process of a semiconductor producer was analyzed. The developed prototype was able to identify waste of electrical energy by providing a transparent combination of electrical energy consumption and machine states. The energy engineers were able to identify several non-productive phases with high energy consumption. They performed successful measures that changed the behavior of the equipment in this process. This resulted in a reduction of approximately 500 megawatt hours of energy consumption every year. The first case study affected the design principles in several ways. Regarding the energy data, it was crucial to save energy and machine data with time and equipment reference as well as to have a reference value for calculations. Physical measured variables and units were mandatory. Regarding the machine data, they had to be saved with the same time and equipment reference as the energy data. The machine event data had to be used to extract machine states and to classify them into productive and non-productive phases.

The second case study used the results and design principles of the first case study for an automobile manufacturer. In this case study, the washing process of produced components was analyzed. The aim was to develop a reusable and transparent decision-making basis by capturing all relevant energy and machine data every second. The goal was accomplished; however, no measures were performed at the end of the case study. New design principles were needed and added for the machine data. The machine event data had to be used to extract task instances as well as their start, end, duration, and an identifier.

In the third case study, a transportation process was analyzed. A robot transported workpieces under laboratory conditions. At one time, the robot received an additional weight and I had to identify this anomaly in the energy data. This goal was accomplished. This case study showed that it is helpful to arrange the equipment and tasks into a hierarchy and to add reference data for the tasks. Therefore, the design principles were changed accordingly.

In the fourth case study, the configurable information model and the methodology were used for a wafer deposition process. The aim was to develop a transparent decision-making basis for energy managers as well as the analysis of electrical and chemical energy consumption in combination with machine data. The already developed design principles were crucial for this case study. The captured knowledge allowed designing the information model. The final design principles are presented next.

4.2 Design Principles and Evaluation Results

The final design principles are (M is equal to machine data; E is equal to energy data):

- M1: Machine event data must be stored with time and equipment reference (same reference as E1)
- M2: Machine states must be extracted and stored from the machine event data. The extracted machine states must be classified as productive or non-productive.
- M3: Additional descriptive attributes can be extracted and stored from the machine event data.
- M4: From the machine event data, a reference to the task instance must be established and stored. The duration of the task instance can be stored. A task can be derived from a task instance.
- M5: Equipment can be arranged in a hierarchy (same hierarchy as E4).
- M6: Tasks can be classified into a hierarchy of activities and processes. Additional attributes of the tasks can be added.
- M7: A reference to the product instance can be established and stored from the machine event data. Additional attributes for the product instances can be added.
- E1: Energy values must be stored with time and equipment reference (same reference as M1)
- E2: Energy values must be stored with a physical measured variable and unit. The time interval to the last value can be stored.
- E3: Energy values must be converted into a reference unit and reference physical measured variable. The energy values can already be present in the reference unit and reference physical measured variable.
- E4: Equipment can be arranged in a hierarchy (same hierarchy as M5).
- E5: To the acquired reference measurement variables, it must be stored whether an aggregation along the dimension time is possible by a sum or as an arithmetic mean.

These design principles are describing the knowledge from the first three case studies and the system architects, whereas the word "must" implies a mandatory and the word "can" implies an optional part of an information model that combines energy and machine data in an industrial plant. During the application of the design principles in the fourth case study, I concluded that M5 and E4 should have a "can" instead of a "must" as their condition. Therefore, this is the only change that I made to the design principles after the evaluation rounds with the system architects. With the use of these design principles, system architects and developers can be guided through the most important steps in the design phase. Therefore, the design principles are helpful for new case studies and can be used by practitioners and scientists that focus on energy-aware industrial manufacturers.

Table 1 shows the evaluation results of the criteria from the methodology section. I shortened the criteria for the achieved objectives (O), reusability (R), completeness (C), applicability (A), and understandability (U) to numeric values, whereas 1 stands for "No", 2 stands for "Yes with restriction", and 3 stands for "Yes".

Table 1. Evaluation results of the case studies: O stands for "objectives achieved", R for "reusability", C for "completeness, A for "Applicability", and U for "Understandability".

#	Evaluation	O	R	C	A	U
1	Prototype	Yes	-	-	-	-
2	Full	Yes	3	2	2	3
3	Prototype	Yes	-	-	-	-
4	Full	Yes	3	3	2	3

Table 1 shows that there are restrictions regarding the completeness and applicability. The industrial manufacturer from case study #2 stated that in the future, more and different energy and machine data should be integrated and tested. In addition, a more granular data basis and the calculation of a variety of key performance indicators should be tested.

In case study #3 and #4, I used the design phase to address these subjects (see completeness for case study #4). However, regarding the applicability of the results, there is a mentioned restriction from the industrial manufacturer (case study #4). He mentioned that an engineer still has to know if there is equipment that might have potential for improving the energy efficiency. This is because equipment usually has to be extended by cost-intensive sensors.

4.3 From Design Principles to a Configurable Information Model

In this section, the configurable information model and the methodology for the configuration are presented. I decided to use CROM, an extension of the UML, for the modeling process (Kühn et al. 2014). The model can be developed with UML (role types become multiple elements and role fulfillments become multiple relations), however, a previous study already showed and explained the benefits to a model when using CROM (Effenberger and Hilbert 2017). The configuration model is shown within the next three figures (see Fig. 1-3).

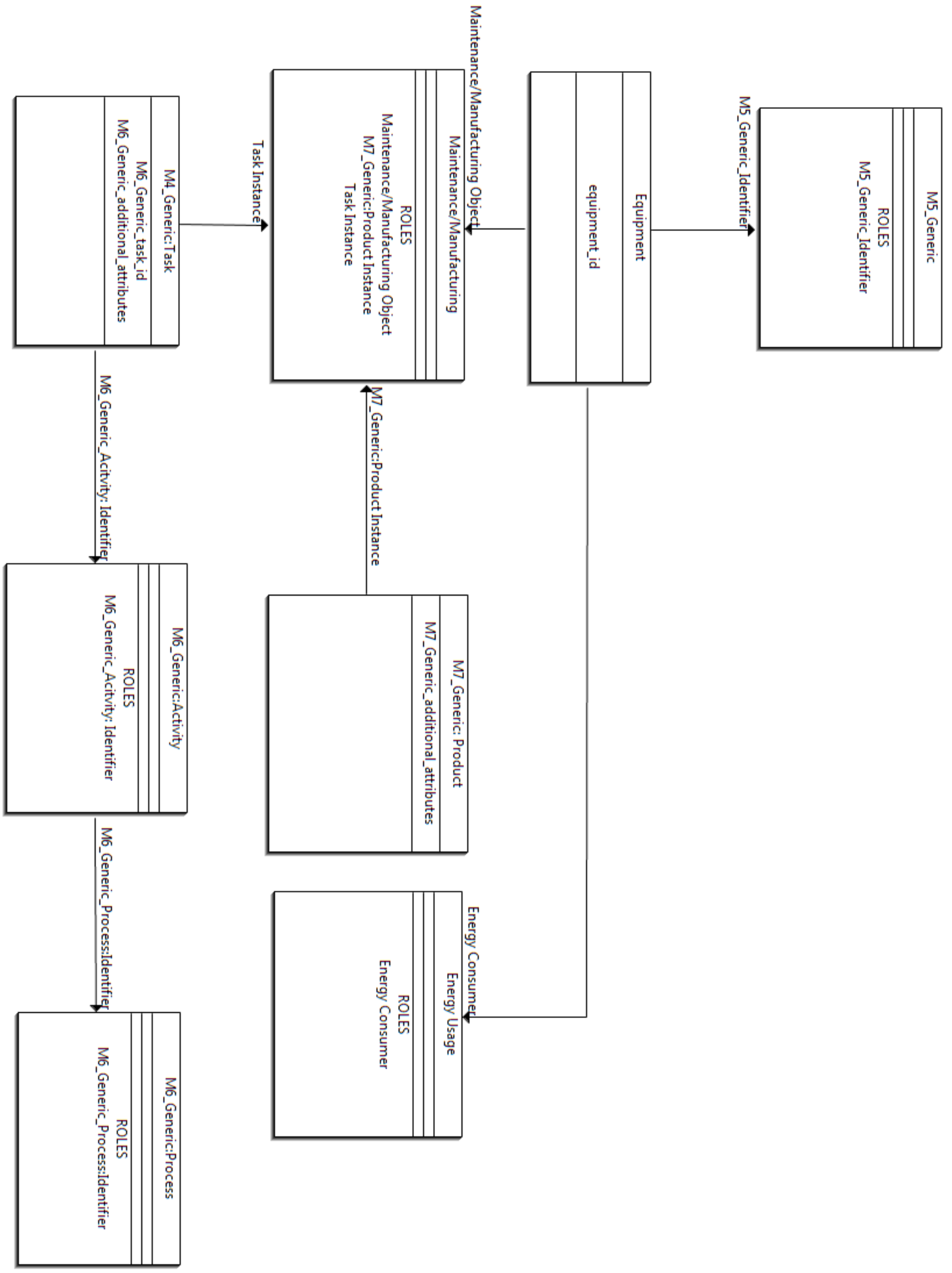

Figure 1. The configurable information model (1/3)

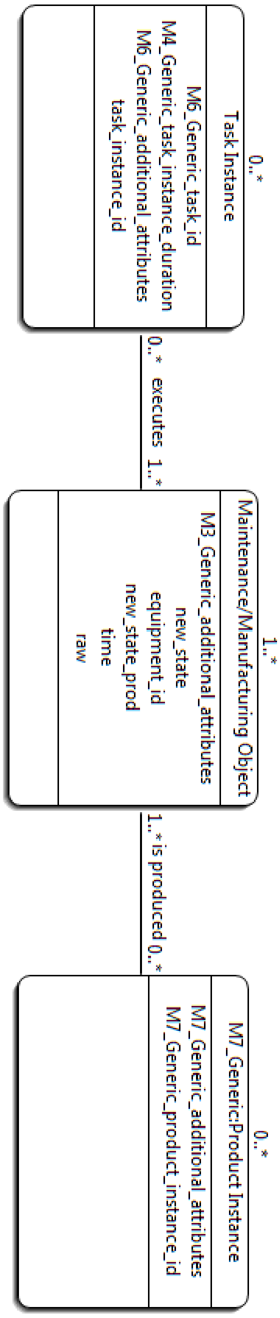

Figure 2. The configurable information model, “Maintenance/Manufacturing” (2/3)

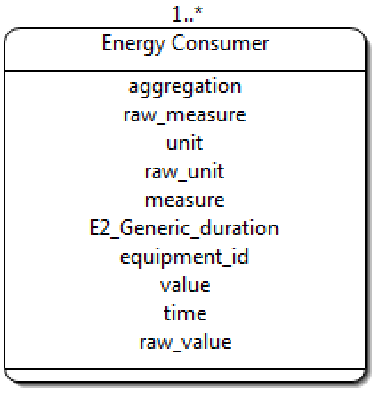

Figure 3. The configurable information model, “Energy Usage” (3/3).

As can be seen from Fig. 1-3, there are generic placeholders in the configuration model that can be identified by the prefix of the corresponding ID of the design principle and the suffix “_Generic”. These placeholders are completely replaced by following the methodology for the configuration. Therefore, the purpose of the generic placeholders is to show which design principles affect which element, relation, role type, role fulfillment, or attribute.

To be able to configure the information model, a methodology is needed. I decided to write basic tasks that can be performed consecutively. Simultaneously, the formulation of the tasks represents pseudo code that can be used for a process model or program. Every task has a number, a reference to the related design principle(s) and a description. Tasks may have sub tasks and conditions. If there is no condition, the completion of one task implies that the user of the methodology proceeds with the next task until there are no more tasks. If specified relations are needed, they are shown in brackets and are only needed if the corresponding elements or role types exist. The tasks are presented next.

Task Number:	01
Design Principle(s):	M1, E1
Description:	Add an element with the name “Equipment” to the model.
Sub Task(s):	-

Task Number:	02
Design Principle(s):	M1, E1
Description:	Add an attribute with the name "equipment_id" to the element "Equipment".
Sub Task(s):	-

Task Number:	03
Design Principle(s):	M1
Description:	Add an element with the name "Maintenance/Manufacturing".
Sub Task(s):	-

Task Number:	04
Design Principle(s):	M1
Description:	Add a role type with the name "Maintenance/Manufacturing Object" (1..*) to the element "Maintenance/Manufacturing".
Sub Task(s):	-

Task Number:	05
Design Principle(s):	M1
Description:	Add a role fulfillment from the element "Equipment" as "Maintenance/Manufacturing Object" to the element "Maintenance/Manufacturing".
Sub Task(s):	-

Task Number:	06
Design Principle(s):	M1
Description:	Add a total of three attributes with the names "time", "equipment_id" and "raw" to the role type "Maintenance/Manufacturing Object".
Sub Task(s):	-

Task Number:	07
Design Principle(s):	M2
Description:	Add two attributes with the names "new_state" and "new_state_prod" to the role type "Maintenance/Manufacturing Object".
Sub Task(s):	-

Task Number:	08
Design Principle(s):	M3
Description:	If there is one or more additional, descriptive attribute that shall be implemented, execute the following sub task for every attribute that shall be implemented. If there is no additional, descriptive attribute that shall be implemented, then proceed with the next task (task 09).
Sub Task(s):	Add the attribute with the respective name to the role type “Maintenance/Manufacturing Object”. If no additional attributes can be added, then proceed with the next task (task 09).

Task Number:	09
Design Principle(s):	M4
Description:	Add a role type with the name “Task Instance” (0..*) to the element “Maintenance/Manufacturing”.
Sub Task(s):	-

Task Number:	10
Design Principle(s):	M4
Description:	Add the attribute “task_instance_id” to the role type “Task Instance”.
Sub Task(s):	-

Task Number:	11
Design Principle(s):	M4
Description:	Add a relation "executes" from the role type "Maintenance/Manufacturing Object" (1..*) to the role type "Task Instance" (0..*).
Sub Task(s):	-

Task Number:	12
Design Principle(s):	M4
Description:	If the duration of a task instance shall be implemented, then add the attribute "task_instance_duration" to the role type "Task Instance". If the duration of the task instance shall not be implemented, then proceed with the next task (task 13).
Sub Task(s):	-

Task Number:	13
Design Principle(s):	M4, M6
Description:	If tasks shall be implemented, then execute all of the sub tasks. If the tasks shall not be implemented, then proceed with the next task (task 14).
Sub Task(s):	execute tasks 13.01-13.04

Task Number:	13.01
Design Principle(s):	M4, M6
Description:	Add the element with the name "Task" to the model.
Sub Task(s):	-

Task Number:	13.02
Design Principle(s):	M4, M6
Description:	Add the attribute “task_id” to the element “Task”.
Sub Task(s):	-

Task Number:	13.03
Design Principle(s):	M4, M6
Description:	Add the attribute “task_id” to the role type “Task Instance”.
Sub Task(s):	-

Task Number:	13.04
Design Principle(s):	M4, M6
Description:	Add a role fulfillment from the element “Task” as “Task Instance” to the element “Maintenance/Manufacturing”.
Sub Task(s):	-

Task Number:	14
Design Principle(s):	M5, E4
Description:	Execute the following sub tasks for every hierarchy level that shall be implemented. If there is no level of hierarchy to be implemented, then proceed with the next task (task 15).
Sub Task(s):	execute tasks 14.01 - 14.04

Task Number:	14.01
Design Principle(s):	M5, E4
Description:	Add the element of the hierarchy level with the respective name to the model.
Sub Task(s):	-

Task Number:	14.02
Design Principle(s):	M5, E4
Description:	Add a role type to the created element that identifies the hierarchy level name (1..*) and add the suffix “:Identifier”.
Sub Task(s):	-

Task Number:	14.03
Design Principle(s):	M5, E4
Description:	Add an attribute with its respective name and the suffix “_id” to the created role type.
Sub Task(s):	-

Task Number:	14.04
Design Principle(s):	M5, E4
Description:	Add a role fulfilment from the previous created element to the role type that is created in this iteration. If this is the first iteration, the previous created element is “Equipment”. If this is the last created element, then proceed with the next task (task 15).
Sub Task(s):	-

Task Number:	15
Design Principle(s):	M6
Description:	If the element “Task” exists and a hierarchy of activities and processes shall be implemented, then execute all of the sub tasks. If the element “Task” does not exist or a hierarchy of activities and processes should not be implemented, proceed with the next Task (task 16).
Sub Task(s):	execute tasks 15.01 – 15.08

Task Number:	15.01
Design Principle(s):	M6
Description:	Add the element “Activity” to the model.
Sub Task(s):	-

Task Number:	15.02
Design Principle(s):	M6
Description:	Add the role type “Activity:Identifier” (1..*) to the element “Activity”.
Sub Task(s):	-
Task Number:	15.03
Design Principle(s):	M6
Description:	Add the attribute “activity_id” to the role type “Activity:Identifier”.
Sub Task(s):	-

Task Number:	15.04
Design Principle(s):	M6
Description:	Add a role fulfillment from the element “Task” as “Activity:Identifier” to the element “Activity”.
Sub Task(s):	-

Task Number:	15.05
Design Principle(s):	M6
Description:	Add the element “Process” to the model.
Sub Task(s):	-

Task Number:	15.06
Design Principle(s):	M6
Description:	Add the role type “Process:Identifier” (1..*) to the element “Process”.
Sub Task(s):	-

Task Number:	15.07
Design Principle(s):	M6
Description:	Add the attribute “process_id” to the role type “Process:Identifier”.
Sub Task(s):	-

Task Number:	15.08
Design Principle(s):	M6
Description:	Add a role fulfillment from the element “Activity” as “Process:Identifier” to the element “Process”.
Sub Task(s):	-

Task Number:	16
Design Principle(s):	M6
Description:	If additional attributes of the element “Task” or role type “Task Instance” shall be implemented, then execute the sub task for every attribute that shall be implemented. If there are no additional attributes of the element “Task” or role type “Task Instance” that shall be implemented, then proceed with the next task (task 17).
Sub Task(s):	Add the attribute with the respective name to the element “Task” or role type “Task Instance”. If there are no more additional attributes that shall be implemented, then proceed with the next task (task 17).

Task Number:	17
Design Principle(s):	M7
Description:	If a reference to the product instance shall be established from the machine event data, then execute the sub tasks. If no reference to the product instance shall be established from the machine event data, then proceed with the next task (task 18).
Sub Task(s):	See tasks 17.01-17.07

Task Number:	17.01
Design Principle(s):	M7
Description:	Add the element “Product” to the model.
Sub Task(s):	-

Task Number:	17.02
Design Principle(s):	M7
Description:	If there is one or more additional attributes of the element “Product” that shall be implemented, then execute the following sub task for every attribute that shall be implemented. If there are no additional attributes of the element “Product” that shall be implemented, then proceed with the next sub task (task 17.03).
Sub Task(s):	Add the attribute with the respective name to the element “Product”. If there are no more additional attributes that shall be implemented, then proceed with the next sub task (task 17.03).

Task Number:	17.03
Design Principle(s):	M7
Description:	Add the role type “Product Instance” (0..*) to the element “Maintenance/Manufacturing”.
Sub Task(s):	-

Task Number:	17.04
Design Principle(s):	M7
Description:	Add a "is produced" relation from the role type "Product Instance" (0..*) to the role type "Maintenance/Manufacturing Object" (1..*).
Sub Task(s):	-

Task Number:	17.05
Design Principle(s):	M7
Description:	Add the attribute "product_instance_id" to the role type "Product Instance".
Sub Task(s):	-

Task Number:	17.06
Design Principle(s):	M7
Description:	If additional attributes of the role type "Product Instance" shall be implemented, then execute the following sub task for every attribute that shall be implemented. If there are no additional attributes of the role type "Product Instance" that shall be implemented, then proceed with the next sub task (17.07).
Sub Task(s):	Add the attribute with the respective name to the role type "Product Instance". If there are no more additional attributes that shall be implemented, then proceed with the next sub task (17.07).

Task Number:	17.07
Design Principle(s):	M7
Description:	Add a role fulfillment from the element “Product” as “Product Instance” to the element “Maintenance/Manufacturing”.
Sub Task(s):	-

Task Number:	18
Design Principle(s):	E1
Description:	Add an element with the name “Energy Usage” to the model.
Sub Task(s):	-

Task Number:	19
Design Principle(s):	E1
Description:	Add a role type with the name “Energy Consumer” (1..*) to the element “Energy Usage”.
Sub Task(s):	-

Task Number:	20
Design Principle(s):	E1
Description:	Add a role fulfillment from the element “Equipment” as “Energy Consumer” to the element “Energy Usage”.
Sub Task(s):	-

Task Number:	21
Design Principle(s):	E1
Description:	Add a total of three attributes with the names “equipment_id”, “time”, and “raw_value” to the role type “Energy Consumer”.
Sub Task(s):	-

Task Number:	22
Design Principle(s):	E2
Description:	Add a total of two attributes with the names “raw_measure” and “raw_unit” to the role type “Energy Consumer”.
Sub Task(s):	-

Task Number:	23
Design Principle(s):	E2
Description:	If the time interval to the last value shall be implemented, then execute the following sub task. If the time interval to the last value shall not be implemented, then proceed with the next task (task 24).
Sub Task(s):	Add the attribute “duration” to the role type “Energy Consumer”.

Task Number:	24
Design Principle(s):	E3
Description:	Add a total of three attributes with the names “value”, “unit”, and “measure” to the role type “Energy Consumer”.
Sub Task(s):	-
Task Number:	25
Design Principle(s):	E5
Description:	Add the attribute “aggregation” to the role type “Energy Consumer”.
Sub Task(s):	-

With these 25 tasks and their corresponding sub tasks, the complete information model can be developed and configured. In the next section, the application of the tasks for the case studies and the coverage with the real information models are presented.

4.4 Application of the Configurable Information Model

In the first case study, the application of the methodology lead to an information model that is nearly identical to the information model that was used in the case study. The configured information model is presented within the next three figures (see Fig. 4-6). The system functions that were the basis for the additional attributes and decisions during the methodology were: 1, 5, 6, 11, 12, 21, 23, 24, 28-30, 35, 38, 48, 52-56 (system functions are based on a previous study (Effenberger and Hilbert 2016)).

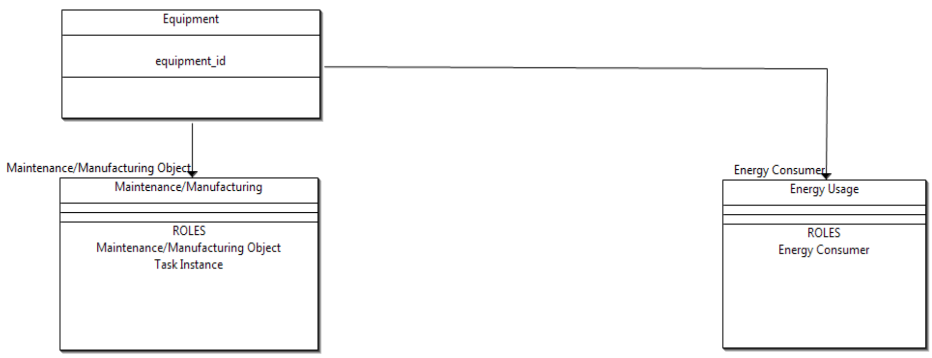

Figure 4. Configured information model of case study 1 (1/3).

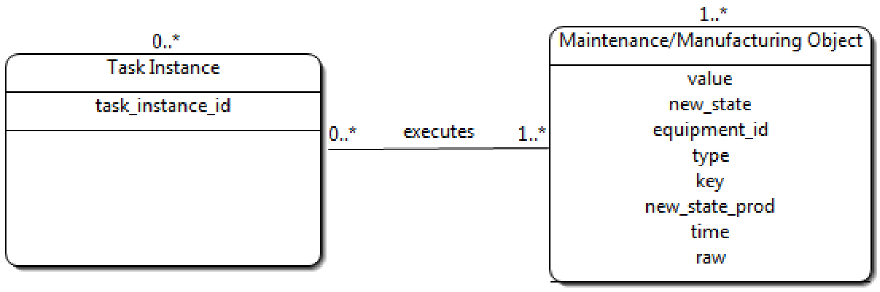

Figure 5. Configured information model of case study 1 (2/3).

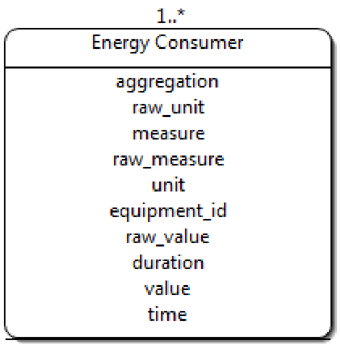

Figure 6. Configured information model of case study 1 (3/3).

Fig. 4-6 show that the tasks 12-17 were skipped due to their conditions (no additional attributes or elements were needed for this first prototype in the case study). For task 08, the additional attributes were “key”, “type”, and “value”. These were used to enrich the machine data with more detailed information (e.g. to distinguish between a notable and a not-notable event).

I noted in the beginning of this section that the information model that is created from the methodology is nearly identical to the original information model from the appendix of this paper. First, due to task 09-11, a role type “Task Instance” with the attribute “task_instance_id” and an “executes”-relation should be implemented. Second, the attribute “duration” is named “raw_duration” in the role type “Energy Consumer” (task 23). Third, due to task 24 and 25, the attributes measure and aggregation are missing.

These discrepancies can be easily explained due to the prototype state of the first case study. At the beginning of the case study, the original information model was far from being complete and only supported a very simple energy analysis. The two additions that should be implemented due to the configuration methodology enrich the information model with more capabilities.

I was able to reapply the data of the first case study to the configured information model. Task 24 and 25 enabled the addition of different energy types and their conversion into a reference unit with a reference value. In addition, due to task 09-11, energy can be mapped to a specific task. Therefore, I was able to identify specific energy patterns for the performance of a certain task. In addition to the achieved, higher quality I have also saved time and therefore costs. While the first case study took about four months in time until the data model was ready to use, this new data model had been developed and integrated within two weeks. Regarding the personnel cost of the system architect in this specific case, this was a saving of 12250 €. In a more real calculation, the savings are probably even higher. The original information model can be found in the appendix of this paper.

In the second case study, a more complex information model was needed due to the requirements. The system functions that were the basis for the additional attributes and decisions during the methodology were: 1, 2, 5, 6, 8-14, 16, 19-21,23-24, 26-30, 33, 35-38, 40, 42, 43, 47-49, 52-56 (system functions are based on a previous study (Effenberger and Hilbert 2016)). The configured information model of the second case study is presented next (see Fig. 7-9). The original information model can be found in the appendix of this paper.

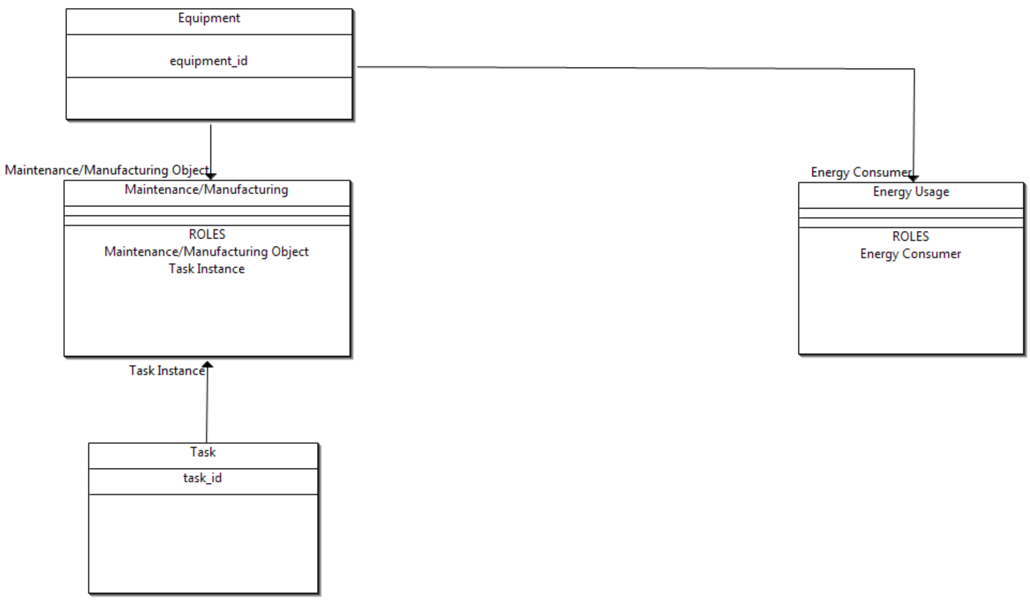

Figure 7. Configured information model of case study 2 (1/3).

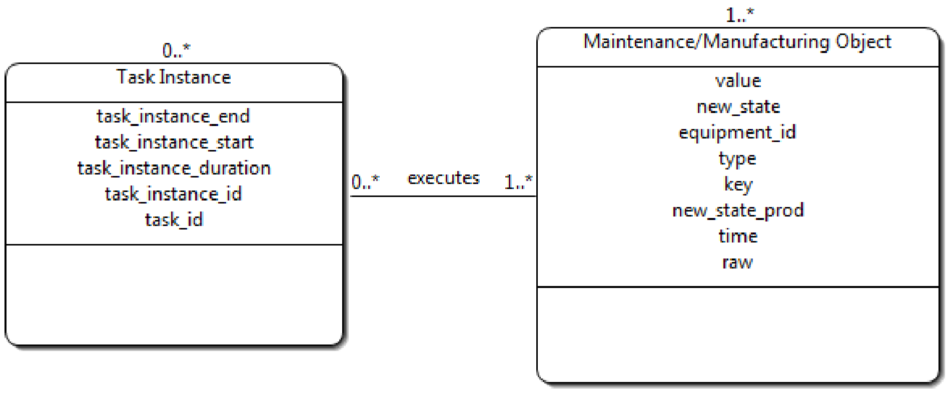

Figure 8. Configured information model of case study 2 (2/3).

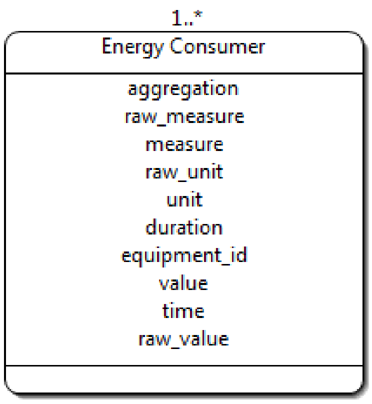

Figure 9. Configured information model of case study 2 (3/3).

Fig. 7-9 show that the task 14, 15, and 17 were skipped due to their conditions (no hierarchies and product references were needed). For task 08, the attributes “type”, “key”, and “value” were implemented due to the same reasons of case study #1. In the execution of task 12 and 23, the durations to the previous value (energetic value and task duration) were implemented. This was needed to identify data gaps for energy and machine data as well as to calculate the average for the energy consumption. However, there are discrepancies between the original information model and the configured information model that have to be explained. For the execution of task 09, 10, 12, 13, and 16, different names for the role type, element, and attributes were used. The role type “Process Step” equals the “Task Instance” and the prefix “task_instance_” is the aquivalent to the prefix “step_”. The attribute “step_class” is the same as “task_id”. The element “Process Step” with the attribute “step class” equals the element “Task” and the attribute “task_id”. In addition to this, the attribute “duration” is named “raw_duration” in the role type “Energy Consumer” (task 23).

On the prima facie, the renaming of the element, role type, and attributes seems irrelevant. However, in an industrial context, standardization should be preferred. Therefore, the ISO/IEC/IEEE 15288/12007 defines processes that consist of activities and these consist of tasks (ISO/IEC/IEEE 2015). In addition, the "Process Step" exists twice with the same label. This may be confusing due to the nature of a describing element and an actual instantiation of a task. This confusion can be avoided with the configured information model. I was able to apply the configured information model to the case study and to improve the discussed points.

In addition, the attributes "unit" and "measure" of task 24 as well as the "aggregation" of task 25 were missing in the original information model. This was a constraint to the original information model and caused that the calculation of reference units and values has to be done at search-time on the system. In addition, the rules for the aggregation had to be implemented on a higher-level and were dependent on the value and measure.

The configured information model enables the option of saving the converted values at the time when the data is stored, therefore reducing the query time of the overall system. However, this implies that more storage is used. In addition, the rules for the aggregation can be taken from the data model and the complexity of the system functions regarding the visualization is reduced. In addition to the achieved, higher quality I was able to save time and therefore costs. While the first case study took about six months in time until the final data model was developed and implemented, this new data model had been developed and implemented within one month. Regarding the personnel cost of one system architect in this specific case, this was a saving of 17500 €. In a more real calculation, the savings are probably even higher.

Regarding case study 3, a high congruence between the original information model and the configured information model can be found (see Fig. 10-12). The system functions that were the basis for the additional attributes and decisions during the methodology were: 1, 2, 5, 6, 8-14, 16, 19-21,23-24, 26-30, 33, 35-38, 40, 42, 43, 47-49, 52-56 (system functions are based on a previous study (Effenberger and Hilbert 2016)). The original information model can be found in the appendix of this paper.

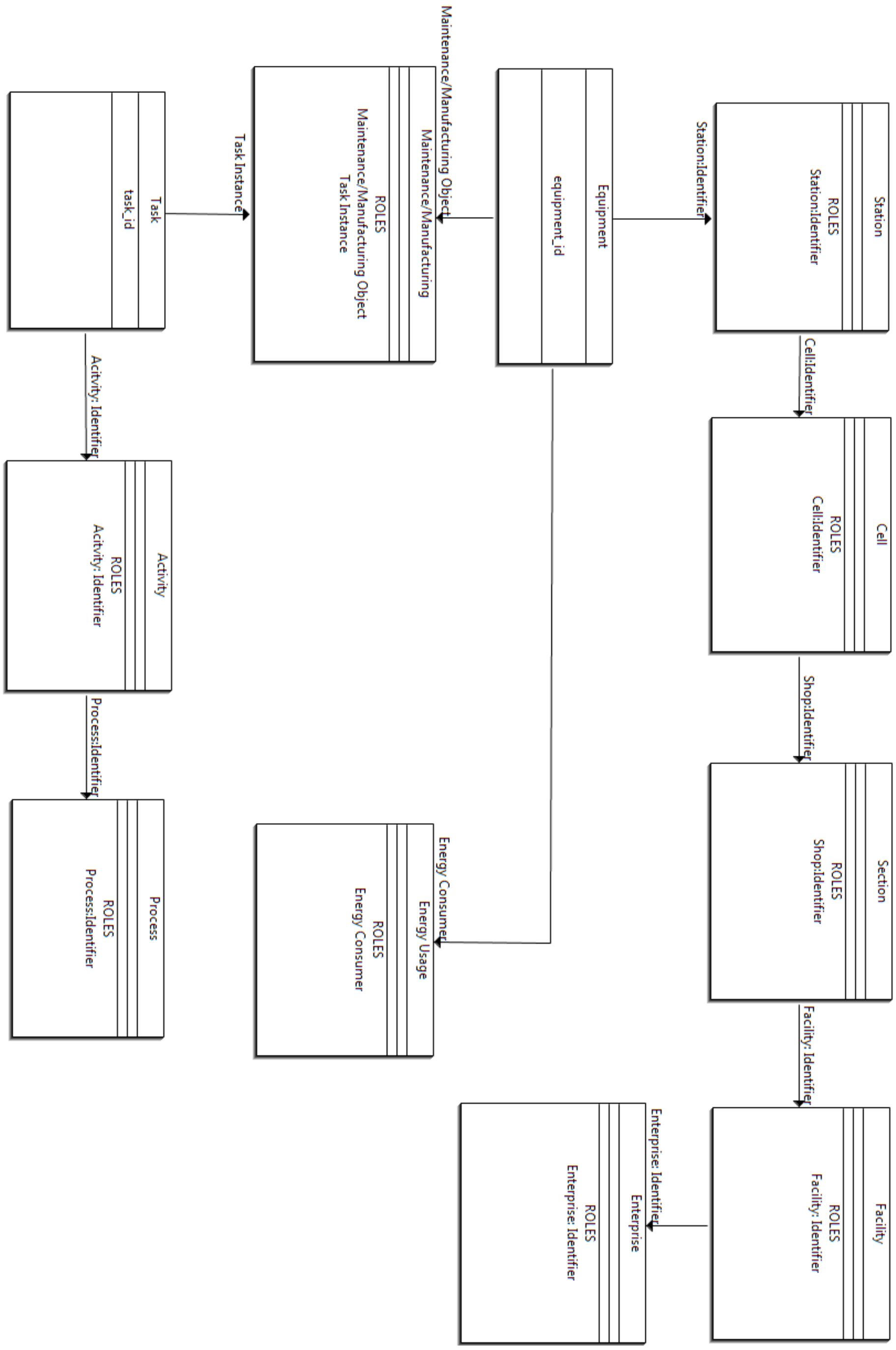

Figure 10. Configured information model of case study 3 (1/3)

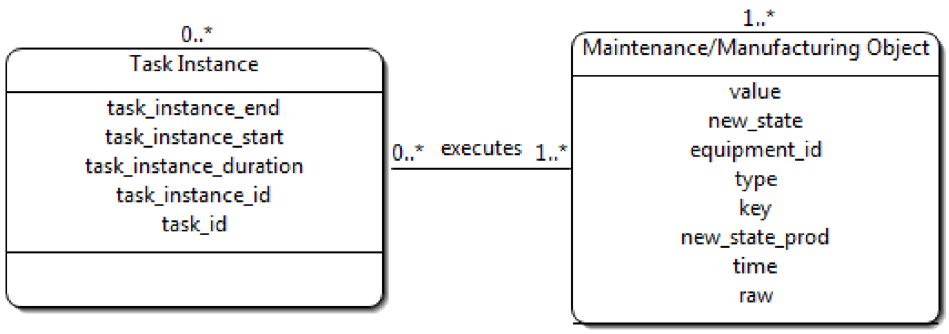

Figure 11. Configured information model of case study 3 (2/3)

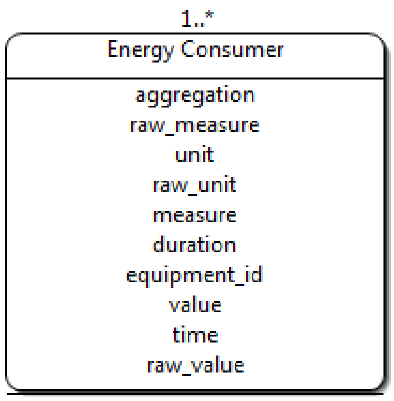

Figure 12. Configured information model of case study 3 (3/3)

Regarding task 08, the same attributes ("type", "key", "value") of the previous case studies were implemented. In this case study, I used these attributes to show raw events at the same time as non-productive behavior of the equipment occurred. Task 12 und 13 were implemented (same reasons as in the previous study). The hierarchies of task 14 and 15 were implemented, whereas the ISO TC184/SC5/WG1-N58 (equipment, station, cell, section, facility, enterprise) was used as an orientation for the hierarchy levels of task 14 (shop_id was used instead of section_id) (McGuffin et al. 1988).

During the execution of task 16, the task_instance_start and task_instance_end were added to the role type "Task Instance" as additional attributes in order to enable the analysis of energetic costs of a certain task. Task 17 was skipped (no product reference was needed). The only discrepancy between the original information model and the configured information model is that the attribute "duration" in the energy consumer is called "raw_duration" in the original information model (task 23). However, this is not important for the application of the information model. Therefore, the configured information model was not applied to the data of the case study again. The original information model of case study 4 is already published in a previous article (Effenberger and Hilbert 2017). The system functions that were the basis for the additional attributes and decisions during the methodology were: 1, 2, 5, 6, 8-14, 16, 19-21,23-24, 26-30, 33, 35-38, 40, 42, 43, 47-49, 52-56 (system functions are based on a previous study (Effenberger and Hilbert 2016)). The configured information model is presented next (see Fig. 13-15).

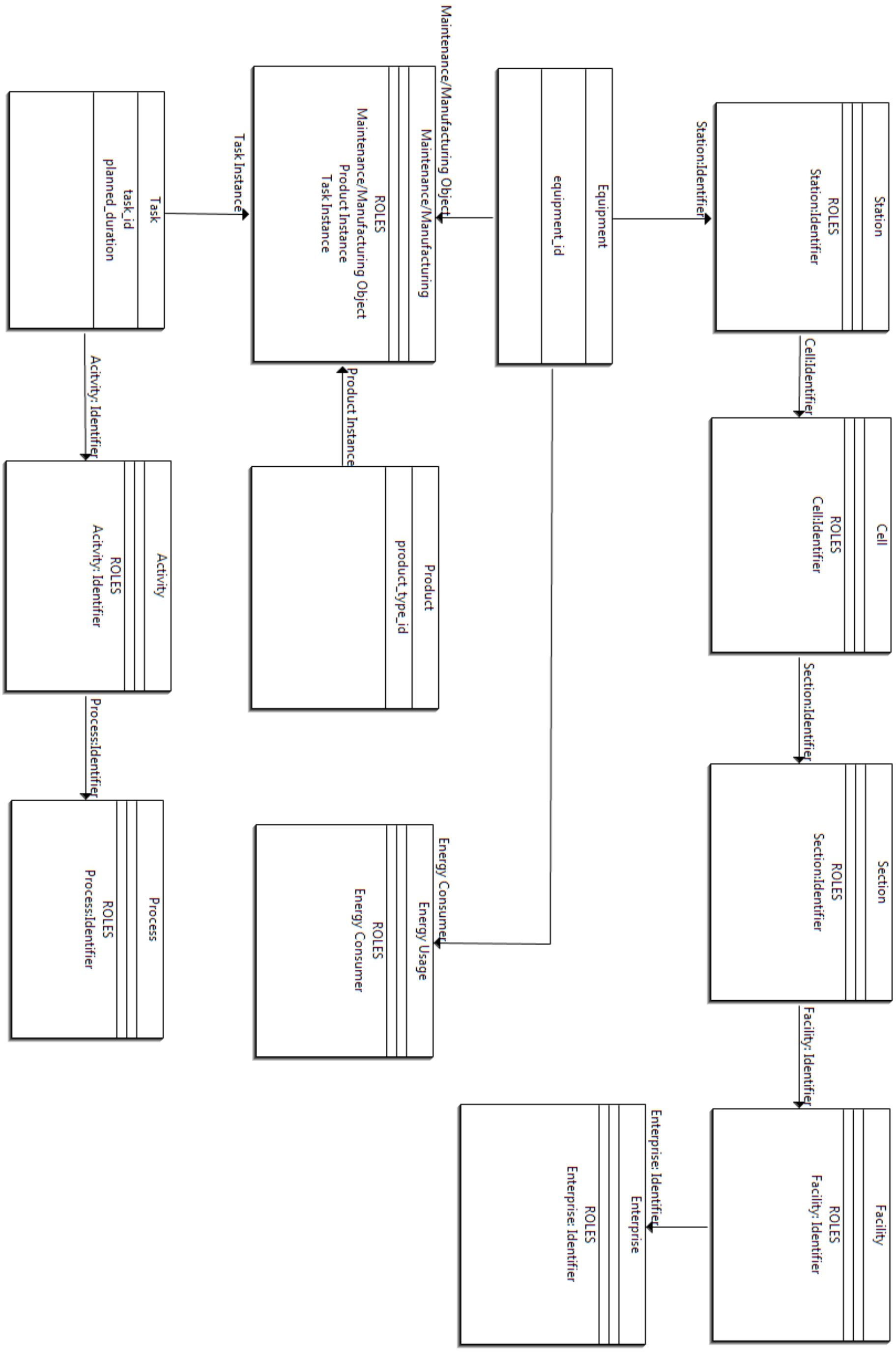

Fig. 13. Configured information model of case study 4 (1/3).

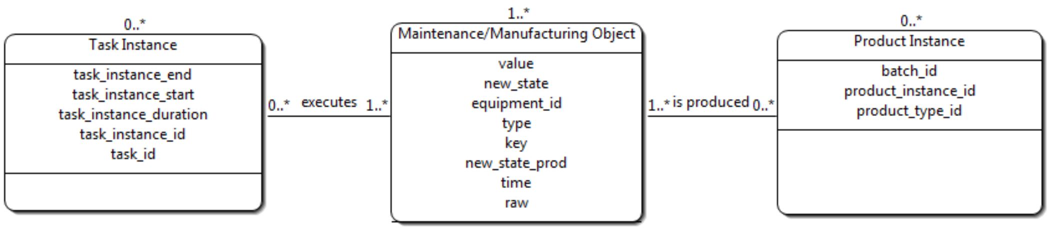

Fig. 14. Configured information model of case study 4 (2/3).

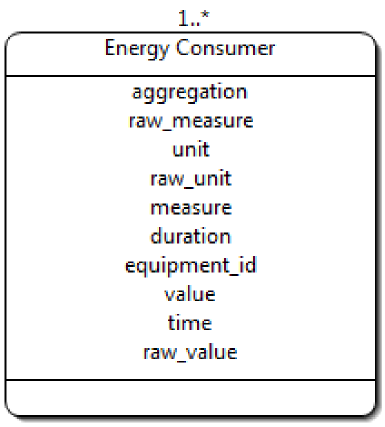

Fig. 15. Configured information model of case study 4 (3/3).

The three attributes “type”, “key”, and “value” from the execution of task 08 were implemented as well as the duration from task 12 and the “Task” of task 13. The same hierarchies as in the previous study were used for the execution of task 14 and 15. For the execution of task 16, the attribute “planned_duration” was implemented for the element “Task” as well as the attributes “task_instance_start” and “task_instance_end” for the role type “Task Instance”. For task 17, a product reference was implemented. The attribute “product_type_id” was added to the element “Product” and the role type “Product Instance”. In addition, the attribute “batch_id” was added to the role type “Product Instance”. This enabled the assignment of products and batches to a certain time at the equipment. This assignment enables the link between the execution of tasks and the energy consumption of the product instance, e. g. for the calculation of the energetic footprint of a certain product or batch. For task 23, the attribute “duration” was implemented.

There is one discrepancy between the original information model and the configured information model. In the original information model, the product fulfills two roles (one to the element “Maintenance/Manufacturing” and one to the element “Energy Usage” as “Product Instance”), whereas the configured information model only needs a role fulfillment from the Product as “Product Instance” to the element “Maintenance/Manufacturing”. Both approaches are correct; however, I discovered that with the usage of CROM, the equipment already fulfills two roles. Therefore, with the linkage of a role Type “Product Instance” to a role fulfillment of the element Equipment, a link to the role type “Energy Consumer” is given implicitly. This can be easily explained; if the product is processed at a certain time at the equipment, then the task and the energy consumption can be identified at that time. Therefore, a second role type for “Product Instance” is not needed.

4.5 Integration of the Configurable Information Model and System Functions into existing Architectures

Due to the fact that most architecture descriptions include an information model, the integration of a configured information model into an existing architecture with the same scope seems trivial. Regarding a reference architecture description (ISO/IEC/IEEE 2011), the information model can be implemented as an information view and the correspondence rules apply to the system functions in the allocation & decomposition view of the previous study (Effenberger and Hilbert 2016). Regarding Zampou et al., the system functions are already integrated into the architecture (Effenberger and Hilbert 2016). Therefore, due to the link of the system functions to the configurable information model, the integration is possible.

However, the application of the configurable information model in other architectures with a similar scope might be interesting. A recent study regarding demand side management proposed an architecture with an observer and controller that is used to support decisions regarding the flexible usage and procurement of energy (Häfner 2017). In the performed expert interview in this study, the missing link between the energy consumption, production planning, and regulation is mentioned by the first expert (Häfner 2017). The configured information model can integrate predicted values or pricing models due to the possibility of additional attributes on the role types “Maintenance/Manufacturing Object”, “Task Instance”, “Product Instance” as well as the elements “Task” and “Product”. It can provide information regarding the energy consumption on the equipment-level for the predictions. As can be seen from the case studies, the configured information model is able to close the mentioned gap of the expert and support the architecture.

Therefore, the configured information model might be a basis for the components “Monitor”, “Log File”, “Predictor”, or “Data Analyzer” of the proposed architecture. The configuration model can be part of the “System under Observation and Control” and be able to supply the basis for the decisions regarding the equipment-level.

5 Conclusion and Outlook

In this article, I identified 12 reusable design principles by extracting the knowledge of developed information models from three industrial case studies as well as by evaluating the results with two system architects in three evaluation rounds. The design principles support scientists and system architects in the development of a configurable reference model as well as in the configuration of possible instantiations for the combination of energy and machine data for energy-aware industrial manufacturers. The evaluation showed that the application of the 12 design principles lead to a reusable, complete, and understandable decision-making basis for improving the energy efficiency.

Based on these results, I developed a configurable reference model for the combination of energy and machine data for energy-aware industrial manufacturers with the design science research methodology. The proposed reference model can be configured by a methodology that consists of 25 main tasks and several sub tasks that are derived from the design principles. I instantiated the information model for the fourth case study and discussed the application and benefits of the usage of the configurable reference model. Furthermore, the reference model was reapplied to the previous three case studies. I therefore showed that the reference model is reusable and therefore a useful and relevant decision-making basis for system architects. Furthermore, I was able to show that the quality increases and that a system architect can save time (two weeks instead of four months in the first case study, one month instead of 6 months in the second case study) and costs (savings of 12250€ in the first case study and 17500€ in the second case study) when using the configured reference information model. In the context of energy informatics, this is a crucial contribution to the knowledge base, especially considering the fact that there are currently no reference models for this class of problems (Effenberger and Hilbert 2018).

However, there are some restrictions. Equipment usually has to be extended by sensors before every relevant data can be measured and used by an information model, which leads to additional costs for an industrial manufacturer. Therefore, the identification of the equipment which has potential for improving the energy efficiency is limited by the available data and the cost of additional sensors. Furthermore, the configurable information model was only applied to one new case study and then reapplied to the three previous case studies. On the one hand it is therefore possible that changes to the model have to be made in the future. On the other hand, there is no independent reference model that can be compared with this configurable information model in the context of energy-aware industrial manufacturing. Furthermore, the increased quality and the savings in terms of time and costs after the reapplication in the first three case studies might be influenced by the previous gathered knowledge of the case studies. However, the savings are based on the personnel cost of the system architect in the case studies and are probably even higher when considering other employees and cost factors.

In addition, the integration of the reference model in an architecture with a similar scope is discussed. Obviously, due to the different demands, the proposed reference information model will not be able to fulfill all of the requirements. However, it can support all requirements and problems that deal with energy and machine data on the equipment-level. Therefore, the reference model might be a basis that can be extended in order to be applied in other scenarios, e. g. for energy procurement.

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APPENDIX D-II: APPENDIX OF THE ARTICLE

Appendix A

Original information model of case study 1:

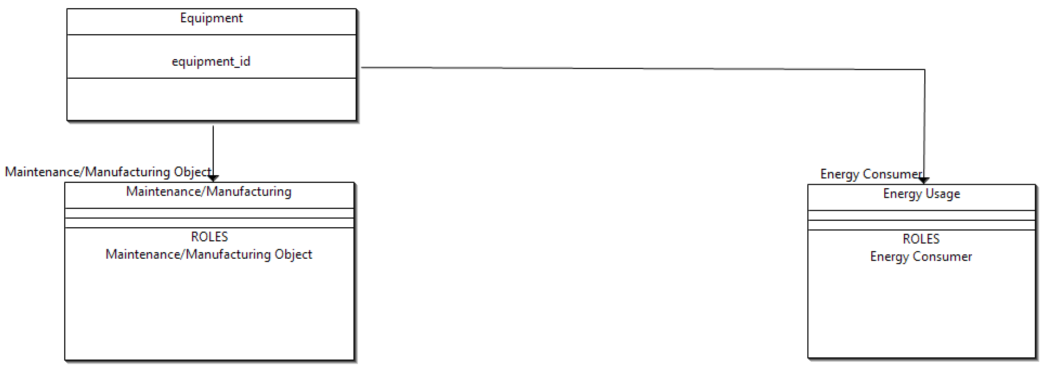

Fig. 16. Original information model of case study 1 (1/3).

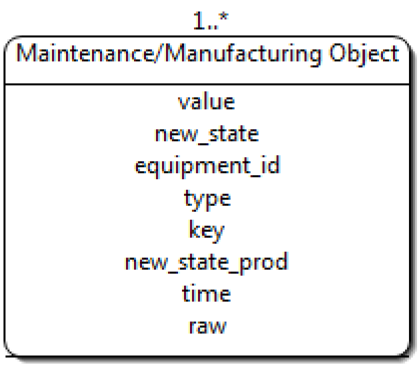

Fig. 17. Original information model of case study 1 (2/3).

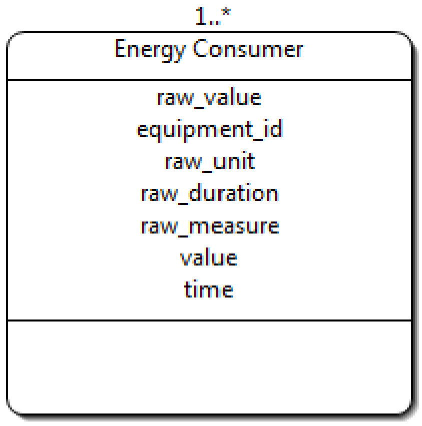

Fig. 18. Original information model of case study 1 (3/3).

Original information model of case study 2:

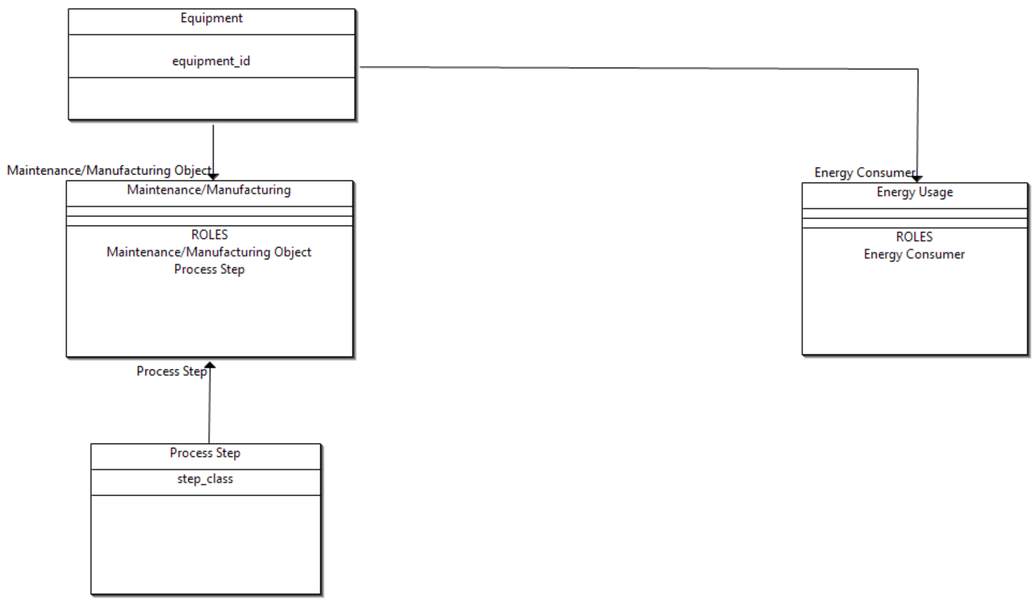

Fig. 19. Original information model of case study 2 (1/3).

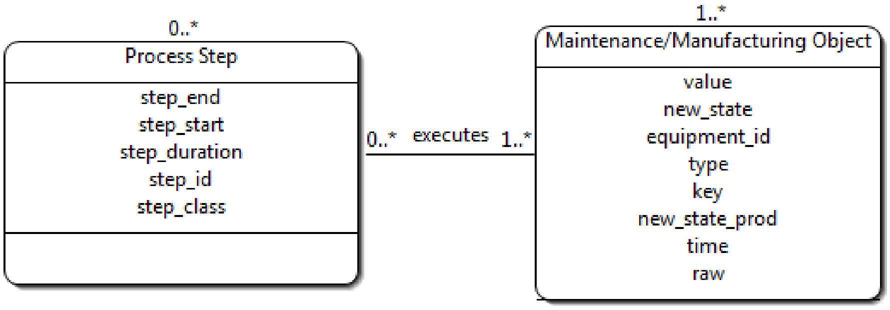

Fig. 20. Original information model of case study 2 (2/3).

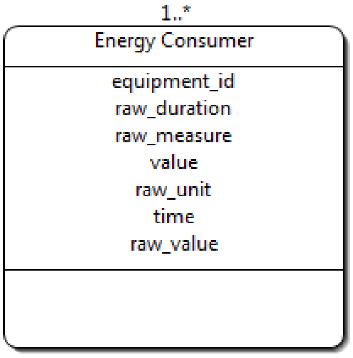

Fig. 21. Original information model of case study 2 (3/3).

Original information model of case study 3:

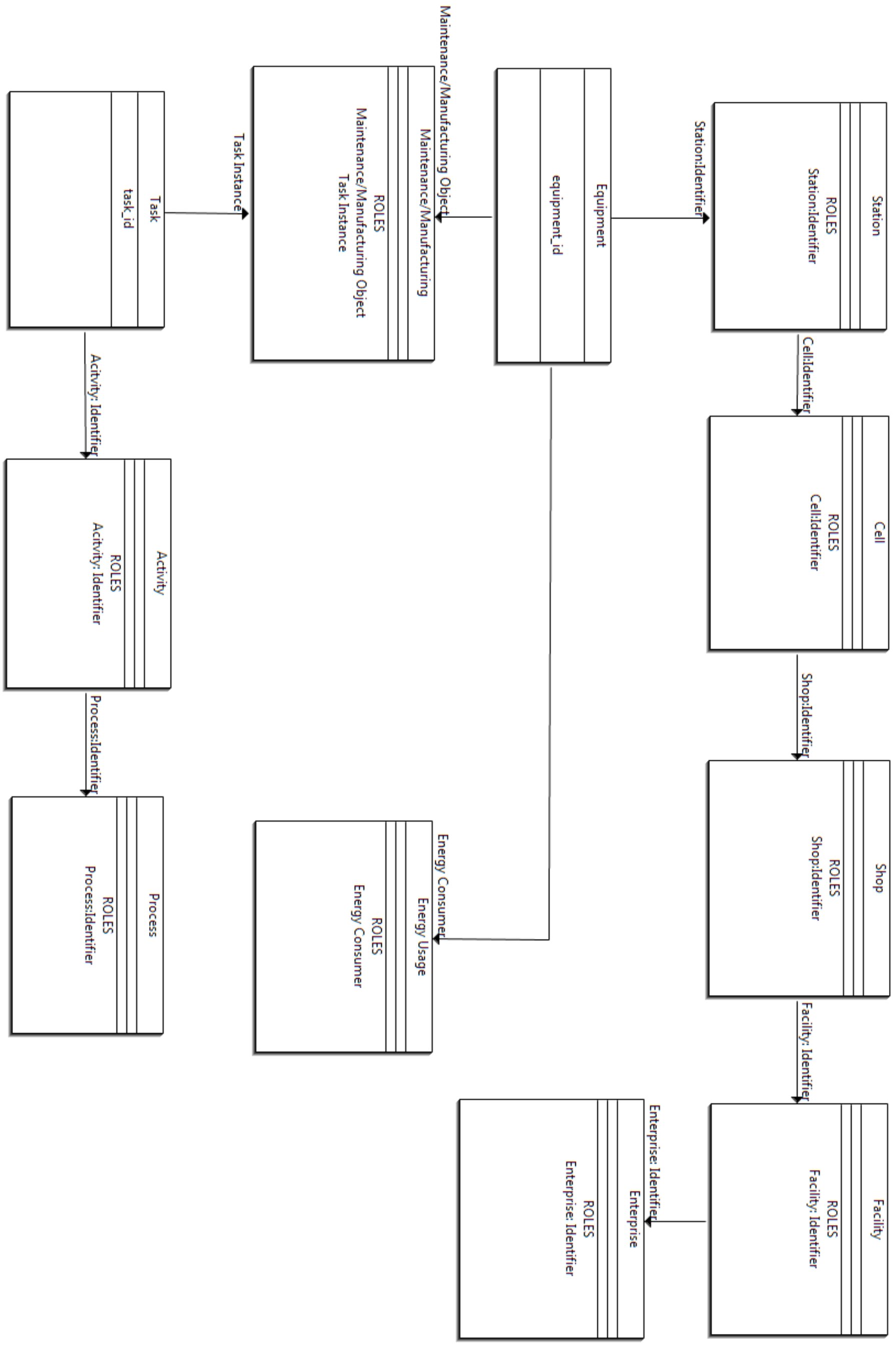

Fig. 22. Original information model of case study 3 (1/3).

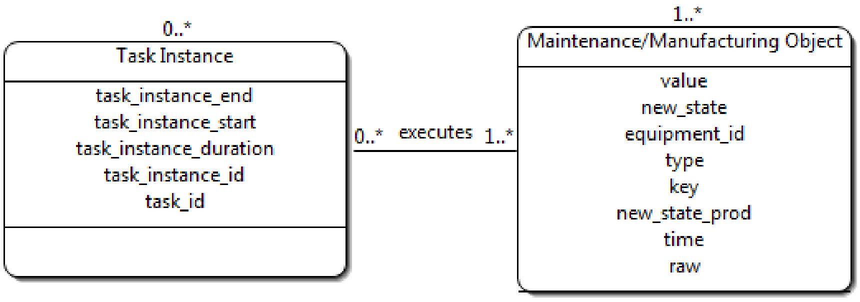

Fig. 23. Original information model of case study 3 (2/3).

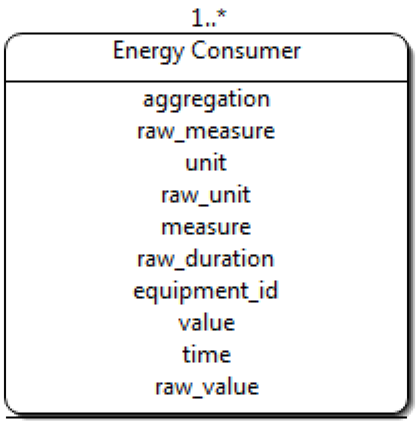

Fig. 24. Original information model of case study 3 (3/3).

The original information model of case study 4 is already published in a previous article (Effenberger and Hilbert 2017).