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Methodology and model for predicting energy consumption in manufacturing at multiple scales

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Abstract

Certain fields of manufacturing, like casting, forming or cutting, may cause high energy load. Especially under the consideration of renewable energy sources it is beneficial to negotiate production schedules and consumption forecasts with the energy supplier. This would enable an optimized management of energy sources and infrastructure components on the supplier side, helping to reduce costs. Optimal and balanced expenses for production would be the consequence.

The problem of power consumption prediction in manufacturing was subject of many studies in the past. Most of them either consider the physical modeling of processes at a very detailed level, or they introduce tailored prediction models for specific production processes. Thus, it is hard to apply their results to other uses cases in different scenarios.

As a consequence, a generic methodology and model regarding power consumption prediction in manufacturing is required in order to cover the variety of processes, machines and materials. Furthermore, an approach must support flexible levels of granularity for predicting the energy consumption of manufacturing processes. On the one hand, a whole factory may be the object of investigation while, on the other hand, predictions for finer-grained levels, such as certain parts of a machine, are required to allow for specific optimizations.

Our contribution is twofold. First, we propose a generic model for the specification of the power-consuming machine. A tree-based compositional approach supports arbitrary levels, depending on the structure of the machine, or external factors, such as company policies. This approach is highly extensible since the models are stored in ontologies. Second, we propose a methodology for static and dynamic modeling of power consumption for every structural level. Based on that model the prediction can be realized. In addition, we provide an example implementation and prediction for a continuous casting machine process.

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Keywords: Energy efficiency; Predictive Model; Ontology

1. Introduction

Current change and trends in German and European energy markets demand for a transition to flexible energy consumption in industry wrt. the produced energy [1]. Production planning must take the energy supply into account which is decentralized due to both the German Renewable Energies Act (EEG) and Europe's climate and energy

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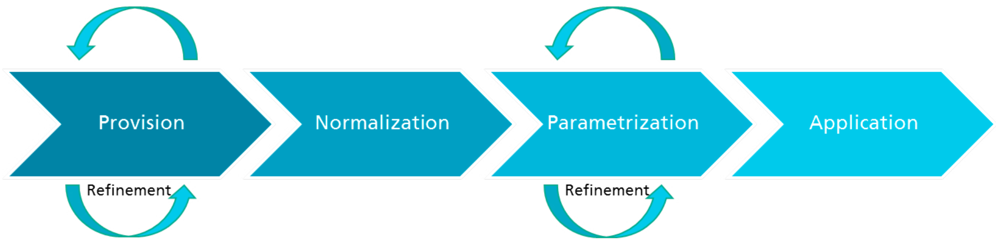


Fig. 1. Methodology for predicting energy consumption in manufacturing processes.

targets [2]. In order to realize flexible control of industrial energy consumption energy-related data must be made accessible from both the consumers and the suppliers.

Consumers have to provide information about their energy-consuming infrastructure. The level of abstraction of such data can vary depending on, e.g., technical prerequisites or just internal regulations. As a consequence, energy-related data might be available for a whole factory only or, in the best case, for concrete aggregates of the machines. The finer grained the provided information is the more flexible the control of consumers can be achieved. More precise information means more potential for energy-related optimization of production processes.

On the other side, suppliers should publish their financing models so that the best point in time of a costumer's production can be scheduled. In this paper, the authors will cover only the part related to the industrial energy consumers.

Due to the lack of a standard which can be used to exchange energy-related data, consumers are free to decide which data format to use. As a consequence, the main problem is that there are two distinct dimensions, *data source* and *data access*, to retrieve data formats from. On the one hand, *data sources* can be, e.g., estimated or measured (historical) data or even a physical model of the energy consumption. On the other hand, such sources can potentially be *accessed* in various kinds, such as, e.g., through an Excel sheet, databases, time series or even via Matlab/Simulink models. We consider this fact as a required freedom for data suppliers, but as a consequence we are faced with an amount of potential data formats to be supported as the cross product data source × data access.

To overcome this problem, a normalized data format is needed that is flexible enough to support all the properties and requirements of the existing conventional data sources. Our approach presented in this paper is based on an ontological representation in order to ensure flexibility. It is divided into two parts: 1) structure of the energy consumer, and 2) specification of its energy behaviour. The former follows a given schema which enables the hierarchical definition of consumers on arbitrary levels of granularity. The latter provides core concepts for specifying static and/or dynamic behaviour of consuming energy. These are needed to be accessed and processed automatically.

In the remainder of this paper we describe a methodology for the iterative specification of energy consumers in Sect. 2. Based on this, the formal grounding for defining the structure and our approach of specifying the static energy behaviour models is presented in Sect. 3. To complete the approach, our solution for defining the dynamic energy behaviour is described in Sect. 4. Our implementation and a demonstration for a continuous casting process is given in Sect. 5. The related work in Sect. 6 and the future work outlined in Sect. 7 conclude the paper.

2. Methodology to enable iterative specification of consumers

As mentioned before, a general approach and a normalized data format is required to support the exchange of arbitrary energy-related data. To enable prediction of energy consumption for manufacturing processes we propose the high-level methodology in Fig. 1 which is refined and explained in the following.

Our proposed methodology consists of four main steps. In the beginning, the **provision** of energy-related data initiates the process. To predict energy consumption such data is separated into the consumer's structure and the relevant consumption information corresponding to the structure. We explicitly link this information in order to emphasize which unit consumes a particular amount of energy. Furthermore, we propose an iterative approach for providing the energy-related data to respect the hierarchical nature of an energy-consuming entity. Consider, e.g., a *continuous casting machine* located in a *factory*. The machine consists of several *aggregates* and *units*, such as the torch cutting machine, the tundish handling device or the lubrication system. Each of them consists of various *sub-parts* which in turn consume energy of their own. Depending on the required level of detail, we propose an iterative methodology for providing this data. The finer grained the provided information of energy-consuming parts, the more precise the energy model and the more potential for optimization. This means that coarse-grained results can be achieved quickly when providing information at a higher scale. This can be, e.g., the total consumption measured for the whole machine. A provided energy consumption at this abstract level is easy to realize but cannot be used for precise analysis. In contrast, providing energy consumption at a lower level, such as the main or auxiliary aggregates, is more precise and productive and unproductive performance can be distinguished. Information at this lower scale is suitable for analysis and optimization of manufacturing processes. This means that this step in the proposed methodology should be complemented by a demand-driven **refinement** process, depending on the scale of required level of detail for the specific purpose.

The second step is the automatic **normalization** of the provided data into a *general format*. This format must be precise enough to support meaningful access to the data, without loosing details. Furthermore, it must be flexible in the sense that use-case-specific customizations and/or individual characteristics can be modelled. Consider, e.g., *phases* which are intended to be distinguished in different processes. In every phase a unit consumes a particular amount of energy. They can never be generalized but still should be queried in a specific way. Every process, machine, production line, plant and factory is different but must be considerable. To support the automatic normalization we propose an import mechanism. For every different source format an importer must be implemented which transforms the data into our general format. This format respects the compositional hierarchical nature of energy-consuming entities. The main concepts for specifying the structure of consumers are clear and selected in order to be easy understandable. Thus, a specific importer for a particular source format can be implemented quite facile. A detailed explanation can be found in Sect. 3.

At this stage the provided information (structure of consumers and energy consumption) can be considered as the static energy-related behaviour since it represents the consumption for one specific process. Thus, it cannot be used to predict the consumption for other setups or use-cases. Therefore, in this phase the provided static behaviour is intended to be **parameterized** for the purpose of creating variation points. As a consequence, properties of the manufacturing process that influence the energy consumption can be bound to different values. Based on the provided static energy-related data it is intended to be **refined** iteratively, so that quick results can be achieved. Thus, properties influencing energy consumption are identified and it is possible to specify the dynamic energy-related behaviour of consumers in this phase. In Sect. 4 our approach of parameterization is explained in more detail.

After the iterative refinement of the parameterization the resulting model can be used for predicting the energy consumption for different properties. In this sense the previously identified and specified parameters now must be bound to specific values. Such parameters might be, e.g., thickness of a material or the load in a process. This **application** of the parameterized model in conjunction with the concrete values then results in the prediction of the new energy consumption for the particular bound parameters.

3. Modelling consumers' structure and static behaviour

Our proposed methodology is based on a component model of the the system under consideration. Depending on the requirements on the energy consumption models each component has associated models for the energy consumption in steady state or in regard to its dynamic behaviour. This approach may be described as some sort of grey box modelling that combines known facts about the internal structure and principal mathematical relationships of the system with further numerical parameters that need to be determined by experimentation.

An extensive overview on modelling of systems is given by Yang and Marquardt [3]. They studied the structure of so-called multiscale models: mathematical system models, whose relations connect partial models from different levels of detail (scales). For example, such multiscale models are able to combine effects of heat conduction in molecular or atomic scale with a macroscopic model of a cooling system. Furthermore, those models are different to standard box models of systems in that they have an explicit representation of logical and physical relationships between system components and therefore a semantic model of the system structure.

Yang and Marquardt's conceptualization of multiscale models is based at its core on Bertalanffy's general system theory [4] and also builds on works of Bunge [5,6] as well as Wand and Weber [7].

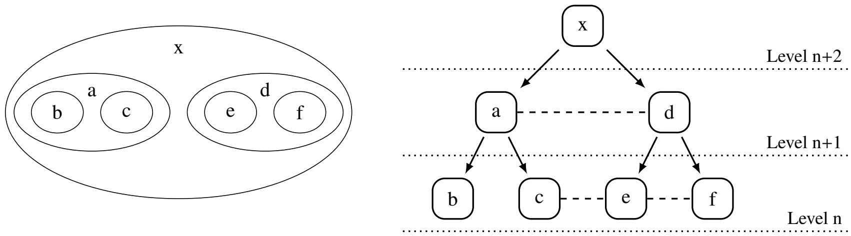
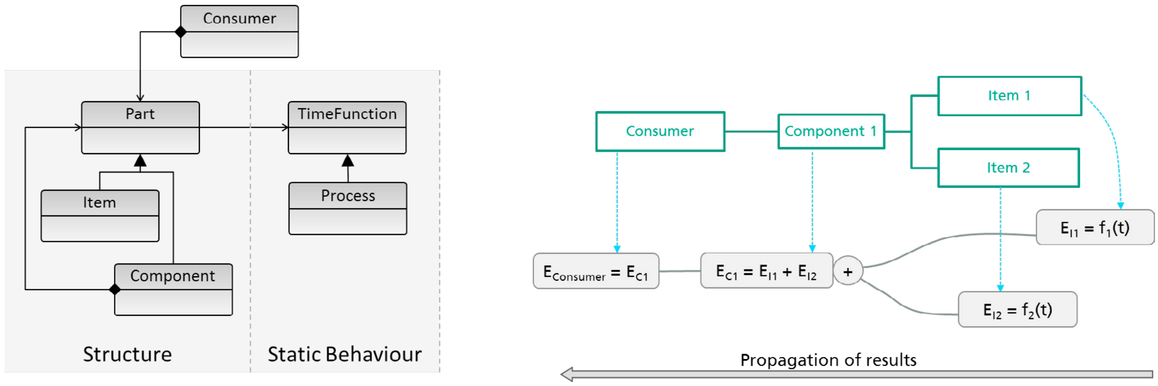


Fig. 2. Part-whole relationships, system levels and couplings (cf. [3, pp. 825 and 828]).



(a) Concepts for structure and static energy-related behaviour.

(b) Instantiation and propagation along the tree.

Fig. 3. Specification of structure and static energy-related data of consumers.

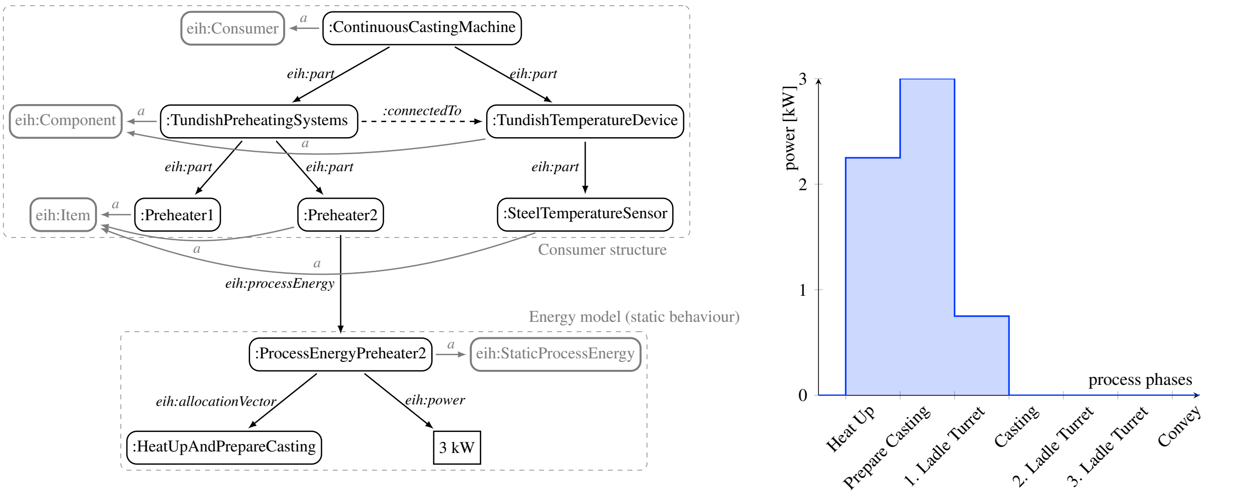
The latter can be regarded as an ontology according to [8] and is also mentioned as such in previous work as in [9] where it is called Bunge-Wand-Weber (BWW) ontology. Yang and Marquardt use this ontology as a basis to define a comprehensive mathematical definition of general systems extended by the aspect of multiscale modelling.

Fig. 2 shows basic concepts of the system models as used in the presented approach. A system is characterized by a set of connected objects which can be deconstructed into a set of components by part-whole relationships. Each of those components owns multiple properties whose values are described by state functions that describe the state of the system in a specific context (e.g., dependent on time, location and others). Components are coupled if they influence each other in some way. There may exist multiple couplings between two objects that are characterized by force, heat, material or signal transmissions.

For the formal representation of such models a framework is required that enables the description of the system components as well as physical and logical relationships between them. In the following the main concepts for specifying the structure and static energy-related behaviour of consumers are explained which then can be used as a (programming) interface by users. For the sake of comprehensibility these concepts are depicted in Fig. 3a where we used the notation of the Unified Modeling Language (UML) [10]. The specific properties of the concepts and multiplicities are omitted in this figure but are explained in the following.

The entry point is to specify a *Consumer*, such as e.g. the continuous casting machine. At this point the user already can decide at which scale to start modelling. Such a level of granularity can also be a production line or a particular machine. A *Consumer* consists of several *Part*s. A *Part* is an abstract concept which can either be an *Item* or a *Component*. An *Item* is intended to be a smallest energy-consuming unit in the whole system. Thus, it can be, e.g., a feeder in the continuous casting machine if it should not be decomposed further. *Component*s group together other sub-*Part*s and therefore contain children. By this parent-child (or part-whole) relationship a tree-like structure is modelled in which *Items* are the leafs.

In order to enable (programmatic) access to the energy-related static behaviour of a *Consumer* we provide the interface *TimeFunction*. As the directed arrow in Fig. 3a indicates a *Part* can refer to a *TimeFunction* which means that they can be modelled independently. This approach emphasizes the iterative nature of the methodology: first the



(a) Represented in RDF. (b) Energy consumption related to process phases.

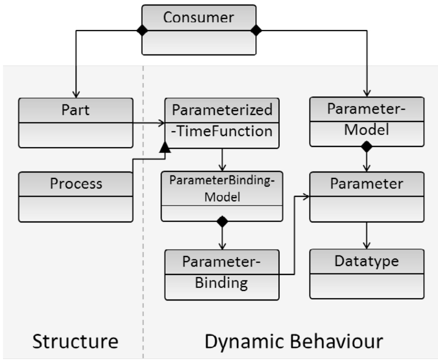
Fig. 4. Example models for continuous casting machine.

whole structure can be modelled before the static behaviour is specified. Similar to *Part* the interface *TimeFunction* is an abstract concept which can be realized by a *Process*. A *Process* reflects an energy consumption over an amount of time which is intended to be characterized by an instance of this concept. In the upper part of Fig. 3b an example instantiation of a *Consumer* is illustrated, whereas the lower part shows the related instances of *TimeFunction*s. This figure also shows how the calculation of the static energy consumption is processed. For a particular node in the structural tree and a particular point in time the energy consumption is calculated as the sum of the underlying child consumptions. This approach enables the calculation of energy consumption for every nodes in the system's tree. Calculated values are propagated along the tree up to the point where it is requested by users.

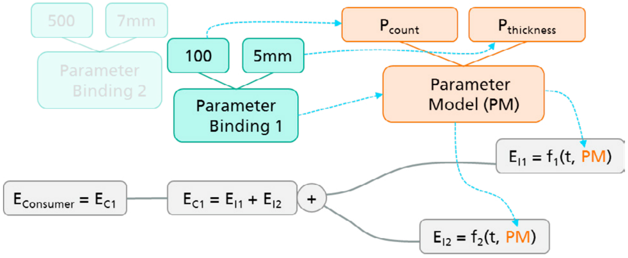
The described modelling approach is based on the idea to regard system models as directed graphs in which the nodes map to individual system components and edges map to part-whole relationships or couplings between them. The Resource Description Framework (RDF) [11, pp. 28–49] uses directed graphs for data representation and hence is well suited to model systems by means of the approach outlined above. Fig. 4a outlines an example of such a system model for a continuous casting machine. The upper part shows an excerpt of the hierarchical structure of the machine (which is a `eih:Consumer`). Its parts are defined by using the RDF property `eih:part`. The structural model of the consumer may also contain topological connections established with the RDF property `eih:connectedTo` as in the given example between `:TundishPreheatingSystems` and `:TundishTemperatureDevice`. Each component of the system may be associated with an energy model. The example uses an instance of `eih:StaticProcessEnergy` to model static energy consumption of the respective item by using an allocation vector a and a power rating P. The allocation vector contains values a_p in the range $[0, 1]$ for each process p in the system to model the portion of the given power rating P_p that should be accounted for this process. Corresponding to the excerpt of Fig. 4a the consumed energy of `:ProcessEnergyPreheater2` mapped to the according process phases is depicted in Fig. 4b.

4. Modelling consumers' dynamic behaviour

As explained in Sect. 2 in the phase of *Parameterization* the energy-related dynamic behaviour is modelled. We argue that this step should be accomplished iteratively based on the previously provided structure and static behaviour. As can be seen in Fig. 5a iterative refinement can be achieved by further specialization of *Process*es since this concept is not only a *TimeFunction* but also a *ParameterizedTimeFunction*. Thus, a previously modelled *Process* can now be parameterized by specifying a *ParameterModel* for the *Consumer*. Again, both are separated in order to enable iterative specification. In the *ParameterModel* one can define potential properties of the system which influence the energy consumption. Therefore, a *ParameterModel* contains several *Parameter*s. Every *Parameter* must refer



(a) Concepts for dynamic energy-related behaviour.



(b) Parameter model and parameter binding along the tree-based structure of a consumer.

Fig. 5. Parameterization for dynamic energy-related data of consumers.

to a *Datatype* in order to ensure that parameters are compatible in the calculation and that they can be visualized appropriately. For the continuous casting machine such parameters might be, e.g., the *thickness* of a slab or the *count* of runs to process. Fig. 5b illustrates this example of a *ParameterModel* in the upper-right (orange) part. This specification of a *ParameterModel* is realized before the `Application` phase (see Sect. 2). Since defined *Parameter*s are independent from a particular *Process* it is needed to specify a *ParameterBindingModel* which is intended to bind parameters to concrete values. Therefore, a *ParameterBindingModel* contains several *ParameterBinding*s. Every binding refers to a *Parameter* and sets the value (not illustrated in Fig. 5a) which must conform to the *Parameter*'s type. With this approach different bindings can be instantiated for different contexts or situations. The upper-left light-green part of Fig. 5b shows two concrete bindings. In addition to a particular point in time such *ParameterBinding*s are applied to the *ParameterModel*. Thus, a previously provided static energy-related behaviour is parameterized and be refined and applied to model dynamic energy-related behaviour.

5. Implementation and example demonstration

We implemented the whole approach with all its concepts in Java and used our framework Knowledge Modeling and Management Architecture (KOMMA) [12][1] for representing the RDF-based triples as Java objects. This enables us to consider the RDF classes as conventional Java classes from a programmers perspective. The benefit is that the Java objects form a graph and RDF-based query languages, e.g. SPARQL Protocol and RDF Query Language (SPARQL) [13], can also be used to reason about the whole knowledge base.

To provide users a graphical interface we used the Remote Application Platform (RAP)[2] from the Eclipse community. As an example process we got energy-related data from one of our partners as an Excel table. Thus, we implemented a an importer for the specific format of their energy data tables and can convert their specific data into our general format. Since our approach is extremely flexible and extensible, we could easily provide more process properties while importing the data. As a consequence the Excel tables of our partner can be loaded into the developed web application and the energy consumption then can be visualized. Fig. 6 shows our RAP-based web application and a simplified extract of the continuous casting machine and process. One specific partner extension can be seen, e.g., in the right window where the energy consumption of the selected nodes of the tree (left window) is mapped to concrete process phases of the continuous casting. The visualization is realized with the JavaScript framework D3.[3] As already described in Sect. 2 one has to provide an importer for every different data format. After that the data of that format can be used and analyzed in our RAP-based web application.

[1] `http://komma.enilink.net/`
[2] `https://www.eclipse.org/rap/`
[3] `https://d3js.org/`

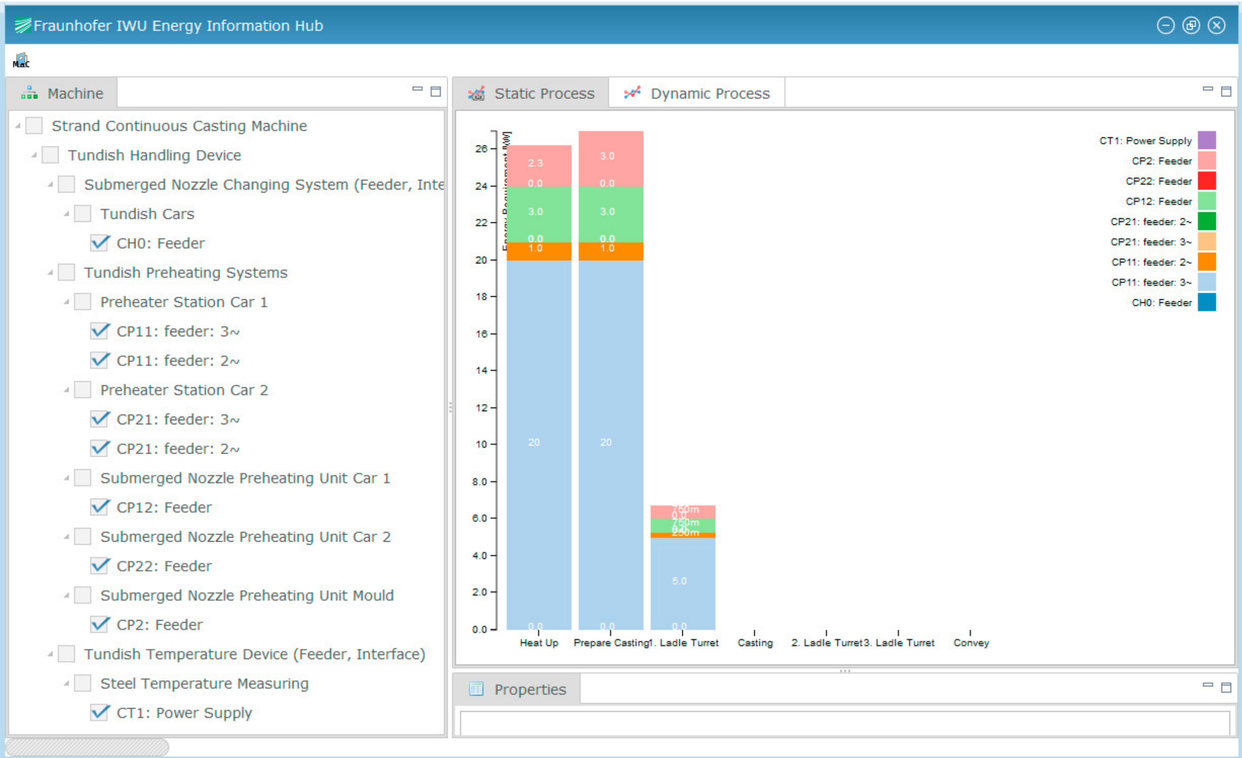


Fig. 6. RAP-based web application for the static energy consumption prediction of an extract of a continuous casting machine process.

6. Related Work

In the general field of energy control in manufacturing many publications exist already. Therefore, we only provide a representative cross section here. E.g., preliminary work for this paper is presented in [14] where the authors illustrate an approach for correlating collected energy consumption data and consumers in manufacturing. Therefore, SPARQL is used to query RDF data in order to reveal correlations. In contrast to this paper, they focus on how to represent consumers' properties and energy-oriented simulation models whereas we provide the formal base for time-dependent static and dynamic energy models.

Similar to our work, important papers are presented in [15–17]. Therein, a power consumption monitoring and optimization concept and the XML-based Energy Information Description Language (EIDL) are contributed. As opposed to our work, users of the EIDL are bound to the XML schema of that language and, thus, cannot model use case-, situation- or process-specific concepts. The solution presented in this paper allows for flexible extension of the core concepts which can still be processed automatically by applying the importer approach.

Other papers that also contribute approaches for specifying energy models are, e.g., published in [18,19]. The former uses finite-state machines (FSMs) to model the energetic behaviour, whereas the latter uses Generalized Stochastic Petri nets (GSPNs). Both approaches specify the dynamic energy-related behaviour but they are restricted to the used formalisms (FSM and GSPN). Applying these formalisms can become quite complex. In contrast, our presented approach is more flexible and allows for the use of any energy modelling formalism, provided that a corresponding importer is implemented. Making other importers available is left over for future work.

7. Conclusion and outlook

In this paper the authors provide a flexible and extensible approach for modeling structure and energy-related behaviour of consumers in manufacturing. It is complemented with an iterative methodology which describes the procedure of step-wisely specifying, first, the structure, second, the static behaviour and, third, the dynamic behavior regarding the energy consumption. We implemented the presented approach with our Java-based framework KOMMA which has the benefit that the whole knowledge base can be queried with RDF query languages.

In the future, we want to implement further specific importers for formats which are used most often in production or which have already proven as effective (such as [18,19]). Furthermore, our developed RAP-based platform is intended to be published in order to establish a community of energy consumers and suppliers to exchange their data.

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