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Hybrid Building Performance Simulation Models for Industrial Energy Efficiency Applications

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ABSTRACT

In the challenge of achieving environmental sustainability, industrial production plants, as large contributors to the overall energy demand of a country, are prime candidates for applying energy efficiency measures. A modelling approach using cubes is used to decompose a production facility into manageable modules. All aspects of the facility are considered, classified into the building, energy system, production and logistics. This approach leads to specific challenges for building performance simulations since all parts of the facility are highly interconnected. To meet this challenge, models for the building, thermal zones, energy converters and energy grids are presented and the interfaces to the production and logistics equipment are illustrated. The advantages and limitations of the chosen approach are discussed. In an example implementation, the feasibility of the approach and models is shown. Different scenarios are simulated to highlight the models and the results are compared.

KEYWORDS

Modelling and simulation, Building performance simulation, Hybrid systems, Discrete event and differential equation system specification, Energy efficient production.

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INTRODUCTION

In the effort of increasing environmental sustainability, the production sector is of vital interest. Industrial production is responsible for 26% of the energy consumption in Europe [1]. Therefore, increased effort is attributed to finding strategies to monitor, reduce and manage the industry's energy demand. These efforts target the significant potentials of energy conservation, as identified e.g. in [2, 3], as well as the possible impact the manufacturing industry could exert on the balancing energy market, as quantified by Paulus and Borggrefe [4] for the example of Germany. The study by Kayo and Suzuki [5] shows that an integrated approach of energy management leads to a significantly higher savings potential. Furthermore, Podgornik *et al.* [6] concludes that providing transparency of energy consumption to users plays a "crucial role in the transition towards a low carbon and sustainable society".

A gap analysis of existing research and industrial needs concerning efficient and effective energy management identified two main development demands: production management with regard to energy efficiency and integration of energy-related performance criteria into Information and Communication Technology (ICT) systems [7].

In order to address these needs, the research project Balanced Manufacturing (BaMa) was initiated. It aims to design a tool chain which anchors the factors energy demand and carbon emissions as control parameters in industrial plant operation. By monitoring, predicting and optimizing the energy demand of the production as a whole as well as the expenditures of individual products, the tool chain provides reporting of energy performance indicators and ongoing management of the dynamic energy demand. This can for example be used for assessing the bottom-up Carbon dioxide (CO_2) footprint of products [8] or for Demand Side Management [9]. According to Deng *et al.* [10] most dynamic Demand Side Management approaches and tools share the characteristic that they are formulated as an optimization problem and the user behaviour is mathematically modelled. The BaMa approach is no exception to that. The core part of the tool chain consists of a simulation model of the production plant and an optimization algorithm. Since the modelling process represents a major effort in every implementation of the tool chain, a well-adapted modelling approach must be provided. Furthermore, it must be taken into account that not only the production equipment causes energy demand but also auxiliary infrastructure such as the building and the energy supply system. Therefore, an approach applicable to all types of energy consumers must be found. Especially the integration of building performance simulation presents a challenge. Traditionally building performance simulation was considered a valuable tool during the design phase of the building life cycle [11-13]. However, simulation models and tools used for supporting design decisions are not necessarily suitable for the purpose of industrial energy management. The models are usually more complex than needed to answer the questions of this application, which in turn leads to a computation time that is not feasible for a tool chain with regular work-flows. More importantly, they lack the possibility to integrate material flows. Although there are ongoing developments in building performance simulation as identified by Clarke and Hensen [14], for example the integration of other domains (such as airflow [15] or user behaviour [16]) and reduction of computation time [17, 18] have been targeted by numerous researchers, yet no suitable solution is available. Therefore, a targeted building model had to be developed.

BACKGROUND

Taking the above mentioned considerations into account, a generic method was formulated in order to ensure its usability in a variety of production facilities. It is designed to address the high system complexity and heterogeneity by dividing the overall system into well-defined manageable modules. These modules allow a focused system analysis independent form the surrounding environment and promote model reusability and rapid assembly. They are called ‘cubes’ and represent a physical part of the production plant, which is mapped into a mathematical ‘cube model’ for the simulation. The cubes are defined by unified interfaces that consolidate the flows, which are relevant for making meaningful statements about a product’s energy expenditures, within the cube boundaries. These flows are:

- Energy flows;
- Material flows incorporating the immediate value stream of products;
- Information flows necessary for energy demand communication or control actions of the cube module.

Unification of all cube interfaces promotes flexibility and hierarchical composability. A more detailed description of the BaMa method can be found in Leobner *et al.* [19].

In order to relate the energy flows to individual products, the cube’s resource expenditures are accumulated and assigned to these products. This leads to the necessity that the value stream has to be described as discrete entities, whereas energy demands and resulting emissions are described by continuous variables. Therefore, discrete and continuous modelling techniques have to be united in the cube models, resulting in hybrid dynamical simulation models, as defined e.g. by van der Schaft and Schumacher [20]. In Omar *et al.* [21], the need for using hybrid simulation approaches when modelling industrial production plants is underlined.

The challenge of modelling hybrid cubes was approached by using the Discrete Event and Differential Equation System Specification (DEV&DESS) formalism proposed in Zeigler *et al.* [22]. The universal basis for computational analysis of systems is the Discrete Event System Specification (DEVS). DEVS specifies structures with inputs, outputs and inner states, satisfying the requirements of hierarchical modularity. The concepts of Atomic DEVS, expressed in the basic formalism and Coupled DEVS, which provide a specification of component relational information, corresponds with the desired hierarchical nature of cubes.

The remainder of the paper is structured as follows: the next chapter will discuss the hybrid cube models, focusing on the building and energy systems. A more detailed description of the models of the production equipment can be found in Raich *et al.* [23]. Thereafter a simulation example using the discussed models is presented and the results for different scenarios are discussed.

CUBE MODELS

The Cube-approach allows dividing different aspects of the building and energy system into well-defined components. Using this technique, four cube classes are specified:

- The building;
- Thermal zone;
- Energy converter;
- Energy grid.

The building represents the solid construction, i.e. the walls, the thermal isolation, the floor and roof. In the building cube model, the heat exchange between neighbouring thermal zones and the surrounding is determined. The thermal zones describe the behaviour of the air of a room, including calculation of the heating and cooling demand. The energy converter cube describes a lossy conversion of energy, for example from natural gas to heat and power. The energy grid cube distributes energy from different sources to consumers and may contain energy storage.

To describe the interactions between cubes, energy and information flows are used. Often both of these interfaces are needed to model the behaviour of interacting cubes.

The information interfaces are used to request power from another cube, usually called a demand. In response the cube then delivers an energy flow, ideally – but not necessarily – of the requested quantity. The requests are, similar to energy flows themselves, continuous flows and therefore can gradually change over time. The presented cubes do not contain discrete interfaces since no entities directly interact with them, making the models purely continuous.

The building cube

The building cube's main function is to calculate the heat exchange between thermal zones and the surrounding. For that purpose it is necessary to know the contact surfaces between the thermal zones, i.e. the shared walls, windows, floors, ceilings or roofs. With this information, called the mapping of thermal zones in the building, the composition of the building is known. The thermal zones receive their heat loss or gain from the building.

The calculation of the heat transfer through the walls is done by a resistance-capacitance model, meaning that a wall is approximated as a capacity, i.e. the thermal storage potential and a thermal resistance. The thermal capacity is aggregated to a lumped parameter for each wall, the thermal conductivity is discretized between three points: the undisturbed room air on either side of the wall and the lumped capacity inside the wall. If two walls connect two thermal zones, the parameters for the walls are aggregated to form an equivalent wall, with the thermal capacities added up and the thermal conductivity (inverse of thermal resistance) averaged by their respective wall area.

The inputs into the building cube are the room temperatures of the thermal zones and the temperature of the surrounding and the ground. The output represents the net heat gain or loss for each thermal zone. The equation for calculating the heat transfer is:

$$\underline{m_{\mathrm{W}}} \circ \underline{c_p} \circ \frac{d}{dt}\underline{T_{\mathrm{W}}} = \underline{\dot{Q}_{\mathrm{W}}} + \underline{\dot{Q}_{\mathrm{W}}}^{\mathrm{T}} \qquad (1)$$

The equation is written as matrices of size $(n + 2) \times (n + 2)$, denoted with an underscore, with n being the number of thermal zones. The parameters $\underline{m_{\mathrm{W}}}$ and $\underline{c_p}$ are the mass and relative thermal capacity matrices of the walls and $\underline{T_{\mathrm{W}}}$ is the wall temperature matrix – all three being symmetrical, and $\circ$ denotes the element-wise multiplication or Schur product. The term $\underline{\dot{Q}_{\mathrm{W}}}$ is the heat transfer from thermal zones to the insides of the walls. It is not necessarily symmetrical, however the whole right-hand side of the eq. (1) is:

$$\underline{\dot{Q}_{\mathrm{W}}} = (\vec{T} \times \vec{I}^{\mathrm{T}} - \underline{T_{\mathrm{W}}}) \circ \underline{UA} \qquad (2)$$

Eq. (2) relates the heat transfer to the wall centre with the temperature gradient, with $\vec{T}$ being a column vector of the thermal zone, surrounding and ground temperatures. With the unity vector of size $n + 2, \vec{I}$ and the symmetrical wall temperature matrix, the term inside the brackets represents the permutation of the possible temperature differences. The matrix $\underline{UA}$ is an aggregation of wall area multiplied by the thermal conductivity. This parameter defines the topology of the building and maps the adjacent thermal zones together. With eq. (1) and (2), the differential equation in $\underline{T_{\mathrm{W}}}$ can be solved. Since the equation is symmetrical, only half of the ODE-system needs to be solved. The output of the cube, the heat gain or loss of the thermal zones, is aggregated by adding the heat transfer for each thermal zone for each wall.

This simple model of the building is considering heat transfer between thermal zones and the surrounding only by heat conduction. Other effects such as the influence of solar radiation, shading and the wind velocity can be incorporated into the cube model structure. However, this is still work in progress.

The thermal zone cube

As mentioned before, the thermal zone cube describes the thermal behaviour of the air volume inside the thermal zone. The temperature of the thermal zone is assumed to be homogenous and no air motion is present. This allows the air to be modelled as one temperature. In contrast to the building cube, the thermal zone cube is considered a composite cube (coupled DEVS). This is necessary since a thermal zone houses different cubes like production equipment or energy systems.

The inputs of the cube are energy ports for receiving the aggregated heat transfer through the walls $\dot{Q}_{\mathrm{W}}$, internal gains from waste heat of cubes inside the thermal zone $\vec{\dot{Q}}_{\mathrm{WH}}$ and heating and cooling energy for conditioning of the air, $\dot{Q}_{\mathrm{H}}$ and $\dot{Q}_{\mathrm{C}}$. Additionally, the outside temperature is needed for calculating the heat loss due to infiltration $\dot{Q}_{\mathrm{I}}$. The outputs of the cube are the thermal zone temperature, heating and cooling demand and ventilation demand. The scalar differential equation describing the thermal zone is as follows:

$$c_{p\mathrm{A}}\rho_{\mathrm{A}}V\frac{dT}{dt} = \dot{Q}_{\mathrm{W}} + \sum\vec{\dot{Q}}_{\mathrm{WH}} + \dot{Q}_{\mathrm{H}} + \dot{Q}_{\mathrm{C}} + \dot{Q}_{\mathrm{I}} \tag{3}$$

The material parameters $c_{p\mathrm{A}}$ and ρ_{A} describe the thermal capacity and density of air, V is the volume of the thermal zone. The temperature of the thermal zone T is the variable to be solved. The right-hand side of the equation contains the heat gains and losses. The waste heat is a vector since multiple sources of waste heat may be inside the thermal zone. All heat gains or losses are direct inputs into the cube except for the infiltration, which is defined by eq. (4). The heat transfer is defined through the temperature difference to the surrounding area $(T_{\mathrm{S}} - T)$. The parameter infiltration rate I dictates the air change rate per hour per thermal zone volume:

$$\dot{Q}_{\mathrm{I}} = (T_{\mathrm{S}} - T)\rho_{\mathrm{A}}c_{p\mathrm{A}}V\frac{I}{3600} \tag{4}$$

The outputs of the thermal zone cube, beside the already covered thermal zone temperature, need to be calculated. For addressing heating and cooling demand, upper and lower set-point temperatures are defined. If the thermal zone temperature exceeds the upper limit, cooling is initiated. Similarly, if the lower set-point is crossed, heating starts. The value for demanded heating or cooling can be determined by any controller that fits the purpose, for example two-point or PID-controller. To achieve high computational performance, a simplified approach can be chosen: When one of the set-point values is reached, the negative of transmission losses, internal gains and infiltration is set as heating or cooling demand. This approach results in the right side of eq. (3) becoming zero, thereby compensating all heat gains or losses and preserving the zone's temperature. Eq. (5) shows the equation exemplary for the heating demand $\dot{Q}_{\mathrm{HD}}$ using the lower set-point temperature T_{setL}:

$$\dot{Q}_{\mathrm{HD}} = \begin{cases} -(\dot{Q}_{\mathrm{W}} + \sum \vec{\dot{Q}}_{\mathrm{WH}} + \dot{Q}_{\mathrm{I}}), & T < T_{\mathrm{setL}} \\ 0, & \text{else} \end{cases} \tag{5}$$

Lastly, the ventilation demand $\dot{V}_{\mathrm{D}}$ is calculated via eq. (6). The ventilation rate v defines the number of air volume changes per hour:

$$\dot{V}_{\mathrm{D}} = V \frac{v}{3600} \tag{6}$$

Energy converter cube

This cube converts energy from one type to another. The conversion may be accompanied by losses, which are converted to waste heat and provided, for example, to the surrounding thermal zone. The inputs of the cube are the power needed for the conversion, power demand of the converted energy and optionally other information. The additional information inputs can be used for internal calculations. An example is the temperature of a heat transfer fluid needed for the calculation of the efficiency factor. Outputs of the cube are the converted power, waste heat and the demand for power needed for the conversion.

The cube model does not contain a differential equation, no state variables need to be calculated. The behaviour of the energy converter depends mainly on two functions, the capacity function and the efficiency function. These functions are not strictly part of the cube model but of the parameterization. This allows for flexibility in the application of this generic cube to a wide variety of energy converters. The capacity function (*Cap*) defines the maximum capacity of converted power the cube can provide. It can be dependent on any amount of information inputs but in a simple case it can be assumed to be constant. The second function is the efficiency function η determining the efficiency factor. This function depends on the partial load factor and can depend on information inputs as well. The Partial Load Factor (*PLR*) is defined using the current power output P_{out} and the current capacity *Cap*, see eq. (7). A simple efficiency function can be assumed to be linearly declining from the nominal output at full load (in this case the working point):

$$PLR = \frac{P_{\mathrm{out}}}{Cap} \tag{7}$$

With the two functions defined, the outputs of the cube can be computed. The converted power output (P_{out}) can be seen in eq. (8). The expression either uses the incoming power (P_{in}) to calculate the output or, if the maximum capacity is reached, outputs the capacity. The factor *sign* can be either one or minus one, depending on outputting heat or cold:

$$P_{\mathrm{out}} = sign\ \min(|P_{\mathrm{in}}\eta|, Cap) \tag{8}$$

With P_{out} being dependent on η and vice versa, a method for breaking this algebraic loop needs to be applied (e.g. using *Cap* from a previous time-step). The next output is the waste heat. Using the energy balance, the waste heat is the difference between incoming and outgoing heat and therefore depending on η. Finally, the demand for power to convert (P_{inD}) is calculated by eq. (9). The demand for product power (P_{outD}) is an input of the cube and therefore available:

$$P_{\mathrm{inD}} = \frac{P_{\mathrm{outD}}}{\eta} \tag{9}$$

When using this cube to describe a more complicated machine, e.g. an absorption chiller, the numbers of energy inputs and outputs increases, but the basic principle remains the same.

Energy grid cube

The energy grid cube distributes energy from one or more sources to consumers. Additionally, a capacity for energy storage can be provided. The inputs of the cubes are power from sources $\vec{P}_{\mathrm{S}}$, power from heat recovery $\vec{P}_{\mathrm{R}}$ and the information on the needed power of each consumer. The difference between energy source and energy recovery is that the latter cannot be requested, but is delivered when available. The outputs of the cube are the power to the consumer $\vec{P}_{\mathrm{C}}$, and power demand from the sources $\vec{P}_{\mathrm{SD}}$.

The models for the grid with and without storage capability are slightly different from each other. In case of the energy grid with storage the defining equation, the energy balance, has a differential term for the change in energy storage *E*. The parameter *C* defines the capacity of the storage. Eq. (10) shows the differential equation for the energy grid with storage:

$$C\frac{dE}{dt} = \sum \vec{P}_{\mathrm{S}} - \sum \vec{P}_{\mathrm{C}} + \sum \vec{P}_{\mathrm{R}} \tag{10}$$

With eq. (10) *E* is calculated. Therefore another equation for defining the requested power from the sources is required. Similarly to the controller of the thermal zone cube, a simple implementation is using a two-point controller. When the lower set-point is crossed, power is requested from the sources until the upper set-point is reached. If more than one source is available, a method for dividing the demand to the different sources has to be defined. The simple case is to distribute the load uniformly.

For the energy grid without storage, the left side of the eq. (10) becomes zero and $\vec{P}_{\mathrm{S}}$ becomes $\vec{P}_{\mathrm{SD}}$, the assumption being that the requested energy demand by the consumer can always be provided.

Interfaces to production and logistics cubes

With the cube classes for the building and energy systems defined, the missing link is the production and logistics systems of a facility. A detailed discussion of the cubes would go beyond the scope of this paper but can be found in Pawletta *et al.* [24]. However, the influence of the production on the energy system and building needs to be considered.

The production and logistics cubes have continuous behaviour similar to energy system cubes but in addition can be entered and exited by entities, i.e. the products. The arrival or departure of entities can trigger a change in the continuous behaviour. The production and logistics cubes interact with the energy system by requesting and receiving energy flows. The waste heat in turn is transmitted to the thermal zone. The logistics, energy systems and building cubes are interdependent on each other, thus justifying the interdisciplinary modelling approach.

RESULTS

To demonstrate the feasibility of the presented models in a greater context, the method is shown on an example facility. It is a simplification of a real production facility that produces baked goods, fresh as well as frozen and is intended to include all relevant aspects (production and logistics cubes as well as energy system and building cubes) to demonstrate an interdisciplinary hybrid simulation.

The industrial building is a compact, square shaped production facility, with administration office areas located on the upper floor of the building, facing north. A representation of the building is shown in Figure 1. The factory is divided into four thermal zones according to space function, material constructions and attributed thermal conditions (Figure 1b). The first zone is the main manufacturing hall with a double height ceiling and an area of 3,500 m². The hall should sustain an indoor air temperature of 18 °C to 28 °C throughout the year. The second zone is the area housing the technical building services of the facility, measuring 1,400 m², with no specific thermal conditioning requirements. The third is the cold storage area with a size of 300 m² and a constant temperature at 4 °C. Finally, on the upper floor are the office areas, the forth zone, with a surface of 2,000 m² and indoor temperatures from 22 °C to 26 °C.

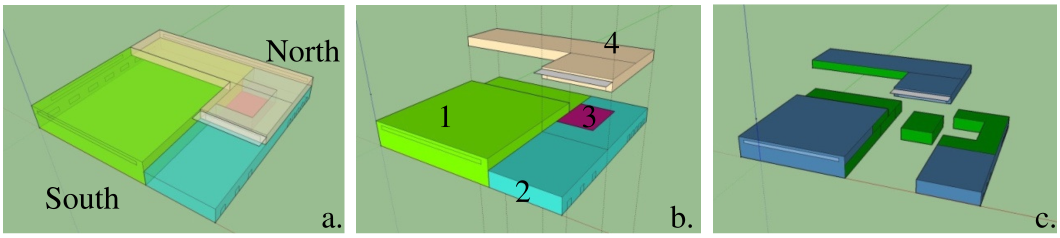


Figure 1. Example building geometry (a); thermal zones division (b); boundary conditions of thermal zones (c)

The zone arrangment is shown in Figure 1c. Interior surfaces between the thermal zones are colored green, the thermal envelope of the building blue. The cold storage, zone 3, is an internal space with no surface exposed directly to the outside weather conditions.

The building is made of reinforced concrete on the ground floor areas and roof surfaces, whereas masonry brick walls are used on the upper floor. All exterior walls are insulated with 20 cm mineral wool insulation and roof surfaces with 24 cm. Furthermore, the wall dividing the two parts of the building, the production hall from the technical space and storage, is a 30 cm thick concrete construction, which at the point of the cold storage room has an additional 10 cm rigid Polyurethane insulation (PUR). The cold storage is also divided with lightweight partition walls of 10 cm PUR from the surrounding technical services areas. To fit the building cube model, multiple walls connecting the same thermal zones are aggregated. The windows are considered in regards to the thermal conductivity only.

The energy system of the facility is situated in zone 2. The electric grid is needed for distributing power to the production and logistics equipment and a compression chiller. The electric grid is modelled as an energy grid cube without storage. The only source for the electric grid is a provider, delivering the energy once requested. The compression chiller is modelled as an energy converter cube, requesting electric power from the grid and delivering cold to a cold grid and waste heat to the thermal zone. The cold grid, an energy grid with storage, distributes cold to zones 1, 3 and 4 and to the freezer. The storage is realized with a two-point controller. Once the lower set-point temperature is reached, a fixed amount of cooling power is requested from the chiller. For the heating of thermal zones 1, 3 and the oven, a heat grid and a gas heater are used. The gas heater, an energy converter, converts natural gas received from the gas provider to heat. The heat grid, again with storage, functions similar to the cold grid as it provides heat to the consumers and once the lower set-point is reached, it requests heat from the heater.

The cube model of the facility with the entity and energy flows visualized can be seen in Figure 2.

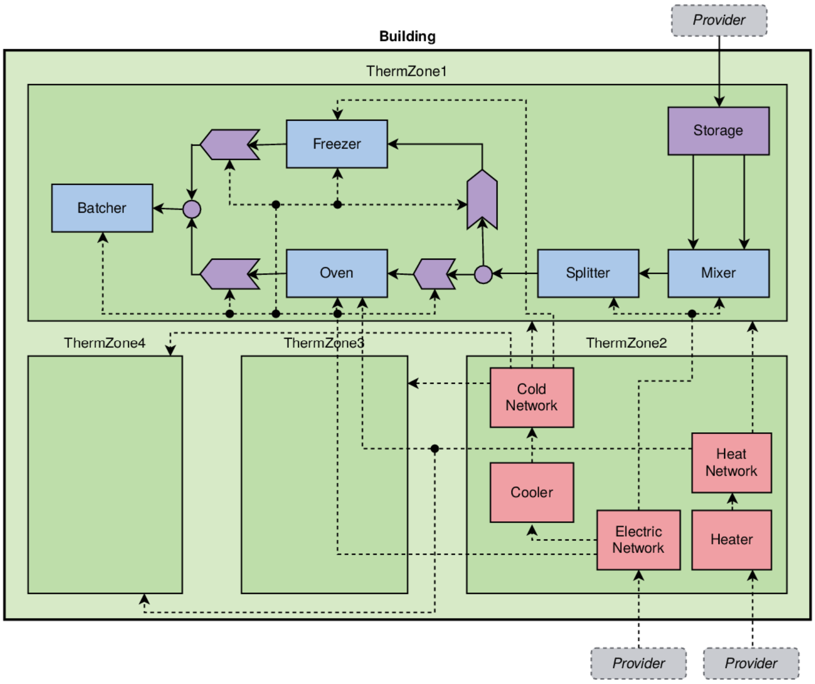


Figure 2. Example model containing production machines, logistics components, energy cubes and thermal building zones

Several production and logistics cubes model a production line for different products. Respective ingredients in the form of simulation entities are pulled from storage and handed through mixing, splitting and packaging stations as well as conveyor belts. The products can either pass an oven for baking or a freezer for cooling, depending on the type of product. Each station is provided with electric energy, oven and freezer additionally receive thermal energy from respective energy grids. A more comprehensive description of production and logistics cube classes can be found in Raich *et al.* [23].

The production schedule for the presented scenarios is shown in Table 1. In order to be able to make justified comparisons of simulation results regarding the energy system and building, all scenarios use the same production schedule, which acts as an input vector for the simulation. During simulation, the production schedule is read and respective commands for state changes in the cubes are triggered accordingly (on/off, standby, set-up, etc.), which enables entities to be processed. All simulation scenarios take place over the course of one day (00:00 to 24:00).

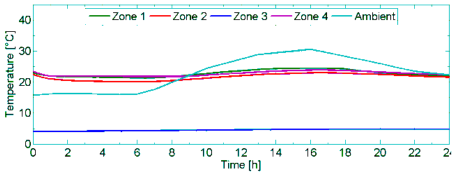
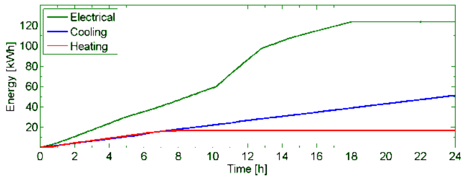
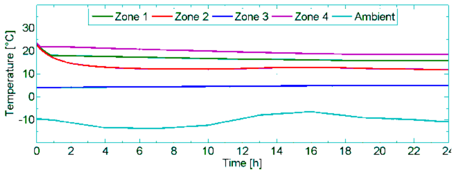
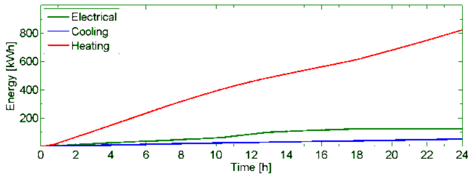
Table 1. Production schedule for the example scenarios

Cube	Time	State	Product type	Quantity
Storage	00:30	prepare	1	8
	06:00	prepare	2	16
Production	01:00	on	1	
	06:30	on	2	
	18:00	off	-	
Oven	00:00	set-up	1	
	07:00	off	-	
Freezer	05:30	set-up	2	
	18:00	off	-	

Additional input is provided by a time series for ambient air temperature, for which two different scenarios are compared. In scenario 1, production takes place during the summer with temperature varying between 16 °C and 31 °C. Scenario 2 compares the same production settings during the winter where ambient temperature varies between −14 °C and −6.5 °C.

The model was implemented using the MatlabDEVS Toolbox [24] as a framework for simulating hybrid systems that employs a formalism similar to DEV&DESS [25]. The toolbox implements an ODE wrapper approach for the continuous equations, which are computed using MATLAB's 'ode45' algorithm. Table 2 compares the simulation results from the two scenarios. The left column shows the temperature curves over time for all four thermal zones as well as input ambient air temperatures, and the right column presents the resulting overall energy demands from electrical, cooling and heating grids, resp. The energy demands differ significantly between summer and winter, especially heating energy, as one might have expected.

Table 2. Simulation results showing energy and temperature comparison between two scenarios

	Temperature	Energy
Scenario 1		
Scenario 2		

The difference between the two scenarios is apparent. In scenario 1, being in the summer, the heating is only used for the oven. The main energy expenses are cooling for thermal zone 4 and the freezer, the chiller in turn using electric power. The thermal zone temperatures follow the ambient temperature as is expected, aside from zone 4 which is constantly refrigerated. The influence of the oven on the temperature of thermal zone 1 is mitigated by the rising ambient temperature. In the second scenario the heating of the building is the overwhelming energy demand. At the end of the simulation period the conditioned zones need heating, although cooling is still necessary for thermal zone 3 and the freezer. Especially interesting is that in both scenarios the starting temperature of the thermal zones seem to be off and start adapting in the first hours of simulated time. This shows the importance of starting conditions, most notably of the wall temperatures since changes propagate slowly.

Finally, Figure 3 depicts the entities being produced over time. According to the production schedule in Table 1, eight batches of product type 1 are being processed between 00:30 and 06:00 (oven) and 16 batches of product type 2 between 06:00 and 18:00 (freezer). As is presented in the simulation results, all products are done by 16:00, which would allow to turn off the production line as well as the freezer two hours earlier than originally planned, thus saving energy.

Integrating all cube categories into a single overall simulation allows incorporating dynamic interactions between the components. For example, the production schedule of the freezer influences the cooling energy demand in the energy grid. The freezer also determines its waste heat into the surrounding thermal zone, which is in turn influenced by the surrounding temperature.

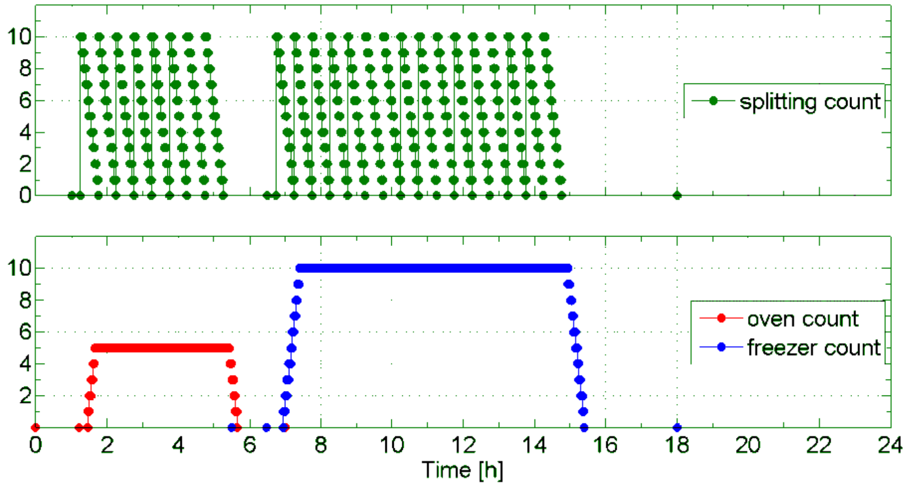


Figure 3. Simulation results regarding production cubes for both scenarios, the plots show number of entities inside the splitting station, oven and freezer over time

DISCUSSION

The presented simulation case study demonstrates the importance of interdisciplinary energetic modelling as well as the feasibility of the chosen hybrid simulation approach. It allows exploiting dynamic effects across the whole system. Furthermore, it shows that the presented cube models integrate well into the simulation using the proposed method. Even though the models are simplified and the incorporation of some aspects is missing, the approach is suited to meet the demand the BaMa project sets for the simulation environment. A fully functioning discrete event simulation coupled with a continuous energy assessment in the same simulation environment is achieved. This represents an advantage in regard to conventional simulation tools. For example, Plant Simulation can be used for the discrete event simulation of the production and EnergyPlus can simulate the building performance. However, with conventional tools, a hybrid simulation incorporating discrete and continuous behaviour is not achievable. Additionally, the integrated approach achieves low computational overhead and high time efficiency needed when coupling the simulation with optimization tools. With added optimization, analyzing and comparing production schedules can enable uncovering additional potential for energy saving measures.

The presented study functions as a proof of concept for the approach and, to a lesser extent, the models. The generic nature of the cube models results in the possibility to reuse the models with a different set of parameters and apply them to other use-cases. Many production facilities use similar equipment (chillers, heaters, belts, ovens, etc.), therefore a reusable library of cubes can be developed. While models for specialized equipment need to be developed for the individual case, the reusability of a substantial amount of cubes helps to achieve a quick assembly of simulation models for predicting material flow and energy demand of a factory.

CONCLUSIONS

Using an interdisciplinary simulation-based approach to industrial energy efficiency analysis facilitates quantified predictions about the behaviour (energy consumption, production durations, etc.) of the overall system with varying production schedules and operating strategies as well as environmental settings (climate, time of year, etc.), taking into account dynamic interdependencies between production, energy system and building hall.

To improve the models further, the next steps are to incorporate additional features and to validate the models with measurement data. A validation is vital for the application of the presented method to decision making processes in industrial production facilities. By expanding the scope, the performance and usability is further tested. Finally the integration of cube models and a hybrid simulation engine into existing automation systems is pursued to give management of factories the tools to not only determine the energetic behaviour of their facility, but to improve the performance.

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