Energy efficient production – a holistic modeling approach

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Abstract—**This paper presents an abstract model for production facilities which is supposed to serve as a universally applicable base for the simulation of energy flows in a manufacturing company. Its goal is to enable integrated analysis and simulation, considering production processes, machinery, systems, and buildings as a whole in order to find the best leverage to optimize overall energy consumption. The requirements on the model and its general structure are explained as well as how its parts relate to specific aspects of a production facility. Furthermore, considerations for implementing a complex simulation on its basis are discussed.**

Keywords—energy efficiency in production, energy system simulation, renewable energy systems

I. Introduction

The energy demand of the production industry accounts for a major part to societies' total energy consumption. In industrialized countries, it accounts for around 40% of the total consumed energy [1]. The potential of reduction is estimated between 30% and 65% depending on the industry sector, according to [2]. However, [3] states that only a fraction of manufacturing companies actively enforce the implementation of energy-efficient technologies in their production plants, although numerous studies outlining the path to a more efficient production process have been conducted, such as [1], [4] and [5].

In order to reduce a producing company's energy consumption the efficiency of the production processes themselves can be improved. Several studies on this approach have been carried out and show significant potential, such as [6], [7] and [8]. Another important sphere of activity identified by [4] is the efficient operation of the infrastructural facilities of production plants. Reference [9] shows that this approach leads to promising results as well. This suggests that combining the mentioned approaches could show even better results.

In order to estimate the efficiency increase and the according financial benefits that could be gained by the implementation of energy-efficient technologies, a global simulation of the production facility seems necessary. The present paper exhibits a generalized model of a production plant that is designed to serve as a base for an integrated simulation of the whole system.

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II. Objectives of the Model

The aim of this work was to design a universally applicable model of a production facility, focused on energy flows. The model should provide a basis for simulations of the entire facility, allowing the involvement of multiple simulation tools. By requirement, it should however be independent of any simulation tools that eventually would be used to carry out the simulation. Therefore, not all the aspects pictured in the model have to be represented in the simulation as well; their selection can be adapted to individual needs. The model should also clearly, yet concisely document all relevant aspects within the whole system and thus be able to serve as a communication instrument for experts of different disciplines collaborating to implement the integrated simulation.

Since the focal points of the model are the energy flows within the production plant, it is not intended to be used for any other optimization task apart from increasing energy efficiency and implementing renewables. Furthermore, it is not intended to serve as the basis for a self optimizing design simulation. It is rather designed to be the foundation for simulation of varying pre-selected scenarios to be manually compared with each other in terms of specified output key data. The model design takes the previous findings of [10] and [11] into account.

III. Structure of the Model

In order to obtain a model feasible as a basis for simulation with a variety of simulation tools, a structure based on a generic notion of components, parameters and variables was chosen.

The system is divided into components. Each component represents a coherent part of the whole system with a defined boundary towards the other parts and is, in some form or other, present in every production facility. The components are not necessarily of a physical nature. Apart from buildings and equipment, abstract aspects like operational strategies and their economic environment need to be described as well. When defining the components it was also taken into consideration that, for each component, at least one single specialized simulation tool should exist that would cover the component in its entirety.

The components are described by well-defined *rules* which determine their behavior. These rules are preferably defined in the form of mathematical equations (e.g., the Fourier equation for heat transfer in a wall). Distinct characteristics of the components (e.g., the size of the building) are described by *parameters*. The values assigned to these parameters characterize a specific instance of the model (a specific production facility). The current state of the components is specified by *variables* assigned to them. The variables are calculated from the rules and parameters and cannot be directly influenced by the simulation user (e.g. heat transferred through a wall).

Last but not least, the components are mutually connected and influence each other. The quantity or information characterizing this influence is an input variable for the dependent component and an output variable for the influencing one. These input and output variables are only modeled if the influence is of a regular and continuous nature. Substantial but rare changes of the system (e.g., reconstruction due to management decisions) are described by a new set of parameters.

The simulation user can only modify the parameters. Only after one run of the simulation is completed, a new set of parameters can be chosen based on the insights gained from the simulation and a new run can be performed. Hence, the goal of the simulation is not to automatically optimize the building and plant design, but to provide a better basis for design decisions.

Because – within a chosen set of parameters – the selected parameters have to be consistent, previous planning of the system is required. This results in dependencies between parameters of different components and the plan. These dependencies are represented as *parameter references* to *plan elements*. The plan elements themselves are not part of the dynamic simulation, but define the parameterization and form a coherent point of reference in order to ensure consistency between the parameters.

By only specifying the boundaries of the components and the interfaces of interaction, this black-box-approach provides a maximum of flexibility to adjust the various components to individual needs in terms of complexity and implementation of the simulation. A graphical overview is shown in Fig. 1.

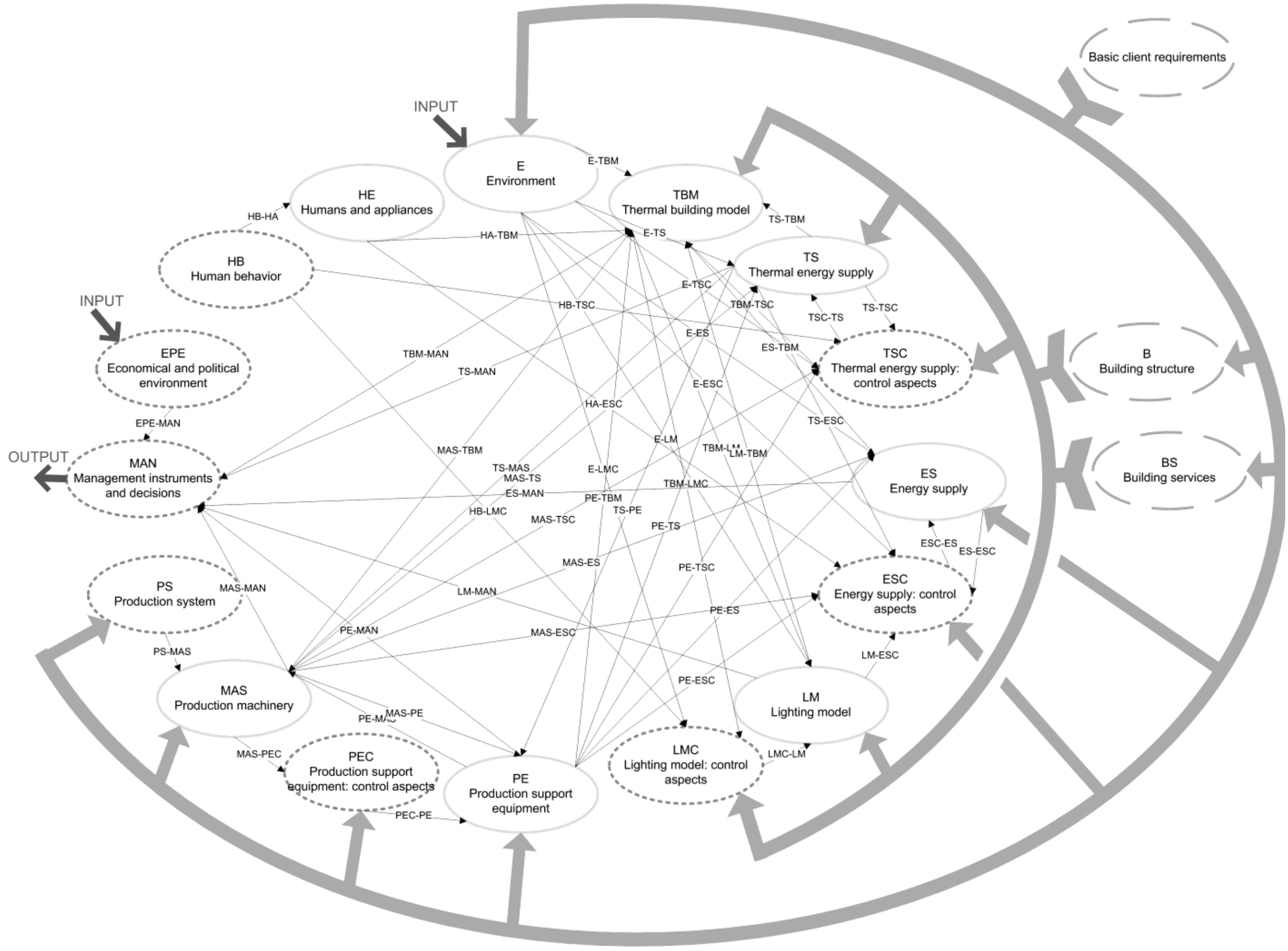

Figure 1. Generic production facility model ("Spider's Web")

IV. Components and Elements of the Model

As discussed above, components are coherent parts of the whole system with a defined boundary towards the other parts. Components do not alter their general and specific characteristics (determined by the rules and parameters) during one run of the simulation. They only change their behavior as far as it depends on the state of variables (e.g., a device is switched on and off).

To express that components not only describe physical parts of the system but also abstract parts, we distinguish between:

- Physical components (PC) (e.g., building structure, machinery, humans, environment) and
- Information components (IC) (e.g., strategies, algorithms, behavioral patterns, political environment).

16 components, which can be presumed to exist in every production facility in one way or another, have been identified. In Fig. 1, physical components are represented by ovals with solid outlines; information components are pictured as ovals with dotted outlines. Subsequently, a short overview of the components of the model is given:

A. Environment (PC)

This component depicts environmental influences, especially weather conditions at the geographic position of the factory over a year. This is an input component, which means it cannot be influenced by the system and therefore has no input variables.

B. Thermal building model (PC)

The thermal building model describes the thermal situation in the building. The component contains the relevant parts of the building structure sectioned into thermal zones, but no building services.

C. Thermal energy supply (PC)

The component "Thermal energy supply" contains all equipment used to supply thermal energy (production, storage, distribution). This encompasses heating, cooling and ventilation of the building's zones, the supply with service water and if necessary process heat as well as cooling of machines and large computer systems.

D. Thermal energy supply: control aspects (IC)

This component describes the control strategies that are applied to all the equipment related to the thermal energy supply, no matter if they are implemented by automation systems or manually.

E. Energy supply (PC)

"Energy supply" depicts the supply of all kinds of machines or equipment with all kinds of energy that is not thermal. This includes external supply, internal production, storage and distribution.

F. Energy supply: control aspects (IC)

The strategies represented by this component coordinate the cooperation of the equipment contained in the component "Energy supply" in order to cover the demand of non-thermal energy of all other components.

G. Lighting model (PC)

The component contains all relevant parts of the building structure as well as those parts of the building services that affect the lighting situation inside the building. Apart from artificial lighting, this also includes shading and daylight redirecting devices.

H. Lighting model: control aspects (IC)

This component describes the strategies applied to provide illumination and glare coverage by using the devices contained in the "Lighting model" component.

I. Production support equipment (PC)

This component contains all the equipment which is needed to support the production machinery and the production process, but has no value-adding function itself. This includes for instance auxiliary supply systems (pressurized air, lubricants) or logistic devices.

J. Production support equipment: control aspects (IC)

This component describes operation strategies for the component "Production support equipment".

K. Production machinery (PC)

Production machinery are all machines, machine tools and equipment which directly contribute to the value-adding production process.

L. Production system (IC)

The production system describes the production planning and scheduling as well as all related processes. The information contained in this component allows estimating the utilization of machines and equipment for any certain period of time.

M. Management instruments and decisions (IC)

This component connects the technical and financial key data provided by the other components in order to assess the system layout in respect of economical criteria (operating results) and ecological criteria (climate relevant emissions). It is an output component, which processes the simulation results and delivers them in the form of management ratios which are significant to a decision maker. The component has no output variables back into the system and thus cannot influence the behavior of the simulated system.

N. Economical and political environment (IC)

Here, the determining factors of the economical and political environment are described which are essential for the "Management instruments and decisions" component to process the simulation results. This is an input component that cannot be influenced by the system.

O. Human behavior (IC)

Human behavior depicts when people are present, how many and where they are in the building, what they do and which appliances (not production machinery) they operate.

P. Humans and appliances (PC)

This part of the system describes the direct, measurable influence by the presence and activity of humans in the building and the appliances they operate in their sole discretion (e.g., computer, coffee maker).

Components can be divided into sub-components to describe more comprehensive details. If necessary, sub-components can be nested.

In addition to the 16 components that comprise the dynamic simulation, the model contains three plan elements supplying the components with coherent parameter values. In Fig. 1, they are represented by ovals with dashed outlines. First, there are the basic requirements of the client such as the general purpose of the facility or its geographic position. Based on these requirements, the plan elements "Building structure" and "Building services" deliver a more detailed parameter specification. This overall "plan" is split into "elements" considering the complexity of the planning process and the fact that these planning tasks are usually carried out by different experts.

V. Parameters and Variables of the Model

Components feature parameters in order to be able to describe the specific characteristics of an instance. The parameters' values are not derived from the rules describing the component or the variables. They can be chosen by the simulation user independently, but of course can be restricted by the choice of other parameters. Parameters can be derived from the plan elements by parameter references, shown in Fig. 1 as block arrows.

As well as with components, the nature of parameters varies. They can consist of a single physical quantity or can be of a complex composition, such as a control strategy. We distinguish between the following kinds of parameters:

- Physical parameters (e.g., the size of a solar collector)
- Information parameters (e.g., a control algorithm)
- Decision parameters (e.g., the existence of a solar collector)

Decision parameters enable the user to take into account that certain elements of a component do not necessarily exist in every instance of the model. Decision parameters usually take the values true or false.

Variables can represent physical quantities as well as abstract information; in either case, they describe the momentary state of a component. The changing of their values over the time characterizes the dynamic change in the system. The variable values result from the values of the parameters, other internal variables and input variables by means of the rules describing the component. During the simulation, they are recalculated and change continuously. Variables cannot be influenced by the user directly. As well as with the components and the parameters, we specify two kinds of variables:

- Physical variables (e.g., temperatures, energies)
- Information variables (e.g., measured or set values)

Since the model is mainly designed for simulation of energy flows, special attention was paid to variables that characterize energy flows. Energy flows may change in response to strategies implemented by information components (e.g., hot water flow through a radiator following a control action, or waste heat varying with machine load determined by the production schedule). Information variables provide the necessary means for modeling information flows whose actual physical representation is not relevant within the model context.

The variable links between the components are shown in Fig. 1 as thin black arrows. Every link can contain one or more variables. We chose not to implement all the theoretically possible links between components, but to select the most relevant ones instead in order to keep the model lean.

VI. Implementation Considerations

The model described in the previous sections is an essential tool in guiding the simulation setup for a specific production facility. By providing a common vocabulary (i.e., components, parameters, and variables), it facilitates – and serves to disambiguate – communication between domain experts, who need to work together to decide which aspects will be chosen for dynamic simulation. This decision also includes selecting the granularity that these behavioral aspects are to be simulated at.

While this decision needs to be made on a by-project basis (or, at least, for a particular class of production facilities) and cannot be fully determined in advance, possible alternatives for implementing the integrated simulation were studied to determine its overall feasibility. Currently, no simulation environment is available that provides ready-made models that would make it possible to run the envisioned integrated simulation "out of the box." It is expected that significant modeling efforts will be necessary.

Given its overall complexity, it is clearly necessary to break down the simulated system into modules. These models should be as self-contained as possible to allow distributed modeling by domain experts. However, these models, each covering a part of the whole system, could "live" within a single simulation environment – or multiple simulation environments could be connected.

Choosing a single environment means making a considerable investment in a particular technology. Domain experts will need to devote considerable efforts and may need additional consulting for distilling their knowledge into models. Together with these models, the knowledge and efforts then remain locked to the chosen tool. Thus, it is preferable to use an open, tool-independent modeling language such as Modelica [14]. Modelica is a declarative language supporting acausal modeling, allowing expressing behavior in equations rather than algorithms. This makes it well suited for modeling physical systems. Expert knowledge is not only documented sustainably and in a well-maintainable format, but also applied efficiently: It is estimated that model development is five to ten times faster than in a procedural environment [15]. Various commercial and non-commercial Modelica-based simulation environments are available.

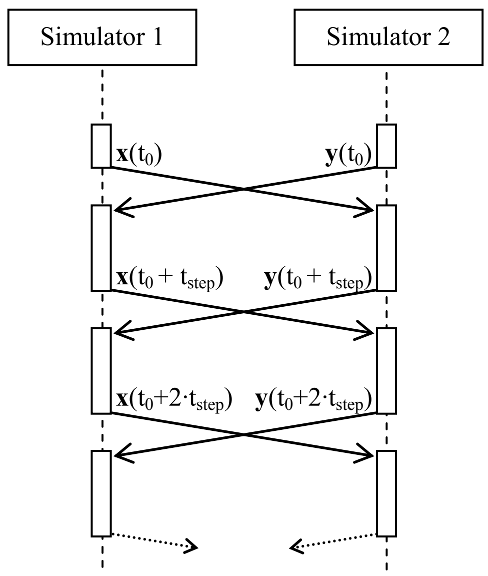

Figure 2. Co-simulation with fixed time step

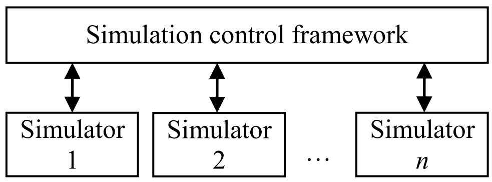

Figure 3. Coordinating multiple simulators

Still, the benefits provided by established domain-specific tools should not be underestimated. While commercial and non-commercial Modelica model libraries covering building structure, building services and human comfort are available, specialized building energy analysis tools – being focused on this task – are still more efficient in terms of usability and computation. The same holds for tools used in other application domains. Also, domain experts already tend to have significant experience using these tools. Moreover, a single modeling language may not cover all needs (e.g., other languages than Modelica may be better suited for discrete-time model components such as digital controllers).

Therefore, being able to use the best (or preferred) tool for each domain would be a benefit. This is straightforward if there are no dependencies between these domains (or none are to be modeled). For instance, heating and cooling loads are usually obtained by simulating a building under the assumption that the heating, ventilation and air conditioning (HVAC) system will be able to handle these loads fully and instantly. A separate simulation may then be run on the HVAC system design to determine if this is actually the case. As soon as feedback between system parts covered by different simulators is to be modeled, however, simulators must be coupled more tightly.

In the simplest case, co-simulation is performed using a fixed synchronization time step as shown in Fig. 2. Starting from a consistent common state, Simulator 1 computes the new value of state vector x after this time step (e.g., building zone temperatures given the current loads and the state of the heating and cooling surfaces), while Simulator 2 computes the new value of state vector y (e.g., hot and cold water flow temperatures following automatic control actions in response to the measured zone temperatures). The updated values are exchanged and the cycle starts over. There is no iteration between the simulators for a single time step. If necessary, simulators can internally use time steps for computation that are finer than the synchronization time step.

As soon as more than two simulation tools are involved, having them communicate via a common framework (as shown in Fig. 3) with clearly defined interfaces considerably increases manageability. It also allows a smoother transition between sub-model implementations, including migration towards a homogeneous model.

Among other benefits, co-simulation allows re-use of existing models and expert knowledge. It also allows easy parallelization. On the other hand, there are undeniable challenges: The required integration effort may be considerable, as interfaces between tools have to be designed and implemented. Also, existing tools may not be designed to support co-simulation at all. Moreover, there are nontrivial implications in coupling different fundamental modeling approaches (most basically, continuous time and discrete events). Fortunately, significant efforts have been made in the scientific community that can be built upon.Among these, the Ptolemy project specifically deals with the combination of different models of computation [16]. Within the project, an open-source software framework was developed where software components execute concurrently and communicate via messages. These components ("actors") can be combined hierarchically; each of them may internally follow different modeling semantics (such as a dataflow model, a continuous-time model, a process network, or a state machine).

Especially relevant to the task of integrated simulation of a production facility, the Building Controls Virtual Test Bed (BCVTB) [17] connects several well-established simulation tools, enabling co-simulation with a fixed time step as described above. It builds upon the Ptolemy framework. Within the BCVTB project, interfaces were implemented that allow EnergyPlus (a popular building energy analysis tool), Dymola (a popular Modelica environment) and Matlab/Simulink to be used as Ptolemy actors. Integration with Radiance (a lighting simulation tool) was demonstrated as well. Before the BCVTB effort, EnergyPlus had no co-simulation support; the new feature has since also been used in a different project outside the BCVTB context [18] for peer-to-peer coupling with Matlab/Simulink.

VII. Conclusion and Outlook

As mentioned in the introduction, previous research has shown different viable approaches to optimize production facilities in terms of energy efficiency. However, the optimization of production processes on one hand and the optimization of related infrastructure (such as buildings or machinery) on the other hand are currently only isolated fields of action. To maximize their potential, these efforts need to be incorporated into a holistic approach towards sustainable production. In order to determine the influences of different optimization strategies on the production itself and on each other, extensive analysis must be carried out.

With our work, we hope to have contributed a universally applicable model on which such analysis, including an integrated simulation, could be based. We chose to divide the system into components of which we only specified the general structure and the interfaces to provide maximal flexibility of use. During the course of our project, the model has already served well as a communication tool between domain experts when discussing relationships and dependencies between parts of the overall system.

In the next step we want to instantiate the model for a specific production facility. The simulation will likely be run using EnergyPlus and Dymola, coordinated by the BCVTB. By applying the model and simulation to a real-world case, we expect better insight into the key parameters governing energy efficiency. We also hope to gain new insights on the influences energy efficiency technologies have on each other and on the operating results of a company. We especially expect the connection between energy savings and financial benefits to be an interesting result, since we assume it to have strong impact on decision making in companies.

To enforce the implementation of energy efficiency increasing technologies, economic incentives and appropriate steering tools will be required. While extensive investigations have been made on key values and evaluation systems concerning parts of the system, such as [17] or [18], there is still need for further research on the link between the ecological and the economic columns of sustainability.

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References

[1] F. Alhourani and U. Saxena, “Factors affecting the implementation rates of energy and productivity recommendations in small and medium sized companies,” *J. of Manufacturing Systems,* vol. 28, pp. 41–45, 2009.

[2] E. Bonneville and A. Rialhe, “Good practice for energy efficiency in industry,” http://www.leonardo-energy.org/webfm_send/2653, May 2006 (last accessed July 30, 2011).

[3] M. Schröter et al., “Energy efficiency in production, wish or reality? (Energieeffizienz in der Produktion, Wunsch oder Wirklichkeit?),“ Frankfurt, Fraunhofer-Institut für System- und Innovationsforschung, 2009.

[4] Fraunhofer Gesellschaft, “Energy efficiency in production. Future action fields,“ http://www.iwu.fraunhofer.de/english/publica/brochures/effpro_en.pdf (last accessed July 30, 2011).

[5] E. Worrell et al., “Technology transfer of energy efficient technologies in industry: a review of trends and policy issues,” *Energy Policy,* vol. 29, pp. 29–43, 2001.

[6] J. W. Fromme, “Energy conservation in the Russian manufacturing industry,” *Energy Policy,* vol. 24, no. 3, pp. 245–252, 1996.

[7] C. I. Pardo Martínez, “Energy use and energy efficiency development in the German and Colombian textile industry,” *Energy for Sustainable Development,* vol. 14, pp. 94-103, 2010.

[8] P. Thollander and M. Ottosson, “Energy management practices in Swedish energy-intensive industries,” *J. of Cleaner Production,* vol. 18, pp. 1125–1130, 2010.

[9] I. Leobner, K. Ponweiser, C. Dorn, F. Bleicher, „Monitoring of energy flows and optimization of energy efficiency in a production facility,” *Proc. 5th Int. Conf. on Energy and Development – Environment – Biomedicine,* Corfu, Greece, 2011, pp. 81–85.

[10] C. Dorn et al., “Energy Efficient Production – Interdisciplinary, Systemic Approach through Integrated Simulation,” unpublished.

[11] I. Kovacic et al., “A holistic model for an energy efficient production facility,” presented at 1st Int. Conf. on Sustainable Intelligent Manufacturing, Leiria, Portugal, June 2011.

[12] Modelica Organization Website, http://modelica.org (last accessed July 30, 2011).

[13] M. Wetter and C. Haugstetter, “Modelica versus TRNSYS – A comparison between an equation-based and a procedural modeling language for building energy simulation,” *Proc. 2nd SimBuild Conf.,* Cambridge, MA, USA, 2006.

[14] J. Eker et al., “Taming heterogeneity – the Ptolemy approach,” *Proc. IEEE,* 91(1):127-144, 2003.

[15] M. Wetter, “Co-simulation of building energy and control systems with the Building Controls Virtual Test Bed,” *J. of Building Performance Simulation,* vol. 3, issue 4, 2011.

[16] “MLE+: a Matlab-EnergyPlus co-simulation interface,” http://www.seas.upenn.edu/~nghiem/mleplus.html (last accessed July 30, 2011).

[17] I. Kovacic, “Building performance evaluation” (in German), in “Beyond sustainability. How can sustainable civil engineering profit from the crisis? (Beyond Sustainability. Wie profitiert nachhaltiger Ingenieurbau von der Krise?),” presented at Internationales Industriebauseminar 2009, Vienna, May 13–15, 2009.

[18] K. Schumacher and R. D. Sands, “Where are the industrial technologies in energy-economy models? An innovative CGE approach for steel production in Germany,” *Energy Economics,* vol. 29, pp. 799-825, 2007.