Energy Flows in Industrial Buildings and Machines using the Example of a Node Model

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Abstract. Within the context of the research project 'HIER! - Production in Air-Conditioned Facilities', financed by the Hessian Ministry of the Environment, Power, Agriculture, and Consumer Rights (HMUELV), the Department for Sustainable Products and Processes at the University of Kassel is developing simulation modules for the energetic evaluation of production systems.

For this purpose, the development of a node model facilitates research into the thermal properties of machines and products. With a focus on energy storage, the study demonstrates a variety of applications for this model, using the example of a cold-storage facility and a plastics processing plant for the reduction of the primary energy requirement from the process to the factory.

Introduction

There is a great energy saving potential in production plants. Savings resulting from the doubling of a company's energy-related productivity with an average energy consumption of 1.4 TWh would equal the annual energy consumption of a city the size of Stuttgart. [1] Even a medium-sized company with an electricity consumption of 10 GWh can save the energy demands of up to 1700 households by raising its efficiency levels to 50%. [10] [11]

Given the increase in environmental awareness, both within society and the political sector, an energy-efficient and environmentally friendly means of production is rapidly becoming more and more important. The energy requirements of the production are determined by so-called crossover technologies, as well as by specific main technologies. Crossover technologies may perform movements within machines and plants, transmit energy, temper and control the procedure.

In most cases, means of lowering energy consumption only come into play outside of the manufacturing machines. Significant savings may be achieved through technologies with a direct energetic link to the production process. Besides their considerable potential, such savings may even render space heating systems obsolete. The concept of energy supply in the form of crossover technology incorporates the provision of auxiliary energy forms, such as compressed air, heat, and cold, as well as the generation of electricity from decentralised combined heat-and-power plants in conjunction with the public power grid. [1]

The thought pattern regarding this topic follows a so-called onion-layer model - from the inside out, in other words, beginning with the process, seen in Figure 1.

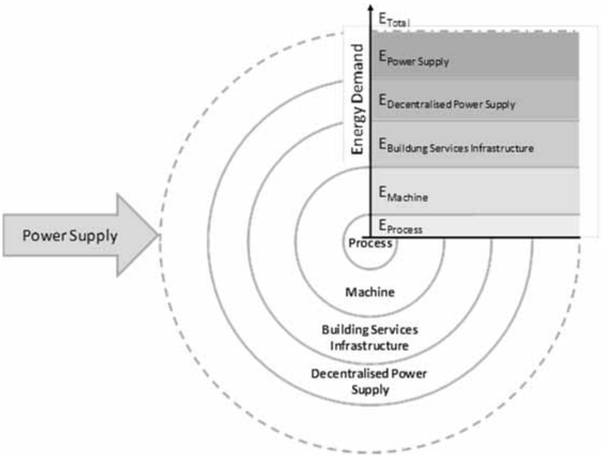

Figure 1. The onion layer model regarding the energy demand of a process [1].

In reality, the energy currents would surpass the individual layers and interact. Air-conditioned production facilities represent the extreme case of energetic linkage of production processes as well as technical building equipment as a cross-sectional task.

During winter, waste heat relieves the heating systems and during summer, every kWh of electricity registered for the proper operation of the machines leads to additional 0.33 kWh in cooling needs. [1] In some cases, such as cold-storage facilities, the energy demand for cooling purposes may even exceed 70 % of the energy demand for the entire unit. [2] In this case, the number of stored goods determines the energy consumption of

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the building services equipment, which, in turn, influences the dimensioning of the entire energy supply. An approach to the energetic optimisation of a cold-storage facility would be the usage of the refrigerated products for energy storage. [1]

As manufacturing companies produce a lot of waste heat, however, the waste heat emanating from the machines influences air-conditioning technology; a heat recovery system reduces the gas requirements within the central heating plant. Awareness of the waste heat from machines, or more specifically, their heating and cooling times, allows for research into the saving of thermal energy for the lowering of energy requirements.

For the thermal analysis of processes and machines, a model, which calculates temperatures as well as currents of energy, is required. The basis for this is the node model developed by the *Department for Sustainable Products and Processes*. The contribution addresses the fundamental approach to modelling, on the basis of which the developed model is used to demonstrate its potential, identified by means of a thermal simulation, in the form of two examples.

1 Development of the Node Model: Thermal Analysis from Processes to Buildings

For the purpose of modelling and simulation of machines and facilities, energy flows for each individual energy source (electricity, heat, compressed air, etc.) will have to be observed separately.

In a practical sense, time constants may differ greatly in regards to thermal processes, due to the fact that real physical and technical processes are always subject to temporal connections. [12]

During the heating of a cold machine, electric power increases at once, whereas a change in the thermal capacity resulting from it might take hours. [5] Thus models demonstrating thermal properties differ significantly from those illustrating the necessary electrical capacity.

Within a body, thermal conduction represents an energy flow; on the surface, additional radiations and convections should be taken into consideration. [6]

A thermal analysis can be conducted mathematically with the help of location-dependant partial differential equations. However, it is possible to perform an incremental calculation with the help of the so-called node model, which links common differential equations.

The location dependency of the partial differential equations is approximated by a division into the various layers of the body. The centre of a layer is thus referred to as a node (Figure 2). [5]

As opposed to the solution of a partial differential equation, the node model reduces the required computing power and provides a substantial increase in flexibility, so that the model can easily be expanded around an internal heat source (such as the heating process of a machine) or a phase transition (such as the cooling of refrigerated goods).

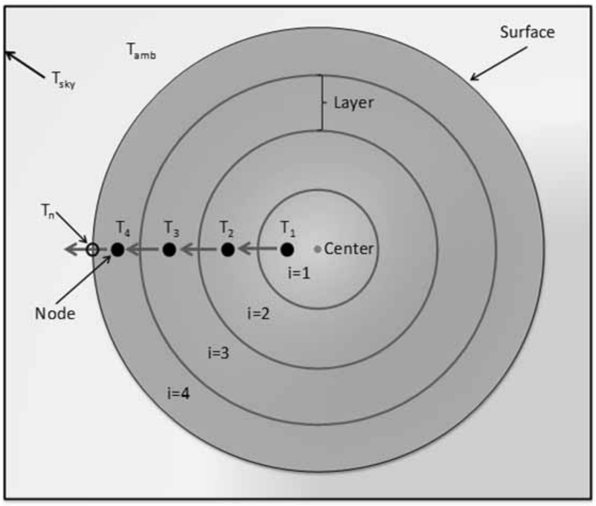

Figure 2. Sectional view of a layer model of a sphere [3].

For every layer, an assessment of mass, performance, and energy is made. Arising temperature differences cause transferred thermal energy flows through heat conduction.

The following equation shows the energy assessment of a node without an internal heat source or phase transition (Equation 1):

$$m_{\mathrm{i}} c_{\mathrm{K}} \frac{dT_{\mathrm{K,i}}}{dt} = \frac{\lambda_K}{\delta} A_i (T_{K,i\text{-}1} - T_{K,i}) - \frac{\lambda_K}{\delta} A_{i+1} (T_{K,i} - T_{K,i+1}) \tag{1}$$

where T_K is the temperature of the body in K, m_i is the mass of the layer in kg, c_K is the specific heat capacity of the body in J/kgK, λ_K is the heat conductivity of the body in W/mK, δ is the distance between the nodes in m, i is the number of the layer and A is the surface measured in m².

In order to focus the calculation not on the outermost node, but on the surface layer, the latter has to be mapped through a massless node. The heat exchange between the body and the surrounding area results from radiation and convection. In the case of many actual machines and facilities, an additional insulating layer has to be taken into account. [5] The temperature of the massless node $T_{K,n}$ is a decisive factor in the calculation of the heat exchange. The convection results from a temperature difference between $T_{K,n}$ and the factory air T_{amb}. In case of the radiation, the temperature of the surrounding wall (T_{sky}) is also relevant (Equation 2).

$$0 = \frac{2\,\lambda_K}{\delta}\left(T_{K,n-1} - T_{K,n}\right) - \alpha_K\, A_{\mathrm{K}}\left(T_{K,n} - T_L\right) - \varepsilon_{\mathrm{K}}\,\sigma\, A_K\,(T_{K,n}^4 - T_{sky}^4) \tag{2}$$

where T_L is the room temperature in K, T_{sky} represents the radiation temperature in K, α_K is the heat transfer coefficient on the surface of the body in W/m²K, ε_K is the emission coefficient of the body, σ is the Stefan-Boltzmann-Constant in W/m²K^4 and n defines the outermost layer.

In reality, both machines and facilities are subject to a great number and variety of internal and external influences. [7] With the aid of the aforementioned modelling, aspects such as production cycles and alternating thermal influences within the model may be taken into consideration. This makes it possible to simulate thermal properties of the individual products, machines, and facilities.

2 Simulation of Cold Storage using the Node Model

The following example uses the node model in order to simulate frozen goods in a cold-storage facility: The frozen products include food, such as meat and fish products, but also special items like medication. This permits analysis of the thermal properties of the products, and thus their evaluation as a useful energy saving device. For this purpose research was conducted into how far the frozen goods could be further cooled down when electricity expenses are low, in order to be able to reduce the cooling during times of higher electricity rates.

A simulation using the node model is created by viewing the frozen goods geometrically as symmetrical objects. The entire heat exchange between the modelled body and its surroundings can be calculated as the sum of the convective heat flow from the surface of the body into the ambient air and the radiation exchange with the surrounding surfaces (e.g. walls and ceilings). In order to assess the thermal requirements of production facilities, the energetic correlation of weather conditions, the building, building technology and production machines has to be realised within the model. The model's validation for use within the cooling area is assessed through a test series of the freezing- and thawing process of several different products. [3]

A simulation conducted within the context of this study compares a model with a fixed electricity rate to a model with an hourly rate (using a variable energy supply). Other options include models with a base load coverage at a fixed price and a more variable purchase for peak loads. In the case of a variable energy supply, it can be assumed that all market participants are familiar with the prices. A prognosis of the prices cannot be made at this time as they are highly dependent on the real-life availability of power plants, fuel prices, and wind forecasts, as well as the demand on behalf of potential clients. [4] An energetic linking of the products in cold-storage and the technical building services allows the identification of the necessary cooling requirements of the frozen products.

Limiting Conditions	**Description**
Simulation	Simulation of a summer month, accounting for different exterior air conditions.
Building	Length, width, height: 60 m x 80 m x 12 m Heat loss through walls: 0.5 W/m²K
People	Number of employees: 10 Monday through Saturday Fresh-air content per employee: 20 m³/h
Refrigerated goods	Storage capacity: 28,800 m³ Pallet spaces: 4,200
Estimated costs	Fixed electricity rate: 100 €/MWh Variable electricity rate: 3.03 – 235.18 €/MWh (average rate: 100 €/MWh) Estimated costs in the case of both model variants include all power generation and grid usage expenses, as well as taxes.

Table 1. Basic conditions of the simulation.

In a cold-storage facility one must constantly ensure that the temperature limits necessary to maintaining product quality are not exceeded. In the following case study the minimum temperature inside the cold-storage room is -18 °C. Depending on their operating condition, the refrigerating machines may be turned off when electricity rates are high and may run at full capacity when rates are low in order to achieve a super-cooling of the products down to a certain temperature limit (marked at -25 °C in this case) and use them as an energy storage device. The estimated results of the simulation are displayed in Table 1.

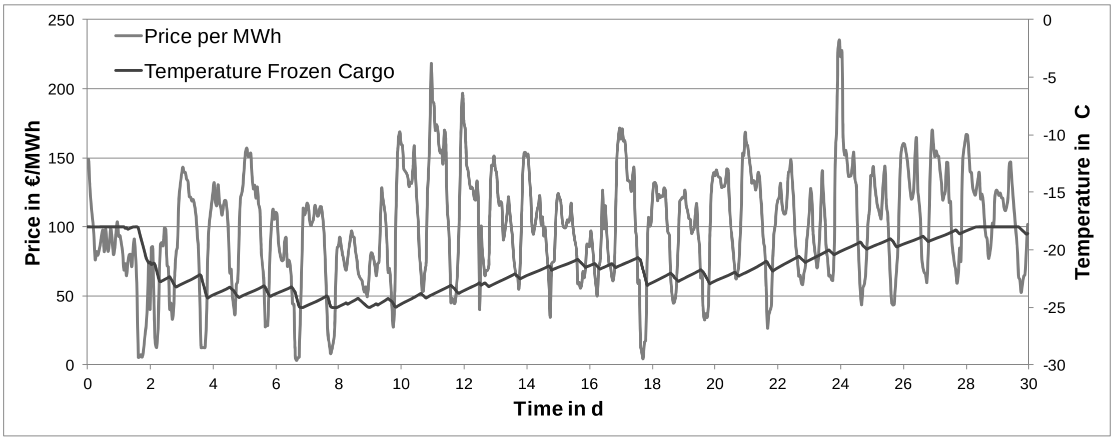

Figure 4. Temperature profile of a cold storage facility**.**

The result of this simulation is the temporally resolved energy necessary for the cooling of the building. This data can help in determining the cooling requirements for the entire cold-storage facility. Figure 4 shows the temperature cycles within the refrigerate goods in the case of a variable energy supply in connection with the individual electricity rates.

It becomes apparent that low electricity costs will make it possible for the refrigerated goods to be cooled down even further, so they may serve as an energy storage device during times when electricity costs are high. As opposed to the model using a fixed price for electricity (at a constant -18 °C), the average room temperature of the variable model would be around 21.65 °C, which would invariably lead to a higher energy demand. Within the context of this observation, 37 MWh of the fixed model compares to the 41 MWh of the variable supply, whereas the expenses are lowered from 3,713 € to 1,854 € a month. This results in a savings of approximately 50 %. The corresponding increase of 12 % in the final energy demand may be viewed as critical.

However, under the assumption that excess electricity from renewable energy sources can be used in such a way, the energy cost-driven operation of cold-storage facilities seems practical on an energy-related level as well, since the conversion ratio of primary to final energy is decidedly better than in the burning of fossil fuels.

3 Simulation of Thermal Loads in a Plastic Factory using the Node Model

As opposed to the refrigerated goods in the cold-storage facility, injection molding machines deployed in the plastics industry have internal heat sources. These lead to a steady heating of the machine until it reaches a static state, in which the added heating power is equal to that emitted into the room. Modelling requires the addition of internal power to the innermost junction of the machinery. Within a cylinder, a screw delivers plastic to the tool. On its way, friction within the cylinder and heat from externally applied heating collars generate the necessary energy in order to plasticise the granulate. Through a nozzle, the machine feeds the liquid mass into the tool, which then shapes the plastic during the cooling process.

Within the machine, the added electric power transforms into thermal power and splits into different parts. One part of the waste heat from the machine is discharged through water cycles, whereas the remainder is emitted into the production hall. [5] In order to increase the accuracy of a simulation in the case of very heterogeneous temperature ranges, a number of sectional modules have to be created for the various structural components and linked in order to contribute to the overall modelling. In this example, the injection moulding machine is divided into numerous spherical and cylindrical sections.

A model validation is made through the real-life operation of machines with accompanying measurements. This results in a division of the in-and outgoing energy and source streams to the individual structural elements.

The modelling was divided into the structural units of tool, extruder, control, and hydraulic system. The simulation clearly demonstrates that the dynamic properties as well as the final temperatures of the four sections differ greatly (Figure 5). In order to develop suitable solutions for an increased energy efficiency based on a simulation of an injection moulding machine, a

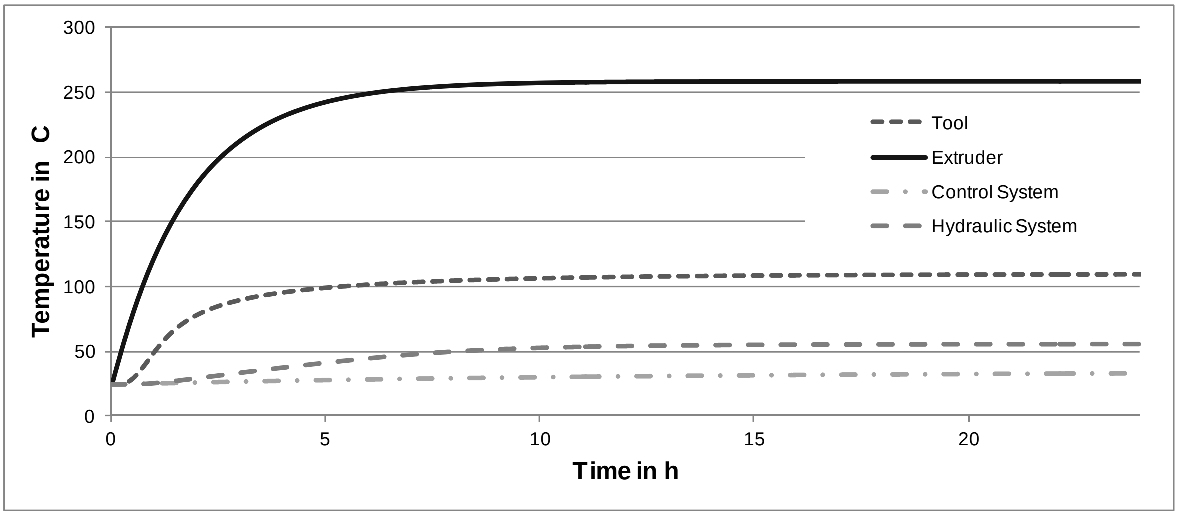

Figure 5. Simulated temperature cycles of an injection moulding machine, divided into four assembly groups.

linking of the described individual module with further components is necessary. In many production halls, for example, a surplus of heat is present due to the waste heat emitted by the machines.

Due to a temporal shift between the heat supplied within the room and the heat needed, significant thermal energy losses often occur. Furthermore, employees are often confronted with cold machines, production and offices after long switch-off periods.

A simulation conducted within the scope of this contribution compares three different heating scenarios within a plastics processing facility.

Additionally, the production plant houses injection moulding machines, which require a combined peak cooling power of about 100 kW. Due to the available thermal energy, heating the production rooms is rarely necessary. The basic approach to this is the use of waste heat for the heating of offices. An example of a building with an area of 420 m² at a room height of 2.50 m is used to demonstrate the possibilities. Production occurs in two shifts between 06:00 and 22:00, excluding Saturdays and Sundays, in order to only make the direct use of waste heat possible in this time frame. Within the simulation, an efficiency factor of 36.1 % is estimated for the transformation of primary energy into electricity [8], while an efficiency factor of 84 % is estimated for the energy chain of the natural gas necessary for the heating process. The actual state assumes a constant regulation of the room temperature at 20 °C.

In the first scenario, a night mode is implemented - in other words, the temperature outside of the operating times has to be at least 16 °C.

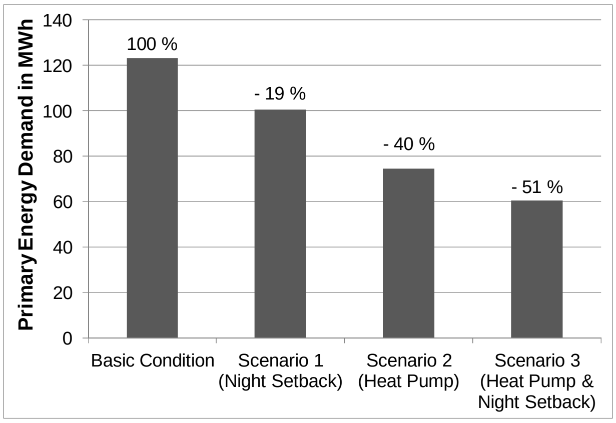

Figure 6. Primary energy demand for heating of a production hall.

In the second scenario, production management uses a heat pump, which uses energy derived from the cooling water of the injection moulding machine. During the day, this heat pump services a thermal energy storage device, while at night it releases its heat to the premises.

The third scenario combines the use of a heat pump in conjunction with the night mode. This process helps in lowering the cooling demands through the use of a heat exchange unit, which, in turn, entails limited electric energy savings. The simulation shows that using the night mode alone would help in saving around 19 % of primary energy and CO_2. Through the use of a thermal energy saving device and a heat pump, the factory can lower the primary energy demand by about 40 %. A combination of both optimisation approaches, however, will result in a saving of over 50 %, as shown in Figure 6.

4 Conclusion

The simulation of thermal processes within machines and consequently in production halls is still in its infancy. The node model shows that through the energetic interlinking of individual systems, complex thermal processes may be depicted in a sufficiently realistic manner.

The node model also represents an important basis for determining necessary cooling and heating capacities as well as room temperature peaks. Especially in the case of unsteady operating conditions (i.e. heating up a room on Monday mornings during wintertime), it provides important information for the layout of heating, ventilation, and air-conditioning technologies. Besides these layouts, both models and associated simulation runs may help assess the practicality of saving and recycling thermal energy. While conventional calculations may show that energy can be saved [9], employing the aforementioned node model may offer an additional dynamic view from the process to the production plant. The model of the cold-storage facility helps to determine the refrigerated goods' thermal properties depending on different operational stages.

This may allow, for example, the energy cost-driven operation of cold-storage facilities. The example of the synthetics plant has shown that businesses should, from a primary energy and finance-related standpoint, try to recycle their incidental waste heat for internal purposes. This may contribute to relieving the strain on existing heating systems.

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