A Process Framework for Modelling of Energy Systems

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ABSTRACT

The use of simulation for assessing and optimizing the performance of energy efficiency in complex consumer systems implies the need to provide reliable system models. The models often need to integrate a variety of aspects which require the involvement of an interdisciplinary team and the reuse of existing models or tools. This paper presents a modelling framework for the process leading to a conceptual model and subsequently to an executable model. The framework specifically addresses the challenges resulting from working in interdisciplinary teams and features a combination of top-down and bottom-up modelling approaches in order to ensure reusability. The relevance of the framework to project success is illustrated by an application example from the field of energy efficient industry.

KEYWORDS

Energy System Analysis, Modelling and Simulation, Energy System Simulation, Energy System Modelling, Energy Efficient Production, Modelling Theory

INTRODUCTION

One of the most important tools to assess and optimize the performance of energy systems is simulation. However, the operating efficiency of an energy system is highly dependent on a number of factors: technical restrictions, consumer behaviour, fluctuating renewable sources, and economic considerations. In this context one of the core research questions is, how to design and operate the often rather complex on-site energy systems of consumers in the most sustainable way.

The undertaking of assembling, executing and interpreting an energy system simulation integrating a number of the aforementioned aspects is no trivial task. Commercially available simulation tools in this field cover a large range of applications like analysis, design or optimization [1] but they usually limit the observed area to the energy system and the building. Accordingly, the integration of other aspects into energy system and building simulation have been identified as recently emerging research areas [2]. As with most simulation applications, a crucial factor for the success of such an integration is the right model, which sometimes is quite difficult to find. Firstly, the model development usually involves a team of experts and

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stakeholders from a number of different disciplines, who need to develop a common knowledge base related to the discussed problem. Secondly, the lifecycle of the model and the simulation can be rather short (i.e. one-time system analysis during planning) and the allocated resources tightly limited. These peculiarities cause an intrinsic motivation to structure the system complexity and the team heterogeneity efficiently and reuse as many previously acquired expert knowledge, tools and models as possible.

In this article we seek to provide a framework, which aims to structure the process towards developing a conceptual and subsequently executable model of a system's relevant energy related aspects. In modelling and simulation (M&S) literature a number of general frameworks providing guidelines for processes and model design have been proposed (e.g. [3]–[6]). Also more specific approaches, e.g. for embedding modelling into engineering processes [7] or for discrete event simulation [8], [9], have been published. However, no literature for conceptual models specifically targeted at continuous systems can be found. Our research tries to fill this gap. The proposed framework is based upon existing frameworks but is specifically tailored to address the aforementioned challenges of energy system modelling. Chapter 2 will describe the framework and Chapter 3 will demonstrate how it was applied in the context of a research project about energy efficient production. The conclusive chapter will discuss the limitations of the chosen approach and indicate some further research demands.

FRAMEWORK FOR MODELING ENERGY SYSTEMS

The goal of the framework is to outline an efficient process to an executable model. It contains a process description that leads first to a conceptual model that describes the given problem situation, then derives a design model for the simulation and subsequently the executable models. The process specifically addresses the reuse of existing models and tools. Therefore, an approach which substantiates abstract models step by step, is applied.

Project Initialization, Problem Formulation and Requirement Definition

As mentioned in the introduction, energy system modelling usually involves a team of experts with different knowledge and skills as well as stakeholders with certain expectations. Simulation team members usually can be distinguished into two main groups: domain experts and M&S experts. We suggest, similarly to [10], to start the process with a team assessment. Initial assessment of the roles and the existing skills within the team can significantly facilitate the further collaboration and prevent misunderstandings. Furthermore, M&S skills of the team significantly influence the conceptual model, as will be explained later on.

After the roles in the team are allocated and the stakeholders identified, the actual modeling process can be started. The first phase deals with the specification of the problem and the definition of the system. According to literature this phase usually contains tasks such as: system description, boundary definition, problem formulation, requirement specification and objective determination. Some sources put great emphasis on the importance of an accurate problem formulation, as it severely affects the credibility of the results [3], [11]. Our experience with interdisciplinary research collaborations has shown that an accurate problem formulation is very helpful and that at least three elements should be included: system description, objective formulation and collection of information and data about the system.

In multidisciplinary teams these three tasks often need to be executed in a parallel manner, because team members have diverging points of views on the nature of the problem due to different level of system knowledge or problem focus. Therefore, it is often necessary to pass through one or more iterations, in which every domain or party first formulates its specific view of the problem and objectives and then after exchange and gathering of additional information and balancing the level of information and expectations, the problem formulations are revised and subsequently should reflect a more uniform picture of the problem. This can be a very tedious, repetitive process, but it decreases the risk of solving the wrong problem. In addition to the different points of view and knowledge backgrounds, domain specific terminology further complicates communication. In order to establish an agreement upon terminology, it has proven helpful to compile a project glossary in which project specific vocabulary or project specific use of common vocabulary is defined.

The next step is a more detailed requirement definition which is based on intended uses and use cases, similar to a software development process. Intended uses could be for instance: analysis, design identification, comparison, evaluation, prediction, selection, optimization etc. Use cases represent exemplary work scenarios the simulation model is required to perform in order to produce valuable results. Finally the requirements on the model can be formulated. It can be beneficial to not only define the intended uses, but also specify the not-intended uses. This is especially advised if there is a large number of potential (personally unknown) stakeholders and it is unclear whether their expectations are in accordance with the formulated objectives. Figure 1 summarizes the process of project initialization, problem formulation and requirement definition.

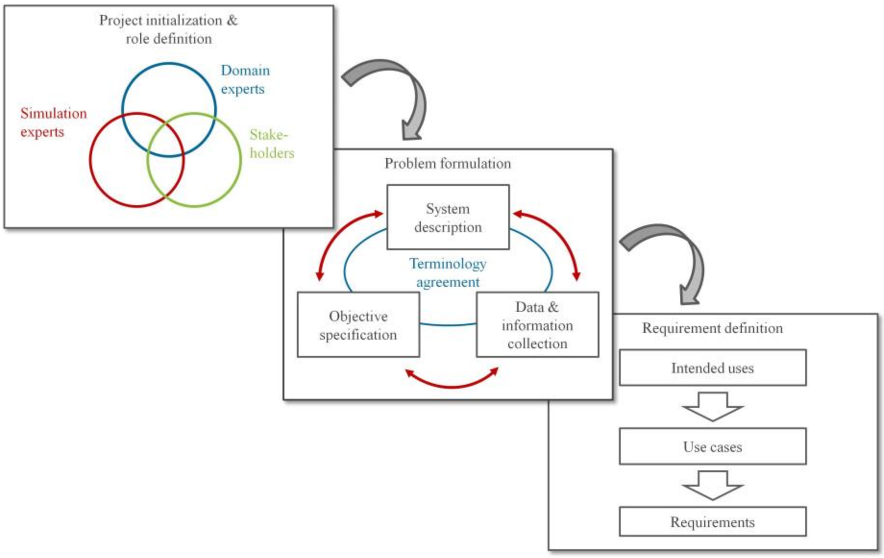

Figure 1. Project initialization, problem formulation and requirement definition process

Conceptual Model and Simulation Design Model

After concluding the problem and requirement formulation we suggest to proceed to the conceptual modelling phase. Ref. [4] defines a conceptual model as a non-software specific description of the computer simulation model. Most approaches to conceptual modelling found in literature, such as [3], [4], suggest to apply decomposition techniques in order to handle system complexity. Decomposition represents a top-down approach, in which an abstract representation of the system under study is formulated ensuring that the elements chosen to represent the system are meaningful from a system or domain point of view and the representation of their behaviour and interaction is valid. In energy system modelling a common decomposition technique is forming balances. The obtained conceptual model is an abstract representation of the system which is then further translated into the simulation design. To proceed strictly according to this top-down approach implies that the conceptual model dictates the simulation design. Ref. [3] argues that this enables the reuse of the more abstract concepts in modelling but inhibits the reuse of less abstract parts e.g. executable models, which is an important concern imposed by resource restrictions. In order to overcome this contradiction, Ref. [12] suggests a conceptual modelling approach based on decomposition as well as composition techniques. Similarly, we have found it profitable to integrate a bottom-up perspective of view into the process by taking implementation considerations into account.

The bottom-up approach integrates model and tool aspects and expert representation aspects into the chosen decomposition. It has considerable impact on the model design and the modelling effort. If the reuse of certain model elements (executable models or specific simulation tools) is intended, syntactic composability between these building blocks of the simulation must be assured. This must be reflected in the chosen decomposition, which has to take into account that i) conceptual model element boundaries do not interfere with model interfaces, ii) the elements of the decomposition can be modelled and simulated in a single simulation tool and iii) the necessary interfaces for exchange with other elements can be provided. A further aspect to consider are the roles of domain and simulation experts in the modelling process. It has been proven to be quite advantageous from an organizational point of view to have clear responsibilities for the simulation elements.

When decomposing a system with the objective to make a statement about its energetic behaviour, the model will generally depict the part of the physical system that is related to the energy flows within the system. So, the conceptual model will most likely include all components within the system boundary that use, convert, supply, distribute energy or influence the energy flows by their intrinsic behaviour (user actions, controllers…). All these relevant parts of the system must be considered and decomposed into manageable units, which we call components. Each component represents a coherent part of the whole system with a defined boundary towards the other parts but is not necessarily of a physical nature. Apart from buildings or equipment, abstract aspects like operational strategies and their economic environment may need to be described as well. If desired, classifications of components can be introduced, such as physical components, control components, processing components, input components etc. Taking the bottom-up approach into account when defining the components, it should also be assured that, for each component, at least one single specialized simulation tool exists that would cover the component in its entirety and a responsibility for the entire component can be assigned to a team member. This, however, does not imply that there can only be as many components as tools or experts are involved. Out of transparency a higher granularity of decomposition can make sense at this state.

According to modelling theory, such as given by Ref. [13], model objects (components) must be described by relational and indicative attributes. Relational attributes relate the components to each other, i.e. describe their hierarchy and interfaces. Indicative attributes provide knowledge about the components in the form of permanent parameters (e.g. storage capacity) or transitional variables (e.g. current state of charge). The components are described by rules (e.g. energy balance) which determine their behaviour. However, the description of the rules of a component is for "internal" use only. To the outside the component is exclusively represented by its interfaces i.e. to the rest of the model it is a black box. This allows combining different modelling approaches, abstraction levels and solvers or tools, and gives simulation experts the liberty to design the model according to preference. Relational attributes are typically realized by connections of variable interfaces, which depict the component's influence upon each other due to their current state. Besides the obvious interfaces exchanging transient variables, data, information and parameters must have sources as well, such as information models, which can be documented as well. Figure 2 illustrates the described top-down/bottom-up approach to conceptual modeling of energy systems and a possible graphical representation of the model.

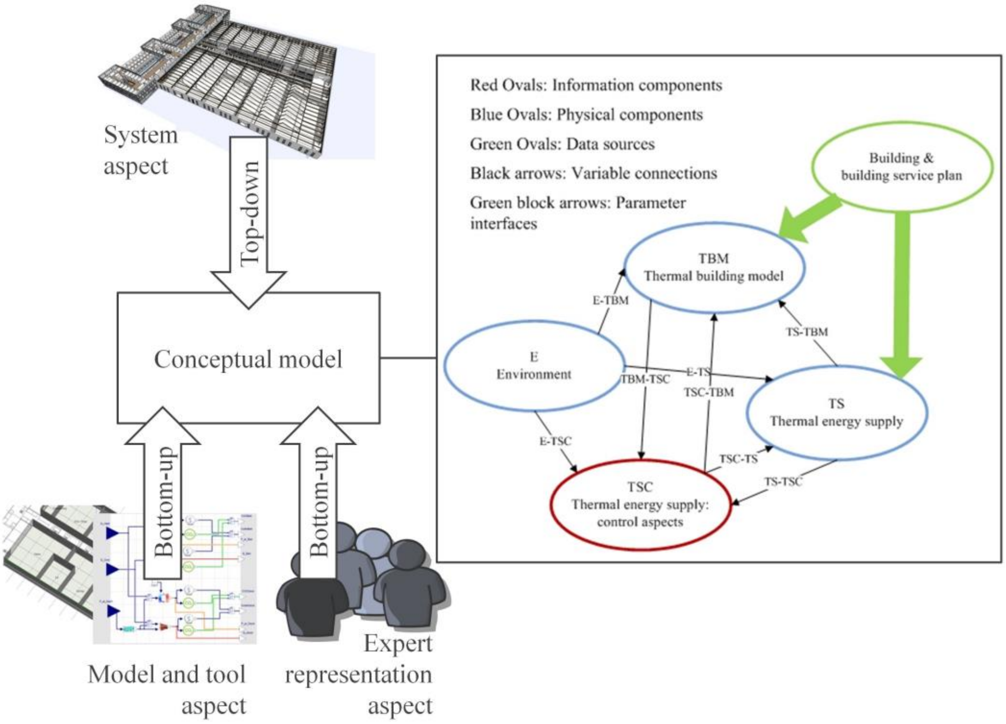

Figure 2. Top-down/bottom-up aspect integration approach to conceptual modelling

From the conceptual model, a simulation design model can be derived which represents the transition to the implementation. The simulation design model describes the allocation of the components of the conceptual model to certain simulation engines or hardware components. It reduces the conceptual model components and interfaces to the submodels and interfaces that must be implemented. If necessary, it should address temporal aspects of the simulation execution (time steps, sequencing, and simulation time) as well.

Documentation, Validation and Implementation

In order to document the conceptual and simulation model a combination of graphical representation and textual description is recommended. According to [14] graphical representations provide a spatial overview and overall description of the problem and offer an excellent summary but are usually incomplete, hiding the majority of the information. The documentation should include a general description of the whole model, which contains the specifications of the problem formulation and requirement definition, and component specific parts, which should be structured equally e.g. by using templates such as proposed by [15].

In terms of model quality assurance and credibility of results, the processes leading to the conceptual model should be accompanied by according measures. Since in the first stages of the development, results are often not very concrete, formal validation techniques are most often not applicable. However, a number of informal validation techniques can be applied to ensure the logical and structural validity, such as desk checking, face validation, walkthroughs and inspections ([5], [16], [17]). These techniques compare the model to the mental knowledge about the system, which is the only available source of information at this stage. Although using knowledge provided by domain experts as reference information for validation is sometimes considered questionable, many researchers have accepted this approach as a practicable alternative if other data is lacking [5], [18]. Another important aspect to take into account when designing the validation process is the role allocation. Simulation team members, stakeholders and also third parties can be involved in the validation process. Ref. [5] suggests that if the simulation team is small, users or third parties should decide the validity of the model. However, if the team is of sufficient size "cross-validating" between domains can be an option.

Considering implementation, a variety of options from development of targeted tools to connecting several simulation environments to a so called cooperative simulation or co-simulation exists. Connecting tools enables the reuse of existing models and familiar simulation tools.

APPLICATION OF THE FRAMEWORK TO ENERGY USE IN INDUSTRY

In this research we focused on holistic approaches towards energy optimization in manufacturing companies. The goal, specified in the grant proposal, was to uncover energy efficiency optimization potentials through energy-flow analysis. A complete system simulation integrating models of the production's micro-structures (processes and machines), production systems, building and infrastructure was to be made available as a planning tool for manufacturing companies.

Project Initialization, Problem Formulation and Requirement Definition

The consortium of the project included a number of manufacturing companies, an interdisciplinary team of researchers from the disciplines of architecture, informatics, economies, mathematics, civil- and mechanical engineering. Within our simulation team the roles of domain and simulation experts often coincided, because the domain experts were considered simulation experts in their particular field and therefore entered the project with a strong preference considering reuse of their respective models and simulation tools.

The proposal of the project stated that the simulations would enable industrial companies to systematically analyze and optimize the eco-efficiency of their production processes and equipment. This defined the system under study (a production company under influence of economic and ecological boundary conditions) but left much room for a discussion concerning the objectives. Parallel with the discussion process about the objectives, the collection of data and information started. In a series of interviews with the manufacturing companies we identified their preconditions, needs and limitations. We found that for the majority of companies the motivation to invest into energy preservation was driven by competitiveness. It also turned out that the boundaries for applying optimization strategies were tightly set. Naturally, the fear of affecting product quality in a negative way or loosing production flexibility turned out to play an important role.

The question what the actual objectives of the simulation could be, was still very unclear during the discussion and information collection process. Finally, we identified the target as a simulation that enables the comparison of scenarios of system configuration concerning economic criteria (operational result) and ecological criteria (climate relevant emissions) based on concrete planning of an object. To this point the discussion process was quite chaotic and progressed relatively slowly, with frequent setbacks. For the project which had a total duration of tree years the target specification documentation is dated at almost a year and a month after the project start.

After this rather frustrating project beginning, we actively started the development of a significant conceptual model by defining intended use, use case and requirements. The intended use was specified as a supporting tool in the planning process of newly built production plants or major retrofits, which analyses alternative scenarios. The typical use case for the model and simulation was identified in an integrated planning process, where a new facility is planned and built. Therefore the model and simulation were required to support expert communication, depict all system parts relevant to energetic and economic performance and produce significant KPIs for decision making.

Conceptual Model and Simulation Design Model

By requirement the conceptual model should be designed as a universally applicable model of a production facility and therefore, document all potentially existent and relevant parts of a production facility. We identified 16 components, which can be presumed to exist in every production facility in one way or another and contribute to the energy balance and economic success. A graphical overview of all top-level components as well as the architectural plan, which provides the information source, is shown in Figure 3. A more detailed description of the conceptual model has previously been published [19].

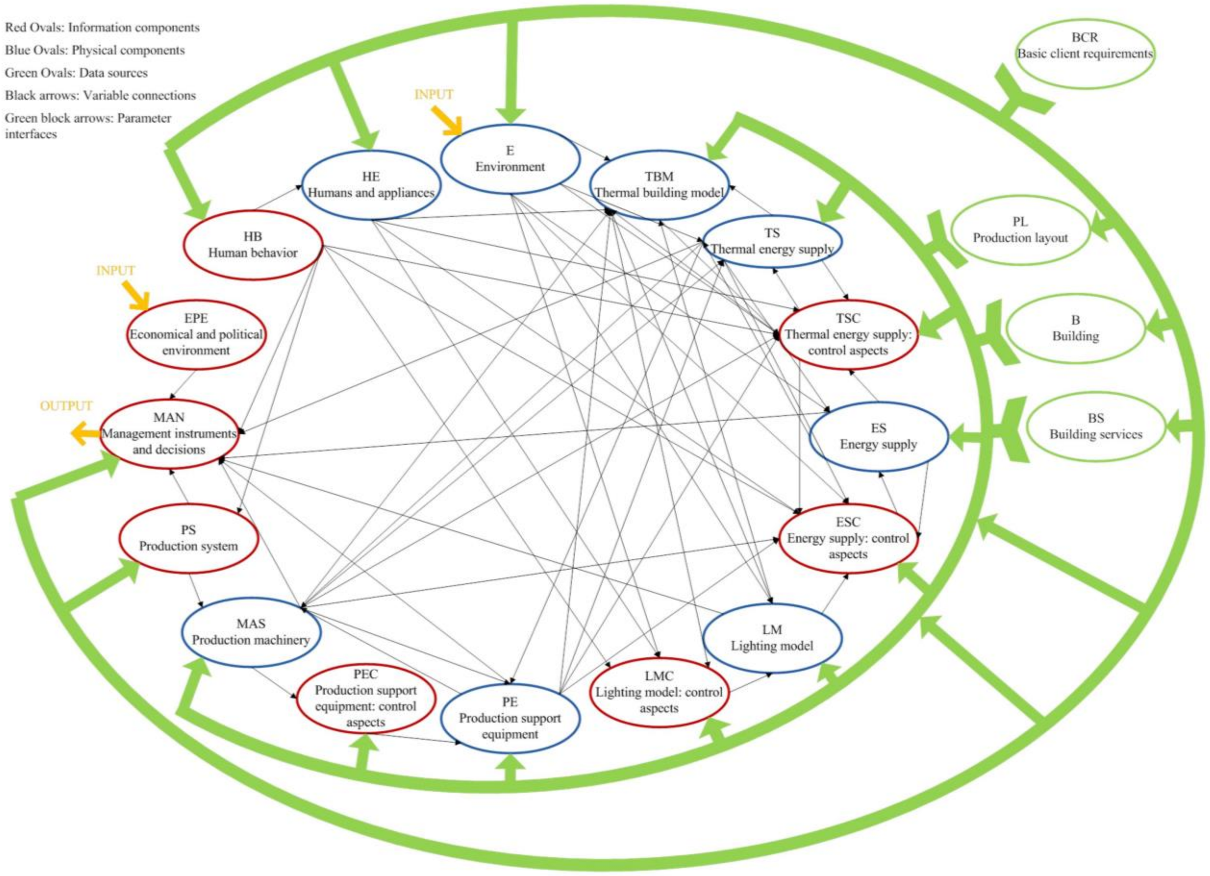

Figure 3. Conceptual model for a production facility

The conceptual model was already designed with the aspect in mind that every component could be executed by one single simulation environment. Therefore, the development of the simulation design model simply consisted of uniting conceptual model components to simulation components and reducing the conceptual model interfaces to the interfaces that must be implemented. In the end five simulation components with 11 variable interfaces were implemented in a simulation framework. The model implemented in the framework is also universally applicable to different manufacturing companies, however, it is adapted to the unique tool preferences of our specific team. So, different levels of reusability were achieved.

Documentation, Validation and Implementation

Documentation of the conceptual model includes apart from the graphical representation roughly 120 pages of documentation. In order to ensure validity and credibility of the model, we applied several validation and verification techniques on different levels of the model (top-level, sub-model-level, component-level) and for the different development stages (conceptual and implementation), using "cross-validation" between expert teams.

Since several different simulation environments were preferred by the experts, it was decided to implement the simulation as a co-simulation. The building simulation environment EnergyPlus was coupled with the two multi-domain simulation environments Matlab and Dymola. The co-simulation was implemented using the co-simulation framework Building Controls Virtual Test Bed (BCVTB) [20]. The simulation was of Jacobi-Type with a time interval between variable exchanges of 15 minutes and a simulation time of one year.

Finally, a case study was carried out as a proof of concept for the co-simulation tool and represents a specific instance of manufacturing companies that can be modeled and simulated with the developed models and framework. A consortium member planning to move the production to a new location provided the ideal application. Three different energy system scenarios were compared in terms of their interaction with the new building and the production (see Table 1). Figure 4 shows the accumulated results. In scenario 1 the energy demand is significantly higher than in the existing plant, whereas in scenario 2 and 3 considerable savings could be achieved. The high demand in scenario 1 results from oversized absorption chillers. These are dimensioned to cover the expected peak loads, but are incapable of operating in part load. This leads to frequent overproduction of cold and an increased gas demand. A more detailed description of the case study can be found in [21].

Table 1. Overview of energy sources in simulation scenarios (taken from [21])

	Scenario 1	Scenario 2	Scenario 3
Heat supply	CHP (natural gas), district heat	District heat	Groundwater well & heat pump
Heat recovery from exhaust air	Heat pump	Heat exchanger	Heat pump
Warm water supply	Solar thermal & electric	Solar thermal & electric	Solar thermal & electric
Cold supply	Absorption chiller	Compression chiller	Groundwater well
Electricity supply	PV, CHP & grid	PV, grid	PV, grid

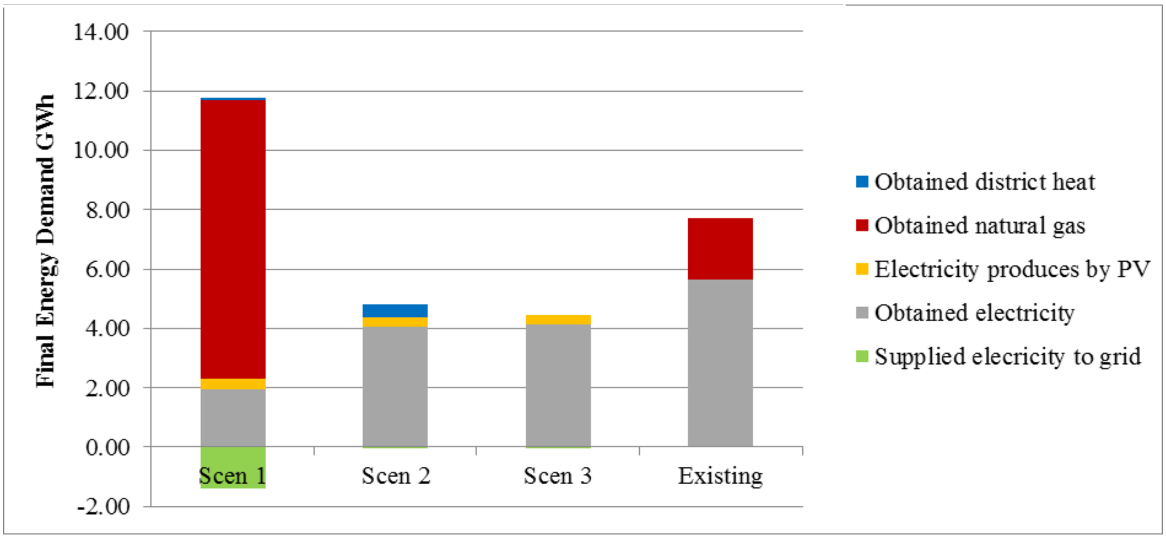

Figure 4. Annual final energy demand of simulated scenarios and existing plant (taken from [21])

DISCUSSION AND CONCLUSION

This paper presents a framework for energy system modelling. The framework includes a description of the process, leading from a research question or problem field to a conceptual model. It furthermore suggests a conceptual model representation specifically targeted at energy system models. The framework was designed aiming at modelling processes in interdisciplinary collaborations, in which the reuse of existing domain specific modelling, simulation and tool knowledge as well as executable models is of interest. In order to illustrate the proposed approach we discussed an application example, which dealt with the development of a software planning tool for optimization of the energy performance of manufacturing companies. This application case features a classic modelling and simulation application (analysis) but a rather challenging modelling task, due to the requirement of universal applicability to all kinds of manufacturing companies.

The discussed project lead to a follow-up project concerning energy efficient production, in which the presented modelling approach showed its versatility as well as limitations. In this project the goal is to develop a simulation based software tool chain for predicting and optimizing the energy efficiency of production plants. Therefore, the simulation implemented in the tool chain has a considerably longer life span and needs to be very modular in order to be able to assemble new instances with limited effort. In this case the reusability of existing models is less of an interest than the internal reusability of the newly developed models. Therefore, for this project an alternate approach, with very rigid decomposition into formalized modules is chosen. This eliminates the possibility for model or tool reuse almost entirely and even calls for programming a tailored simulation environment. This effort only pays off because of the long life span and the gained internal reusability.

So, ultimately there is always a trade-off between reusability of existing elements and internal reusability, which must be reflected in the chosen modelling approach. The stricter the top-down decomposition is applied, the more internal reuse can be gained but also the more effort is caused by the modelling process and implementation. On the other hand the more bottom-up aspects are integrated into the modelling, the more reusability of existing models is gained and initial modelling effort avoided. This conclusion is probably not only true for energy related models, but may apply to other domains as well and could be investigated further.

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