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Applying Energy Building Simulation in the Assessment of Energy Efficiency Measures in Factories

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Abstract

Manufacturing companies have been putting considerable effort in the implementation of energy efficiency measures since many years. By doing so they have been able to reduce energy consumption and increase productivity pursuing sustainable manufacturing practices. However, it has become more and more challenging to identify future energy efficiency measures, which meet the required cost-benefit ratio. The objective of this research is to improve prevailing methodologies used in the assessment of energy efficiency measures. Therefore we augment the system boundaries to the factory level and introduce a methodology that involves energy building simulation. Results show that the methodology proposed herein allows to quantify the propagating effects of singular energy efficiency measures within the factory environment. Besides, the consideration of non-energy benefits (e.g. thermal comfort) becomes possible. Being able to assess the multiple effects of energy efficiency measures is an important step towards the continuous improvement of energy efficiency in factories.

Keywords: energy efficiency; energy building simulation; non-energy benefits; internal heat gains; factories; manufacturing

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1. Introduction and Objective

1.1. Motivation and Problem

Reducing energy consumption by implementing energy efficiency measures has become a broadly adopted practice among manufacturing companies worldwide [1]. However, after having successfully implemented measures such as energy efficient lighting, isolation of thermal processes or fixing compressed-air leakages, the assessment of next level energy efficiency measures becomes increasingly challenging [2]. Researchers identified several barriers preventing the continuous improvement of energy efficiency in industry, stating that the lack of information on quantifiable benefits is a major problem [3, 4].

Identifying new opportunities for energy savings requires a sound understanding, not only of single processes, but also of the associated energy-relevant interactions within the process and factory infrastructure [5]. For that reason interconnections require detailed consideration, especially since the effects of singular measures are propagated across the factory environment [6].

1.2. Objective

The main objective of this research is to foster the implementation of future energy efficiency measures through the improvement of prevailing assessment methodologies.

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1.3. Scope

Schlüter and Rosano for example already expressed the need to evaluate energy efficiency measures in a more holistic manner and presented a strategy for plastic processing plants [6]. Hesselbach et al. also suggested the coupling of different simulation environments in order to assess energy consumption in a more holistic manner [7]. Here we build upon the findings and present a methodology that augments conventional system boundaries from component or machine level to factory level (Fig. 1). The aim is to consider interconnections between machine operation, process and factory infrastructure including also non-energy benefits such as thermal comfort. We specifically address factory environments that use heating, ventilation and air-conditioning (HVAC) systems or production facilities that evaluate the retrofitting of such a system, since these technical building systems are generally associated with major investment and operating costs [8].

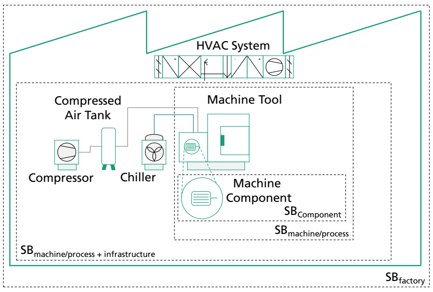

Fig. 1: Different system boundaries in a factory

In the next section we present specific findings on requirements and challenges associated with the implementation of energy efficiency measures in factories. In this context a specific focus is drawn on the operation of HVAC systems. The insights were derived from factory tours and expert interviews at an automotive supplier, an aerospace supplier, a circuit board, a carbide and a milling tool manufacturer.

1.4. Specific requirements and challenges

Costumers of manufacturing companies request narrow tolerances for indoor air-conditioning due to product quality requirements. Besides, constant indoor climate conditions are necessary in order to prevent machine failure, reduce operational standstill and production waste. From an occupational safety perspective, indoor temperature, humidity and air flow have to comply with standards set for example in BGI 7003, ASR A3.5 [9, 10].

A major challenge associated with the implementation of energy efficiency measures in companies is a decision-making practice that focuses on payback period instead of factory life cycle costs. Furthermore energy demand calculations for non-residential buildings according to standards set in DIN V 18599 and VDI 2078 lack informative value and their application to factory buildings is limited [11, 12]. This is due to the fact that energy relevant characteristics of the underlying manufacturing operations (including utilization rate, internal heat gains, shifts system etc.) are not sufficiently represented. Consequently, the assessment of energy efficiency measures at the interface between manufacturing operations and building energy consumption today is restricted. Furthermore, a sound basis to support investment decisions into the energy efficient design of factory buildings and their associated infrastructure is not available.

Lastly, the nonexistence of consistent measurement concept including the required number of metering points prevent a holistic assessment and make measurement projects difficult and costly to conduct. This is especially true for existing facilities with organically developed machine parks and building infrastructures that imply proprietary measurement and monitoring systems both at machine and building system level.

2. State of research

2.1. Factory life cycle and non-energy benefits

The consideration of energy aspects during a factory life cycle (Fig. 2) and within the related planning activities such as green and brownfield planning, tuning and adoption (including the implementation of energy efficiency measures) is motivated by the prospect to reduce investment and operating costs.

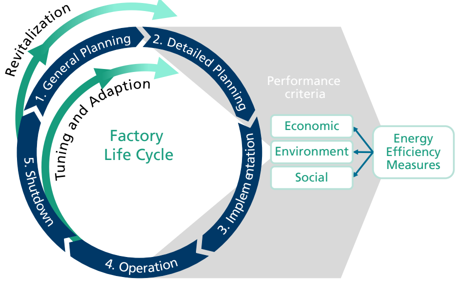

Fig. 2 The factory life cycle (own illustration adapted from [13])

Besides, non-energy benefits need to be considered. They have shown to be able to outperform conventional savings related to investment and operating cost. Furthermore, their consideration can improve the cost-effectiveness of energy efficiency measures and therefore promote their implementation [3, 14, 15].

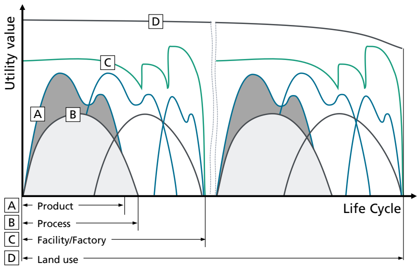

Fig. 3: Comparing different life cycles and their respective utility value [16]

Flexibility represents a competitive advantage in case that costumer needs, markets and products change. Picturing the different characteristics of product-, process- and factory life cycles (ref. Fig. 3Fig. 3), flexibility, reconfigurability and transformability of workstations, manufacturing processes and their associated facilities represent an important planning premise [17, 18]. Life cycle considerations imply a long-term perspective and can shade light on the effects of complex planning decision considering different performance criteria [13, 19]. The disadvantages and limitations of life cycle analysis are the underlying assumptions on the probabilities of occurrence of future events. This can only be partly solved by the development of scenarios [20].

Given the afore mentioned, we cluster the performance criteria of energy efficiency measures according to the triple-bottom-line economic – environment – social (Fig. 4)

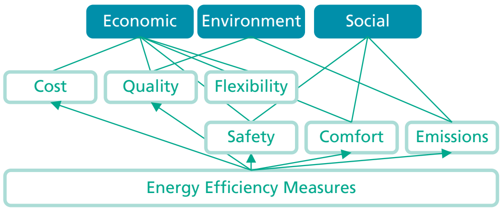

Fig. 4 Performance criteria of energy efficiency measures including non-energy benefits

2.2. Energy building simulation (EBS)

Among architects and civil engineers computer simulation (incl. energy building simulation) is considered a valuable tool to improve life cycle costs in houses and commercial buildings. Besides indoor air quality and other comfort criteria can be assessed during early design stages (Fig. 5) [21].

Computer simulation also offers the possibility to assess alternative building designs and control strategies of technical building systems as well as running multi-objective-optimizations according to predefined criteria [22].

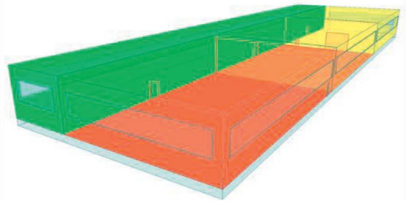

Fig. 5: Zone model of factory building including colour coded visualization of indoor temperature

Though different approaches to apply computer simulation in the design of factories can be found in scientific literature [23-26], its use in planning practices is still underrepresented and further evaluation is required. One particular example is the investigation of the relationship between energy consumption for machine operation, auxiliary processes and the technical building infrastructure. Further insights into state-of-art approaches on how to apply computer simulation in the manufacturing context can be found in [27]. In this research we use the simulation environment IDA ICE due to its equation-based approach and the easy-to-use interface.

2.3. Internal heat gains from machine operation

Table 1 shows an existing guideline on how to consider internal heat gains from machine operation. For the specific case of forming processes the standard VDI 3082 suggest to consider a value between 100 – 200 W/m² or 15% – 20% of the installed machine load as internal heat gains [28].

Table 1: Guideline for heat gains caused by machine operation [29]

State of machine	Example	Heat releases as % of installed load
Machine standby	Main switch turned on	5%
Machine ready	Ready for operation	10%
Machine operation	Temporary max. load	20%

3. Methodology

In Fig. 6 we propose a procedure model on how to integrate energy building simulation during energy related planning and evaluation activities (including the assessment of energy efficiency measures) in factories.

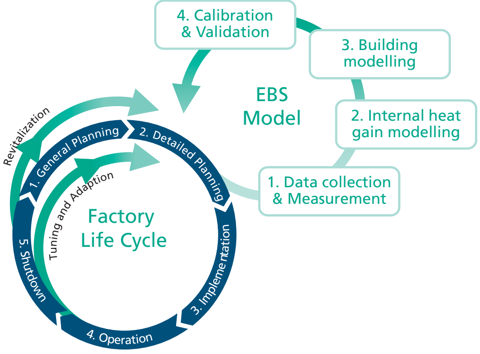

Fig. 6 Applying energy building simulation during planning and evaluation of energy efficiency measures

The consecutive steps are data collection, internal heat gains and building modelling, model calibration and validation. The results obtained are quantified energy savings effects at factory level (including non-energy benefits) due to the implementation of energy efficiency measures.

3.1. Modelling internal heat gains from machine operation

In order to represent the inner load characteristics caused by machine operations more accurately, a thermodynamic model based on the finding of Schlüter et al. [30] was adopted (Fig. 7).

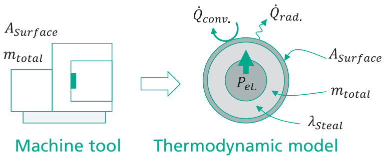

Fig. 7 Abstraction of manufacturing processes in a thermodynamic model

Based on the model, available input data (e.g. electric power consumption) of an arbitrary manufacturing process (e.g. machine tools, hardening furnaces etc.) can be translated into a heat release curves that represent the thermodynamic behaviour (e.g. thermal inertia).

Eq. (1) represents the thermal balance equation at the level of the machine housing. Eq. (2) describes the thermal mass of the manufacturing process.

$$\dot{Q}_{mach.}(t) = P_{elec.}(t) - \left(\dot{Q}_{conv.}(t) + \dot{Q}_{rad.}(t)\right) \quad (1)$$

$$\dot{Q}_{mach.}(t) = m \cdot c_p \cdot \frac{dT_{surf.}(t)}{dt} \quad (2)$$

The differential equation derived from solving Eqs. (1) and (2) can be approximated by Eq. (3) resulting in Eq. (4).

$$T_{surf.}(t + \Delta t) = T_{surf.}(t) + \frac{dT_{surf.}(t)}{dt} \cdot \Delta t \quad (3)$$

$$T_{surf.}(t + \Delta t) = T_{surf.}(t) + \frac{P_{elec.}(t) - \left(\dot{Q}_{conv.}(t) + \dot{Q}_{rad.}(t)\right)}{m \cdot c_p} \cdot \Delta t \quad (4)$$

Depending on the availability of measurement data and their temporal resolution, batch protocols, including temperature profiles or electric load profiles can serve as valuable input data. Eq. (7) follows from using (4) with Eqs. (5) and (6).

$$\dot{Q}_{conv.}(t) = \alpha \cdot A_{surf.} \cdot \left(T_{surf.}(t) - T_{env.}\right) \quad (5)$$

$$\dot{Q}_{rad.}(t) = \varepsilon \cdot \sigma \cdot A_{surf.} \cdot \left(T_{surf.}^4(t) - T_{env.}^4\right) \quad (6)$$

$$m \cdot c_p \cdot \frac{dT_{surf.}(t)}{dt} = P_{elec.}(t) - \alpha \cdot A_s \cdot \left(T_{surf.}(t) - T_{env.}\right) - \varepsilon \cdot \sigma \cdot A_s \cdot \left(T_{surf.}^4(t) - T_{env.}^4\right) \quad (7)$$

The model considers the assumptions and simplifications shown in Table 2.

Table 2: Model assumptions and simplification

Assumptions
• 100% of measured/effective electric power $P_{elec.}(t)$ is transformed into thermal energy
• The machine material composition is homogeneous and steal
Simplification
• The temperature $T_{env.}$ in the zone is constant
• The heat capacity of the machine material composition c_p, thermal conductivity λ, heat transfer coefficient α and the emissivity ε are constant and not temperature-dependent.

3.2. Calibration and validation of model performance

The validation of the calibrated simulation model is conducted based on statistical indices suggested in literature, mean bias error (MBR) (8) and coefficient of variation of root mean square error CV(RMSE) (9) [31].

$$MBR\ [\%] = \frac{\sum_{i=1}^{N}(m_i - s_i)}{\sum_{i=1}^{N} m_i} \quad (8)$$

$$CV\ RMSE\ [\%] = \frac{\sqrt{\frac{\sum_{i=1}^{N}(m_i - s_i)^2}{N}}}{\bar{m}} \quad (9)$$

Both indices show the bias between measured and calculated values. Whereby, the advantage of CV RMSE over MBR is that no cancellation effects (positive bias compensates for negative bias) occur. Table 3 gives an overview on different performance criteria set in standards and guidelines.

Table 3: Acceptance criteria for calibration of models [31]

Standard/guideline	Monthly criteria (%) $N = 12$		Hourly criteria (%) $N = 8760$	
	MBE	CV RMSE	MBE	CV RMSE
ASHRAE Guideline (2002)	*5*	*15*	*10*	30
Efficiency Valuation Organization (2002)	*20*	-	*5*	20
U.S. Department of Energy (2015)	*5*	*15*	*10*	30

3.3. Non-energy benefits – Building comfort criteria

In this research the thermal comfort was assessed based on the criteria predicted mean vote (PMV) and the related percentage of dissatisfied (PPD). For the evaluation of thermal comfort we considered a metabolic rate of occupants to be 2 Met representing activities that involve movement, walking, lifting heavy loads or operating machinery. [32]

4. Results and Discussion

The procedure model was applied in a manufacturing company in south-eastern Germany. The objective of the case-study was to analyse different drive technologies (hydraulic vs. electric) used in forming processes[1] and assess their impact on total energy demand considering also the related process and building infrastructure. The indoor climate conditions of the associated factory zone (floor plan area equal to 224 m², room height: 5.2 m) are controlled by a central HVAC system with evaporation humidifier. The temperature and humidity setpoints are 22°C and 40%. The air exchange rate varies between a min. of 3 and a max. of 6 times per hour. Power measurements were conducted using mobile metering equipment during a period of two weeks (Fig. 8)

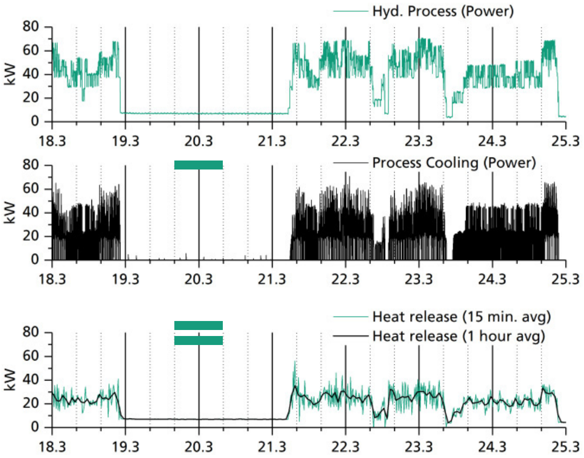

Fig. 8 Electric load curve (week) and resulting heat release and zone

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[1] Previous studies at machine level revealed saving potentials of up to 90% comparing the electric power consumption of a hydraulic to a servo-electric forming process of equal performance.

Energy meters were used in order to characterize the load profiles of three hydraulically driven machine tools located in the zone. The heat discharged by the central process cooling unit was measured with a clamp-on ultrasonic flow meter. Additionally, indoor and outdoor temperature were recorded for the same period.

Subsequently the derived load profile was translated using the thermodynamic model for internal heat gains presented in 2.3. The models performance is shown in Fig. 9. The authors acknowledge that the model requires further evaluation. Yet, due to the consideration of thermal mass and thermal inertia it was possible to increase the model accuracy and increase the stability of the simulation.

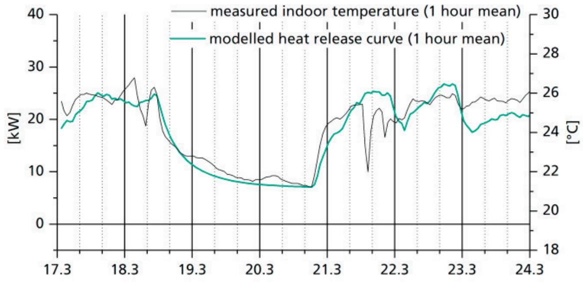

Fig. 9 Modelled heat release curve and measured indoor temperature

After implementing the heat release curve in IDA ICE the building model was validated according to the acceptance criteria from ASHRAE and U.S. Department of Energy shown in section 3.2. - Table 3. Given the two-week measurement period the criteria were adapted assuming a linear correlation between acceptance criteria and measurement points. Based on 1 hour average and $N = 336$ MBE $\leq$ 0.4% and CV RMSE $\leq$ 1.2% indicate good calibration of the simulation model. In the presented case study the variation is MBE 0.04% and CV RMSE 0.08%.

Next, a simulation for a full year was performed. For that purpose it was assumed that the load characteristics from the two-week measurement period (three shifts, no production on weekends and national holidays) are representative for the whole year (Fig. 10). Though load profiles vary depending on customer demand and machine utilization this assumption can be considered a baseline scenario.

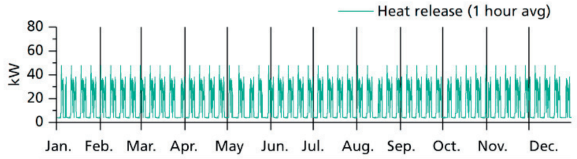

Fig. 10 Heat release from machine operation into factory zone (year)

The first simulation results underline the necessity to specify the heat release from machine operation by measurement data. Fig. 11 shows the results for maximum installed cooling capacity and annual energy demand. Comparing guideline values from section 2.3 to measured and modelled heat release curves, it is found that the derived maximum installed cooling capacity and the annual energy demand are either over- (6% and 24%) or underestimated (15% and 13%). We conclude that specifying internal heat gains increases the quality and reliability of simulation results. This helps planners to reduce safety margins in the design and prevent efficiency losses during partial-load operation of overdimensioned equipment .

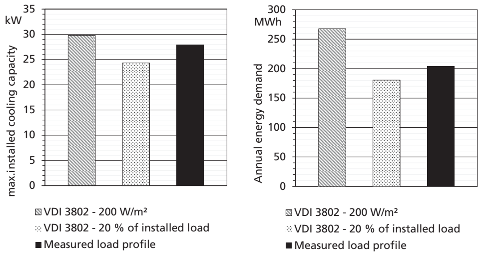

Fig. 11 Comparing different approaches to consider internal heat gains

The second simulation considers four different scenarios comparing a hydraulically (1. with/ 2. without standby switch off) to an electrically (3. with/ 4. without standby switch off) driven forming processes. Fig. 12 shows the energy consumption of the process and the related process and building infrastructure.

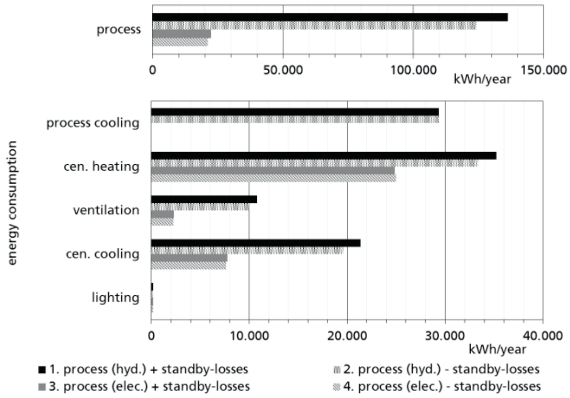

Fig. 12 Composition of energy consumption

Augmenting system boundaries from machine to factory level shows that the propagating effects of energy efficiency measures in the factory infrastructure represent up to 35% of the total energy savings per year (Fig. 13).

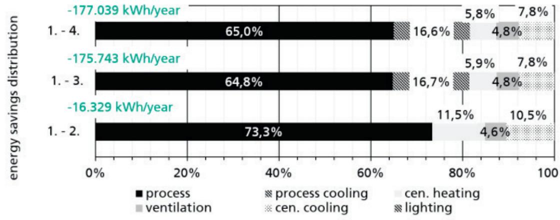

Fig. 13 Distribution of total energy savings

From a life cycle perspective (15 years) a total of 225.000 € (net-present-value – discount rate 6%) and 1780 t/CO$_2$ can be saved during an average operation phase of 15 years (Fig. 14). Lastly, the non-energy benefits are listed in Table 4. showing that PPD can be reduced by 5% (1. – 4.) and the percentage of hours when operative temperature is above 27°C by 13% (1. – 4.).

Reduced maintenance costs are another non-energy benefit derived from choosing an electric over a hydraulic drive system since leakage tests are not required and hydraulic fluids do not need to be exchanged.

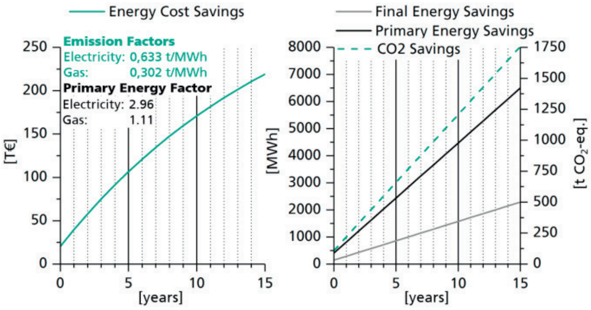

Fig. 14 Life cycle perspective on operating costs and CO_2 savings

Table 4: Evaluation of comfort criteria for the presented scenarios

Criteria Cases	PPD, Predicted Percentage of Dissatisfied	Percentage of hours when operative temperature is above 27°C in the worst zone
1 and 2	11%	13%
3 and 4	6%	0%

5. Conclusion and Outlook

Energy building simulation has proven to be a valuable tool in the evaluation of energy efficiency measures. It assists in order to derive the true impact of an optimization measure considering different domains (machine, auxiliary processes and technical building systems) including also non-energy benefits. Future research will focus on reducing the costs for data acquisition, modelling and linkage of process and building control systems thus enabling data-driven autonomous optimization of factory environments.

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