Concurrent consideration of production processes and building properties for the design of energy-efficient industrial facilities

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ABSTRACT

In the past, the main concern of manufacturing companies was increasing the productivity, reliability, flexibility, and quality of the industrial process. More recently, the energy efficiency of the production process and buildings has become under scrutiny. To enhance the energy efficiency of production facilities, detailed information regarding the production processes, heat emissions from machines, operation level, etc. are necessary. In this context, the present paper describes an ongoing research effort that aims to develop a systemically integrated model of an energy efficient production facility. As a starting point for the inquiry, the case of a new building design for an existing industrial production facility was selected. Toward this end, the existing facility was analyzed. Measurements of the heat emissions from the machines were conducted over a period of multiple weeks. The collected information was further processed to develop an adequate layout for the new building solution. This layout provides the basis for the initial building performance simulation model. The generated model is used to address the impact of different design and operation options on the indoor climate, comfort ramifications (thermal and visual), and energy performance of the industrial facility.

1. Introduction

Increasing energy prices and environmental challenges critically affect the overall economic efficiency of manufacturing companies. Whereas in the past the main concern was increasing the productivity, reliability, flexibility, and quality of the industrial process, more recently the energy efficiency of the production process as well as the energy efficiency of the production buildings has become under scrutiny. To enhance the energy efficiency of production facilities, detailed information regarding the production processes, heat emissions from machines, operation level, etc. are necessary. There are a few studies, which deal with energy efficient manufacturing (e.g. Herrmann and Thiede 2009, Oates et al. 2011, Despeisse et al. 2011). However, they usually do not take the interrelationships between industrial production equipment and processes and the thermal behavior of buildings into account.

In this context, the present paper describes an ongoing research effort (INFO 2011) that aims to develop a systemically integrated model of an energy efficient production facility. Thereby, representations of individual equipment and their combination in terms of the entire industrial production must be aligned with the spatial arrangement and architectural embodiment of the process.

2. Method

As a starting point for the inquiry, the case of a new building design for an existing industrial production facility was selected. Toward this end, the existing facility was analyzed in terms of work flows (delivery, storage, and production), energy flows, emissions (oil, dust, humidity, noise, and heat losses), and occupancy parameters (working hours and shifts for offices and production). Measurements of the heat emissions from the machines (lasers, machine centers, etc.) were conducted over a period of multiple weeks. The collected information was further processed to develop an adequate layout for the new building solution. This layout provides the basis for the initial building performance simulation model. The generated model is used to address the impact of different design options (façade types, window to wall ratio, roof options, HVAC systems, etc.) and building operation options (ventilation strategies, window shading, lighting control, etc.) on the indoor climate, comfort ramifications (thermal and visual), and energy performance of the industrial facility. The predicted implications of these options (specified in terms of scenarios) for savings in building's heating and cooling demand can be thus evaluated and compared with possible higher investment costs. The initial results show the potential in reduction of heating and cooling loads of the aforementioned production facility via the proper configuration of building design features.

2.1 Analysis of an existing production facility

Within the research project "INFO" (INFO 2011, Dorn et al. 2011), an existing production facility in the area of metal working has been analyzed. Data regarding the production process such as machines deployed, occupancy, working shifts, and operating schedules, electricity use, and production output were collected. Since detailed information regarding heat emissions from machines is necessary toward provision of input information for energy efficiency measures, heat emissions by various industrial equipment were measured. Power measurements were performed in the main control box. Thus, all components connected to the main electric supply could be captured. Measurements of single components that were of particular interest were also taken. The measurement principle is shown in Figure 1.

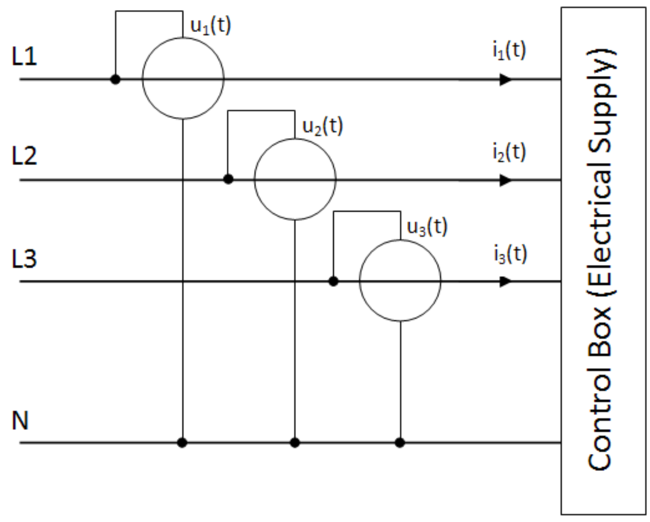

Fig. 1 Measurement setup for heat emissions from machines

The data is generated by simultaneous measurements of the current and voltage of all three phases. The time resolution of these measurements was 50 ms, allowing the generation of reliable data for acceleration and deceleration peaks, which tend to be very short-duration signals. The analysis of these measurements allowed us to determine the energy demand of machines, as shown for the example of Figure 2.

The base load is the energy that is required to sustain the machine even when it is not operating. The variable load is, in this case, due to the cutting process and is dependent on the specific energy requirement to perform the cut. Most of the electrical energy that is required by a production machine is transformed into heat, since energy cannot be stored within the machine. This transformation occurs along the components of the power train, the supply of auxiliary equipment for work piece handling, cutting fluid handling, tool changers, the chip handling system, and in the chip formation itself (Figure 3).

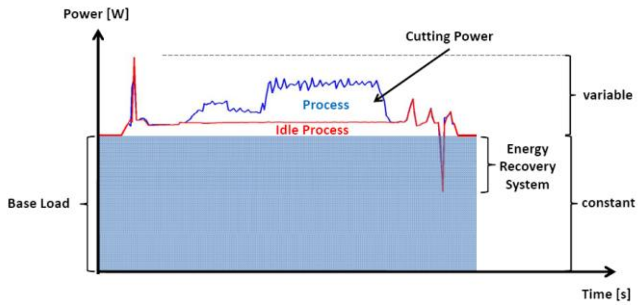

Fig. 2 Example of power use behavior of a specific machine over time

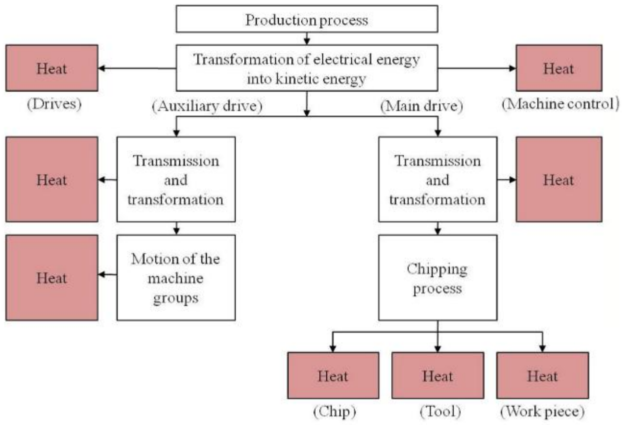

Fig. 3 Thermal transformation of machine components (Gleich 2008)

Previous studies suggest that the net energy of chip formation comprises approximately 5 to 20% of the overall energy consumption (Bleicher et al. 2010). Furthermore, it can be assumed that between 70 and 97% of the total net energy for the chipping process is converted into heat at the chip formation zones, due to deformation and friction processes. The remaining energy fraction consists of the plastic work associated with the chip removal process. The build-up of heat takes place at the primary and secondary deformation zones of the chip (Q_{chip}), at the surface of the tool (Q_{tool}), and at the work piece (Q_{wp}). As it can be seen in Fig. 4, the total heat increase caused by the chipping process depends on the cutting parameters (tool material, cutting speed, chipping thickness, chip angle etc.) and can be described as:

$$Q_{total} = Q_{wp} + Q_{tool} + Q_{chip} \qquad (1)$$

The main fraction of the heat is concentrated within the chip itself (Q_{chip}). A detailed analysis of the chipping process therefore requires a further consideration of the specific energy of the chip, which can be divided into four energy fractions related to deformation, friction, material separation, and material deflection.

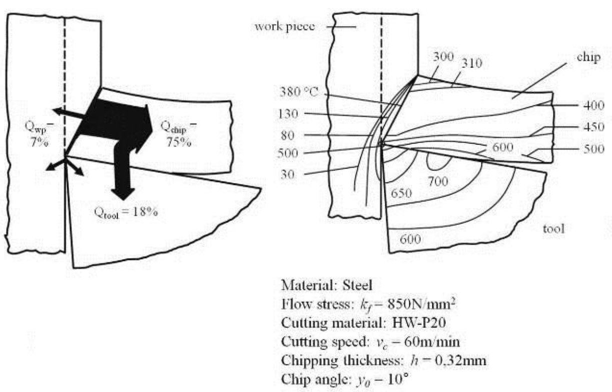

Fig. 4 Thermal behavior of the cutting process (Tönshoff and Denkena 2003)

2.1.1 *Measurements of chipping machines*

Regarding the assessments of determining the amount of heat emissions of machines, electrical power input was measured every second in the distribution box over a period of a week. Figure 5 shows the resulting power [kW] input.

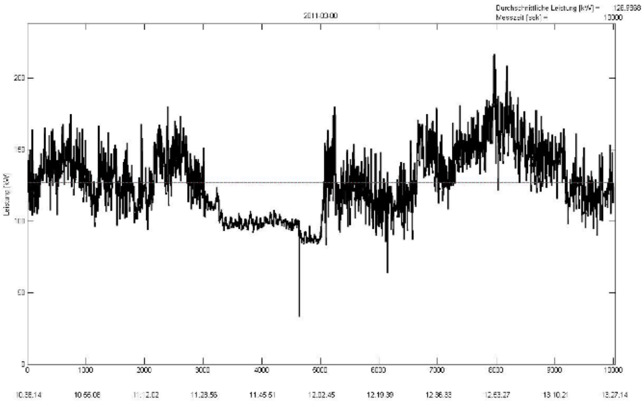

Fig. 5 measurements of chipping machines within a week

The measurement curve displays high fluctuation of the energy input, with values ranging from 90 to 200 kW. The total energy consumption for the measurement week was 13485 kJ resulting in a mean value of 80.3 kW. Since the utilization of the machines during weekend was rather low (displayed in measurement graph), the weighted average of 110 kW was assumed during weekdays and 11 kW during weekend. According to information from the management, the utilization of the production facilities was moderate during the measurement period. Additional measurements will be necessary to determine the energy consumption and hence the heat emission of machines during high utilization periods.

2.1.2 *Measurements of laser cutting-off machines*

To estimate heat emission rates from laser cutting-off machines, an investigation was conducted. Laser-cuting machinery consists of the following components: optical resonator, cooling devices, positioning table, and suction equipment. These components are usually connected to separate power lines due to the high loads necessary for their operation. Since measurements can only be conducted on one power line, the laser cutting machine whose components were all attached to one single supply line was measured. The laser cutting machine has a laser device with a beam power of 3500W, widespread in production engineering. The measured load proves the expected high load during standby, and the relatively uniform energy demand of the laser, which is attributed to the resonator and the necessary energy to keep the gas in an ionized state. Figure 6 shows the performance curve of the laser machine during a period of 3 hours which resulted in a mean value of 112 kW during the measurement period.

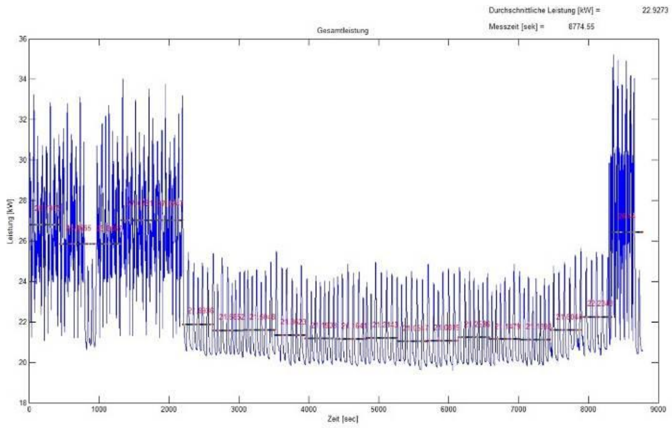

Fig. 6 measurements of a laser cutting-off machine within 3 hours

2.2 New building design

A new building design had to be developed based on collected data and information of the existing industrial facility. The client formulated the following planning aims:

- Maximization of communication between the areas for research and development (R&D) and production hall.
- High flexibility of production areas (modular principle): Due to the flexibility of production process and very short product life cycles, the specialized production areas must be able to adopt new or even completely different functions and uses with a minimum re-fitting effort. For example, the area for metal cutting must be transformable into storage if necessary.
- Expandability of the production facility as well of office and R&D spaces: Since the specific company is constantly growing, the expansion phases have to be considered already in the pre-design. Accordingly, special attention is to be paid to a recyclable and reusable façade.

As a next step, a functional and spatial program (ideal layout), in a form of organigram was developed depicting the areas as well as the relations between spatial units and functions. Finally, a real layout was developed, considering the location and infrastructure together with building orientation and micro-climatic conditions (Figure 7).

Fig. 7 Site plan of the industrial facility

The proposed solution consists of an office block facing north, with the adjacent production hall. The office block with the main entrance for employees and customers is oriented towards the neighborhood. This way, the facility can be conveniently reached from parking spaces and public transportation (underground). At the same time, the production hall is decoupled from the neighborhood, reducing thus the risk of exposure (noise, etc.).

An innovative design aspect may be seen in the introduction of the “bridge”: R&D offices are suspended directly in the production hall, enabling direct visual and – given the short distance – personal connection to the production. Another innovative element is the large patio as the connection between the office block and production hall. The patio is conceptualized as a meeting and communication point and also allows direct visual communication from the main entrance into the production. Next to the patio, the cafeteria is situated. It uses the patio as sitting and serving area. These two units are also useable for events or company presentations.

The flexibility is maximized through the modular construction of 15 x 15 meter modules. Expansion in both east and west directions is possible (Figure 8).

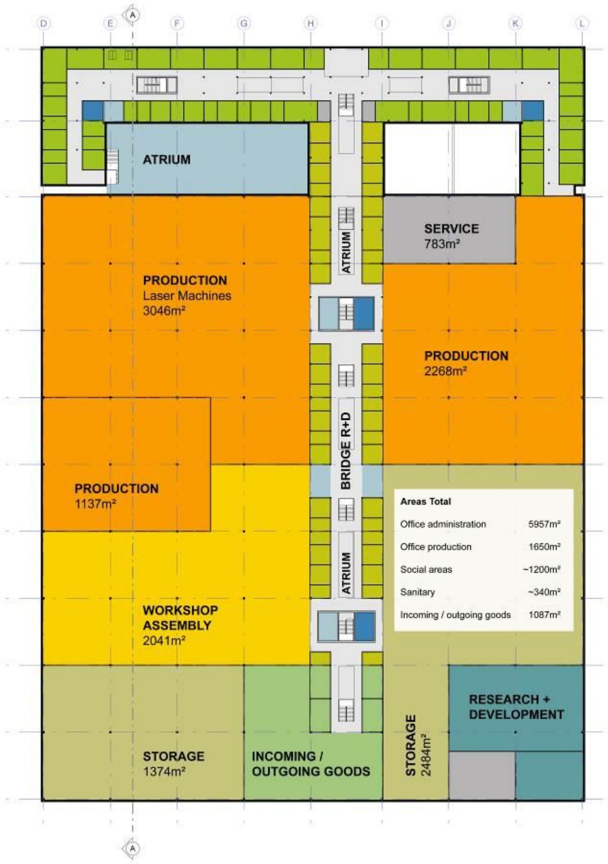

Fig. 8 Floor layout in the new facility design

The shed roof-construction allows good daylight penetration (with less overheating risk) through north-facing glazing, whereas south-facing slopes offer opportunity for PV and solar energy production (Figure 9).

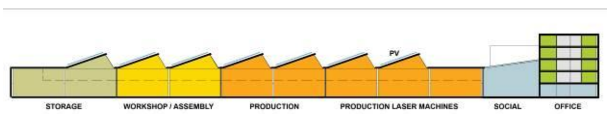

Fig. 9 Longitudinal Section

Small atria throughout the communication bridge could be used as social spaces, but also for night-time cooling. Given this basic design, alternatives are to be explored as follows:

- Different façades (U-values, materials, and vertical versus horizontal glazing).
- Different ceiling heights (8 m, 10 m) to allow flexibility for possible change of use (e.g. storage instead of production) and analyze its impact on indoor climate and energy consumption.
- Different layouts of atria (open versus closed).

2.3 Generation of Simulation model

To illustrate the process, a layout option was developed for the aforementioned model building (see Figure 8). This layout provides the basis of the respective performance simulation model. Toward this end, model input assumptions are made according to the following structure:

1. Geometry and "Semantic" properties of the building elements and components (e.g. thermal conductivity, density, and specific heat capacity of components' constitutive layers).

2. Internal gains, i.e. heat emission rates associated with people, lighting sources, and – particularly important in the present case – machines and devices for industrial production. Typically, there is a lack of empirical information regarding the heat emission associated with industrial machines and processes (together with information regarding the operation schedules of such equipment). These unknown rates, however, have a significant impact on the simulation results (e.g. heating and cooling demands) and must thus be carefully represented in the building simulation models. Thus, in the present study, parametric simulation runs used the measured heat emission rates of the machines (see sections 2.1.1 and 2.1.2).

3. Systems: HVAC (heating, ventilation, and air-conditioning) systems can be modeled at different level of detail and resolution. In the initial optimization phase, such systems may be represented in terms of aggregate efficiency parameters. In a subsequent stage, such systems will be modeled in more detailed.

4. Weather data: To run the simulations, a detailed (hourly) weather file is used (Meteonorm 2010).

For the above mentioned sample building, geometry and construction data provide the basis for the generation of a thermal simulation model (Energy Plus 2011). The industrial facility is assumed to operate in three shifts, namely, shift 1 from 6 am to 2 pm, shift 2 from 2 pm to 10 pm, and shift 3 from 10 pm to 6 am. Assumed input data regarding U-values, maintained illumination levels, and set-point temperatures are summarized in Table 1. The industrial hall was divided into 4 main areas: Area 1 is dedicated to the assembly of the end products. This area is assumed to accommodate small equipment such as drilling machines. In Area 2, six laser machines are accommodated which operate 5 days per week. Area 3 contains production equipment. Area 4 consists of office areas and associated service areas. Figure 10 shows the four areas marked on the floor plan. Heat emission rates were summarized based on the one week of measurement period. The resulting values are summarized in Table 2.

Table 1. Simulation input data pertaining to U-values of constructions, illumination levels and gains, and set-point temperatures.

U-value roof [$W.m^{-2}.K^{-1}$]	0.2
U-value floor [$W.m^{-2}.K^{-1}$]	0.26
U-value window [$W.m^{-2}.K^{-1}$]	1.6
U-value roof lights [$W.m^{-2}.K^{-1}$]	1.3
Maintained illumination level [lx]	250
Internal gains (lighting) [$W.m^{-2}$]	12
Set-point heating during occupancy [°C]	18
Set-point heating set back [°C]	12
Set-point cooling during occupancy [°C]	28
Set-point cooling set back [°C]	32

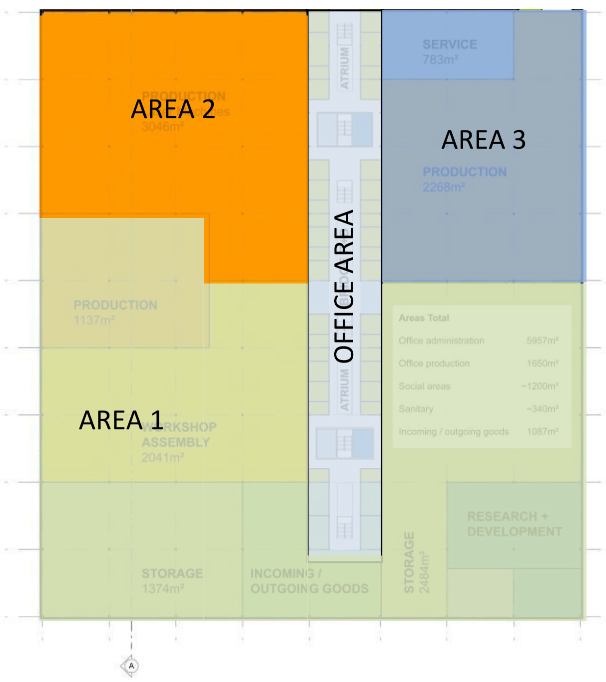

Fig. 10 Plan of the industrial facility

Table 2. Simulation input data pertaining to internal gains and occupancy

Area		Area 1	Area 2	Area 3	Office area
Area [m²]		9095	3026	2252	3312
Nr. of zones		7	1	1	2
Hours of operation per day		24 h	24 h	24 h	12 h
Heat emission rates [$W.m^{-2}$]	week-days	10	37	49	15
	week-end	10	0	5	0
Area per person [m²]		100	1000	100	10
Description		workshop	laser machines	machine centres	office

2.4 Simulation scenarios

Parametric simulations were conducted to compute the relative impact of various options (differences in the energy demand of the industrial facility). Such options included façade type, glazing area, shading, lighting control, and natural ventilation. Accordingly, a number of scenarios were generated, as summarized in Table 3. These scenarios differ in terms of façade type, window area (in terms of the percentage of glazing in the façade), the assumed air change rate (with effective air change rates ranging from 0.2 to 1 h^{-1}), as well as the presence or absence of lighting and shading controls. The lighting control scheme operates the electric lights according to the availability of daylight, and maintains an indoor illumination level of 250 lx. The shading control option operates the shades once the incident irradiance on the façade goes beyond 120 $W.m^{-2}$. Descriptions of different façade types are summarized in Table 4.

Table 3. Scenarios for simulation runs

	facade type	percentage of glazing [%]	additional polycarbonat [%]	ACH [h^{-1}] Summer	ACH [h^{-1}] Winter	Lighting control	Shading
S1	A	10	-	1	0.2	YES	YES
S2	A	15	-	1	0.2	YES	YES
S3	A	20		1	0.2	YES	YES
S4	A	10	25	1	0.2	YES	YES
S5	A	10		1	0.2	NO	NO
S6	A	15		1	0.2	NO	NO
S7	A	20		1	0.2	NO	NO
S8	A	10	25	1	0.2	NO	NO
S9	B	15		1	0.2	YES	YES
S10	B	15		1	0.2	NO	NO
S11	C	15		1	0.2	YES	YES
S12	C	15		1	0.2	NO	NO
S13	C	15		0.5	0.5	NO	NO
S14	C	15		0.2	0.2	NO	NO
S15	C	15		0.5	0.2	NO	NO
S16	C	15		1	0.2	YES	NO
S17	C	15		1	0.2	NO	YES

Table 4. Variation of façade options

Façade type	Exterior panel	Insulation	U-value [$W.m^{-2}.K^{-1}$]
A	Metal	Mineral wool	0.26
B	Metal (zinc coated)	Polyurethane foam	0.1
C	Metal (zinc coated)	Wood fiber insulation panel	0.27

3. Results and Discussion

Figures 11 and 12 show the simulated annual cooling and heating loads [$kWh.m^{-2}.a^{-1}$] for all scenarios (as per Table 3).

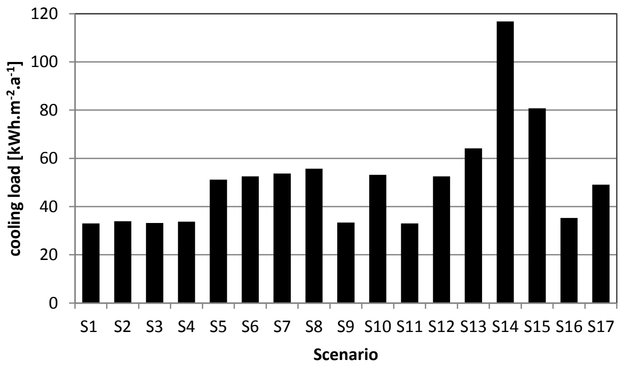

Fig. 11 Simulated annual cooling load (area 1-3) for all scenarios [$kWh.m^{-2}.a^{-1}$]

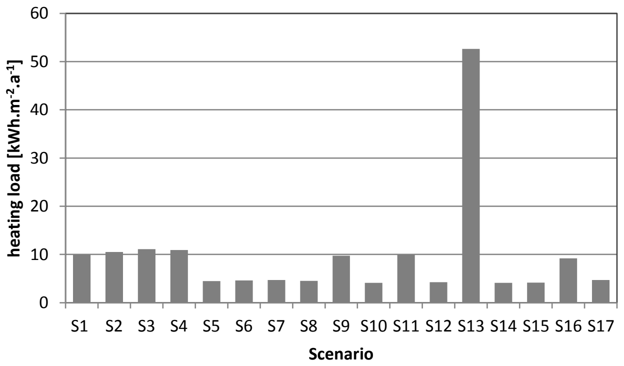

Fig. 12 Simulated annual heating load (area 1-3) for selected scenarios [$kWh.m^{-2}.a^{-1}$]

The simulation results lead to a number of observations:

- Comparison of different glazing percentages in the façade does not show significant differences in terms of cooling and heating loads. For example, scenarios S1 (10%) and S2 (15%) display similar loads. Likewise, scenarios S5 (10%) and S8 (10% glazing and 25% PC) are rather similar in view of the resulting loads. The same holds true for different façade types (S2, S9, and S11), as they do not display noteworthy differences in terms of cooling and heating loads. This is in part due to the building's high compactness and high internal loads.
- Higher ventilation rates in winter result in high heating loads. An increase in the air change rate from 0.2 h^{-1} (S12) to 0.5 h^{-1} (S13) resulted in a heating load increase of approximately 50 $kWh.m^{-2}.a^{-1}$. However, lower ventilation rates result in an increase in cooling loads (scenarios S13 and S14). Scenario 12 (with low ventilation rates in winter and high ventilation rates in summer) displays both a considerable heating load reduction and a modest reduction of the cooling load.
- Scenario S16 with the lighting control feature reduces internal gains due to lighting, thus reducing cooling load and increasing heating load. Additionally, the scenario shows that, in this case, energy demand for lighting could be reduced by 38% if proper lighting control measures are implemented.
- Automated operation of external shading reduces solar gains and thus results in a slight cooling load reduction. The best performing scenarios in the present study are S9 and S11, which combine features such as lighting and shading control together with effective ventilation regimes, reducing thus both heating and cooling demand.

These results display the potential of building design and operation optimization via parametric simulation-assisted analysis of candidate designs and available technological alternatives.

4. Conclusion

This paper presented the preliminary results of an integrated simulation approach within the ongoing research project "INFO". The project background, scope, and challenges were discussed. As a partial contribution, the impact of different design and operational options (e.g. ventilation rates, lighting and shading control) on the indoor climate and energy performance of an industrial facility was specifically explored via parametric simulation runs. Results show, that cooling loads are in this case more pronounced than heating loads, which is caused mainly by high heat emission rates from machines during the production processes. On the other hand, scenarios pertaining to different façade types did not show a noteworthy impact on the thermal performance of the industrial facility. The results underline the importance of effective operation regimes (for lighting, shading, and ventilation system). Moreover, the research underlines the importance of empirical information concerning heat emission from production machines and the associated operation schedules for a reliable simulation-based assessment of industrial buildings' energy and indoor environmental performance.

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References

Bleicher F., Dorn C., Renger U. 2010. Untersuchungen zur Energieeffizienz von Werkzeugmaschinen, Tagungsband Industrielles Symposium Mechatronik, Linz.

Despeisse M., Ball P., and Evans S., 2011. Design of tactics for sustainable manufacturing. in: Proceedings of the 1st international conference on sustainable intelligent manufacturing, June 28-July 1, 2011. Leiria, Portugal.

Dorn C., Kovacic I., Orehounig K., Oberwinter L., Bleicher F., and Mahdavi A., 2011. Energy Efficient Production – Interdisciplinary, Systemic Approach through Integrated Simulation, in: "*Sustainable Development Of Energy, Water And Environment Systems,* Croatia, Zagreb, Paper-Nr. 430, 13 S.

Energyplus 2011. Energy Simulation software, http://apps1.eere.energy.gov/buildings/energyplus/, last accessed October 2011.

Gleich S. 2008. Simulation des thermischen Verhaltens spanender Werkzeugmaschinen in der Entwurfsphase, Dissertation, Chemnitz.

Herrmann, C., and Thiede, S., 2009. Process chain simulation to foster energy efficiency in manufacturing. *CIRP Journal of Manufacturing Science and Technology*, Vol. 1, No.4, pp.221-229, 2009.

Info-Project 2011. Interdisziplinäre Forschung zur Energieoptimierung in Fertigungsbetrieben http://www.projekt-info.org

Meteonorm 2010. Global Meteorological Database, Version 6.1. www.meteonorm.com

Oates M. R., Wright A., Greenough R., Shao L., 2011. Understanding resource flows in a factory, international conference on sustainable intelligent manufacturing environment – a graphical approach, in: Proceedings of the 1st international conference on sustainable intelligent manufacturing, June 28-July 1, 2011. Leiria, Portugal.

Tönshoff H. K., and Denkena B., 2003. Spanen, Springer Verlag, Berlin.