Energy Efficiency Measures for Existing Factory Buildings

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Abstract

To contribute to carbon neutrality, energy efficiency measures in existing factories must be evaluated holistically, considering not only production and technical building equipment but also the building itself. In this study, a package is introduced as part of a simulation library which aims to identify integrated energy efficiency measures. The package enables the user to simulate building related efficiency measures independently or combined with machines and technical building equipment. Special focus is placed on the efficiency measure hereafter referred to as enclosure, which designates a thermally activated construction around a number of machines to facilitate the capturing of waste heat emitted to the ambient air. A comparison with measured data shows a good agreement of the return temperature for stationary conditions. Furthermore an application example for the package is given.

Keywords: building stock, refurbishment, TABS, industrial buildings, energy system optimization

1 Introduction

The goal of the *European Green Deal* adopted in 2019 is to achieve carbon neutrality in Europe by 2050 (Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung 2023). Buildings alone account for 40% of the global energy consumption (Nejat et al. 2015) and thereby significantly contribute to the global greenhouse gas emissions. Reducing energy consumption and using greener energy sources for the building operation is therefore crucial to achieve lower overall carbon emissions. Industrial buildings are no exception, but pose a special challenge because of the different industrial processes that take place in them. The need for the integration of building simulation into the planning procedure to assess energy saving potentials as well as non-energy benefits like thermal comfort is frequently addressed in the literature (e.g. by Gourlis and Kovacic (2017) and Bleicher et al. (2014)). Weeber, Ghisi, and Sauer (2018) propose a procedure model how to integrate energy building simulation in the assessment of energy efficiency measures in factories, using *IDA-ICE* as building simulation software. They also emphasize that although computer simulations are considered a valuable tool among architects and civil engineers, they are still underrepresented in planning processes. Smolek et al. (2018) explain this by too much complexity and too high costs of the building design tools

for the purpose of industrial energy management. They address this problem by developing a building model consisting of manageable *cubes*.

Maier et al. (2021) describe the holistic approach followed by the *ETA factory* in Darmstadt, where building, production equipment and building services are interlinked mainly by thermally activated building structures (TABS). Low temperature waste heat captured by TABS can then for example be lifted to a usable temperature level using a heat pump (as e.g. described by Ramschak et al. (2018)).

As part of the research project *ETA im Bestand*, the simulation library *ThermalIntegrationLibrary* (TIL) has been developed for the identification and evaluation of energy efficiency measures in existing factories and was described by Theisinger et al. (2023). A special focus of this library is the interconnection of building, building equipment and machines. As *Modelica* is a popular tool for hydraulic grids and sophisticated control strategies (described e.g. by O'Donovan, Falay, and Leusbrock (2018)), it was chosen as a modelling language for all subsystems. Thereby time-consuming co-simulation and the usage of commercial building simulation software could be avoided.

Within the TIL the *FactoryBuildings* package aims to provide the user with easy-to-use basic building models as well as example factory buildings assembled from data collected within the research project. These example models can be dragged and dropped to be simulated along with the machine models as described by Theisinger et al. (2023). The *FactoryBuildings* package is intended to create a link between the available information of an existing building, the experience of the person responsible for the building, and the often time intensive model set up and simulation in *Modelica* by facilitating the modeling to such an extent that the barrier for use is minimized and a plausibility check with experience is possible.

The structure of the package is presented in Section 2.1. The correct implementation of the enclosure model introduced in Section 2.1 is validated using measurement data obtained from an experiment with a small demonstrator in Section 2.2. Furthermore an application example of the package is given, applying a few simple efficiency measures to an exemplary production hall (Section 2.3). The respective results are presented in Section 3.

2 Methods

2.1 The FactoryBuildings package

The *FactoryBuildings* package relies to a large extent on the well known *Buildings* library described by Wetter et al. (2014) in addition to the *ModelicaStandardLibrary* (Modelica Association and contributors 2020), both in terms of models and structure of the package. The package browser is shown in Figure 1 and contains the following sub-packages:

- *BaseClasses*: Contains the framework for the use of the building model within the factory system model described by Theisinger et al. (2023).

- *BuildingModels*: Contains examplary models consisting of one or more thermal zones ready to use in a factory model along with the machines. Furthermore examples are provided to evaluate building related energy efficiency measures including the machine waste heat as load profiles only.

- *Controls*: Contains a semi-ideal heater to facilitate simulating heating and cooling loads using a range of set temperatures over a whole year, described in Detail below.

- *HeatTransfer*: Contains data as known from the *Buildings* library.

- *InternalGains*: Contains models to facilitate the input of boundary conditions regarding heat sources and sinks used in *PartialBuildingModel* (described below).

- *ThermalZones*: Contains the base class *Partial-BuildingModel* which makes use of the *Buildings.ThermalZones.Detailed.MixedAir* model, extended by *ProductionHall*, which facilitates modelling thermal zones like production halls and office spaces, and *Enclosure*, which can be used to model room-in-room concepts. The *ProductionHall* and *Enclosure* Model are described in more detail below. Furthermore modelling examples and examplary industrial building models are provided.

- *Types*: Contains types like weekdays for convenience.

- *Utilities*: Contains utilities used throughout the library.

The *ProductionHall* model consists of the *MixedAir* model as well as of a collection of different convenient submodels for ventilation, infiltration, schedule based internal gains, thermal bridges and various for clarity conditionally generated connectors, which facilitate a coupling with technical building equipment. A simplified room temperature control allows for a quick generation of
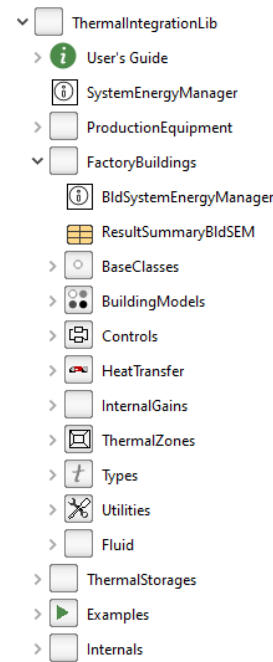

Figure 1. TIL package browser

useful heating and cooling loads. Furthermore the inclusion of efficiency measures like an enclosure or TABS is facilitated by conditionally generated submodels and parameters reduced to the essentials. For the mapping of TABS the *Buildings* model *ParallelCircuitsSlab* is integrated. The *Enclosure* model is based on the same principle as *ProductionHall* but does not allow external walls and uses temperature inputs rather than a weather bus. It should be set up by connecting its room-facing constructions to corresponding surfaces of the surrounding room in order to allow the radiation calculation.

As the time step of the simulation is variable and at the same time the thermal zone should not be thermally conditioned within a certain temperature range, the implementation of an ideal heater/ cooler is not trivial. Our solution is described in the following: The semi-ideal heater model checks whether the current room temperature falls below or exceeds a certain minimum and maximum threshold. The error between the current value and the threshold is fed into a first order function if the current temperature is not between the minimum and maximum limit. A gain constant with a standard value of $V \cdot 1.3 \ \frac{\text{kg}}{\text{m}^3} \cdot 1005 \ \frac{\text{J}}{\text{kg·K}}$, where V denotes the zone volume, may be specified by the user to be multiplied with the error (in K). A corresponding heat flow is then prescribed to the heat port respecting a specified minimum and maximum power for heating and cooling. The graphics view of the model is shown in Figure 2. It may be advisable to adjust the gain constant depending on how the zone is equipped, which is why we recommend to check the results of the air temperature before proceeding.
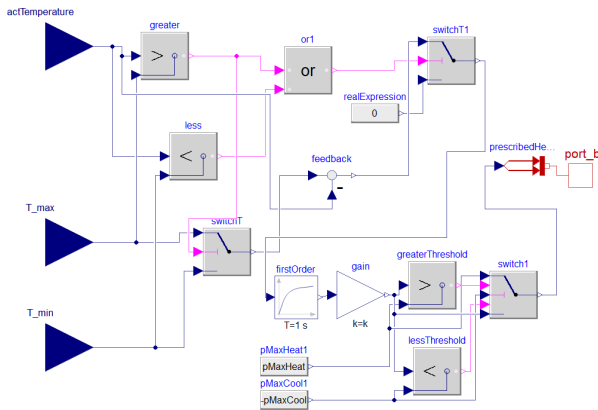
Figure 2. Graphics view of the semi-ideal heater model

2.2 Validation of the enclosure model

Measured data obtained from an experiment with a small demonstrator (1.82 m x 0.4 m x 1 m) is used to validate the correct implementation of the enclosure model. The experimental setup is shown in Figure 3.

The envelope of the demonstrator consists of vacuum insulated micro-reinforced high-performance concrete (mrUHPC) embedded in a steel frame. The respective properties are summarized in table 1.

Table 1. Properties of the construction layers

Property	Concrete	Vacuum insulation
Layer thickness [m]	0.05	0.02
Thermal conductivity $\left[\frac{W}{m \cdot K}\right]$	5 [*]	0.007
Specific heat capacity $\left[\frac{J}{kg \cdot K}\right]$	1100	900
Density $\left[\frac{kg}{m^3}\right]$	2500	195

[*] Hauser (2016)

The four walls are thermally activated each using a capillary tube mat located in the centre of the concrete layer. The connections are arranged according to the Tichelmann system so that supply and return lines of each mat sum up to about the same length, the two shorter mats are connected in series. The dimensions of the cross-linked polyethylene (PEX) capillary tubes are 3.5 x 0.5 mm arranged in parallel at a distance of 10 mm between one collector pipe each for supply and return. The supply and return pipes outside the demonstrator (about 4 m each) are non-insulated.

When the measurement is started the air temperature in the demonstrator is approx. 13.8 °C. At this time, the water is not yet circulating through the system. 28 minutes after the start of the measurement the pump supplying the TABS is turned on (total volume flow rate of 0.19 $\frac{m^3}{h}$, supply temperature of approx. 9.7 to 10.1 °C). The water temperatures are measured with PT1000 sensors with a tolerance of $\pm$ 0.3 K at 21 °C. The surface temperatures are measured with NTC sensors with a tolerance of

$\pm$ 0.2 K at 0 to 70 °C. The ambient temperature during the experiment is approx. 21.4 °C.

The model is set up in *Dymola*. The inlet temperature, mass flow rate and surrounding temperature are read in from a file containing measured data over 2.5 hours. The demonstrator is modelled using the *Enclosure* model with TABS. Inside the demonstrator, the connecting insulated pipe between the short wall TABS is considered as well as the longer supply or return pipe of each wall respectively. To account for the thermal losses of the non-insulated pipes outside the demonstrator, a series of experiments is conducted and the heat transfer coefficient is fitted according to the measured temperature difference to 15 $\frac{W}{m^2 \cdot K}$. Furthermore an air exchange by infiltration of 0.15 h^{-1} and a heat flow rate of 0.05 $\frac{W}{m^2 \cdot K}$ by thermal bridges to account for the steel frame are assumed. The model is shown in Figure 4. The results are described in Section 3.1.

2.3 Evaluation of energy efficiency measures

Besides the application of the building model as a production environment the *FactoryBuildings* package also enables the user to evaluate building related energy efficiency measures without the machine models. Including the machine waste heat as load profiles offers the advantage of a reduced computational effort, which facilitates the simulation over a whole year. The TIL thereby offers a solution for the relevant time frames for both production and building efficiency measures.

For the simulation of the building related efficiency measures the same models as for the factory simulation can be used. The *BldSystemEnergyManager* model extending the *SystemEnergyManager*, which centrally evaluates the energy demands of the factory components (as described by Theisinger et al. (2023)), can be used to compare a reference building with a refurbished building version.

To illustrate the application described above, an exemplary production hall is equipped with efficiency measures. The production hall was constructed 1994 and has a rectangular base area of about 7800 m^2. The external walls consist of sandwich- and cassette constructions with 8 cm PUR foam resp. 12 cm mineral wool. The flat roof is insulated with 12 cm PIR and the floor is a 20 cm thick concrete slab. The windows are double glazed. Furthermore air change rates of 0.15 h^{-1} by infiltration and of 1.5 h^{-1} by ventilation are assumed and weather data of Frankfurt, Germany is used, while the ground temperature oscillates between 0 and 20 °C. As internal gains 130 people with a heat output of 75 W each are considered along with lighting of 15 $\frac{W}{m^2}$ at an efficiency of 12%. 50 machines with 10 kW waste heat output to the room air (taken from an exemplary machine within the research project) are operated from 8:00 till 17:00. The minimum and maximum set temperatures are specified as 19 and 25 °C when the space is occupied resp. 16 and 30 °C when the space is not occupied.
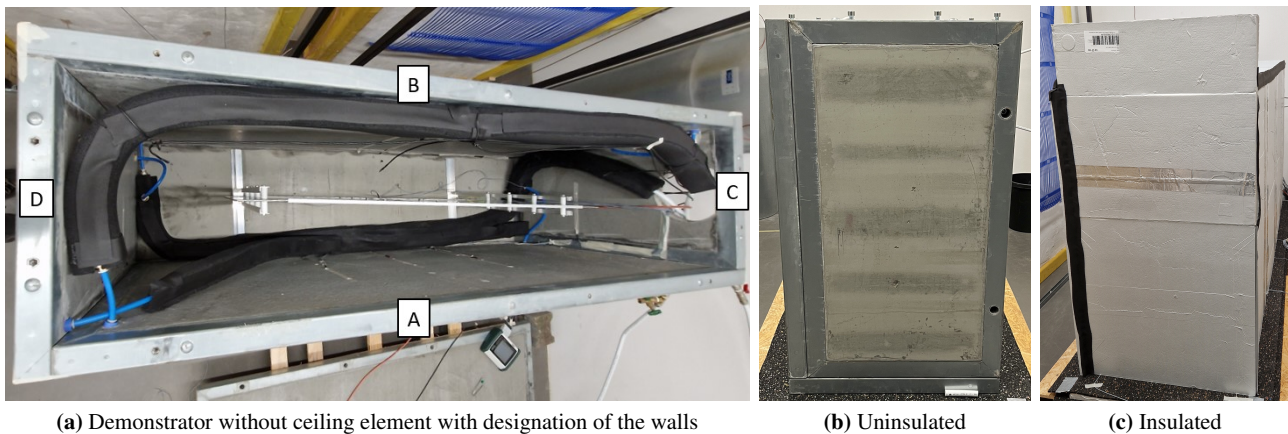
(a) Demonstrator without ceiling element with designation of the walls

(b) Uninsulated

(c) Insulated

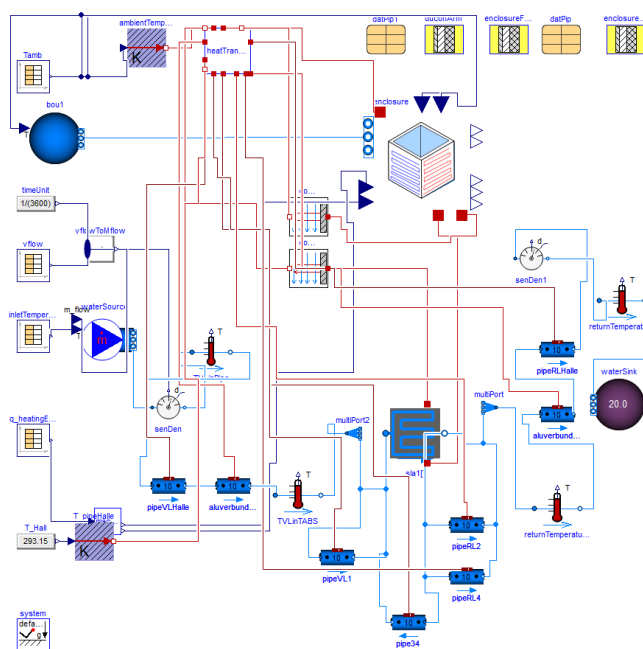**Figure 3.** Experimental setup

Figure 4. Graphics view of the *Dymola* model of the experimental setup

To improve the energy efficiency of the industry hall, firstly a retrofit insulation of the floor is considered, as the energy demand of the hall is heating dominated. This could be an option for the owners in the course of a major restructuring. Secondly modern lighting is integrated with 15 $\frac{\text{W}}{\text{m}^2}$ at an efficiency of 40%. Furthermore a 500 m^2 PV plant with 100 kWp is integrated. The integration of renewables is not an efficiency measure in the classical sense, but should still be considered when changes of the building envelope and technical building equipment are planned. The two versions of the model are dragged and dropped in the model containing the *BldSystemEnergyManager*. For the evaluation, the user may specify energy prices and and CO$_2$ factors. The results are described in section 3.2.

3 Results

3.1 Validation of the enclosure model

In Figures 5 and 6 the simulated and measured return temperatures and inner wall surface temperatures of the enclosure described in Section 2.2 are compared. While in the transient cool down of the construction at the beginning of the experiment the simulated and measured return temperatures differ up to 1.4 K, the difference decreases to 0.2 K while steady state is approached. This behaviour can be observed using the epsilon-NTU as well as the finite difference method implemented in the *Buildings* radiant slab model for the heat transfer between fluid and slab, and corresponds to its limitation to steady state applications as described in the user's guide (Wetter et al. 2014). The rise in the measured return temperature before the pump starts is due to the fact that the fluid temperature in the pipes where the sensor is located is initially not in equilibrium with the ambient air temperature. The jump in the simulated return temperature at the beginning of the experiment is due to the initial temperatures of the water volumes in the various pipes which differs from the respective room temperatures and could only be modelled approximately.

The surface temperature sensors are located approx. in the centre of the inner wall surfaces respectively. As shown in Figure 6, the measured and simulated surface temperatures differ up to 0.6 K two hours after the pump is switched on and even more at the beginning of the cool down. While in the model the heat transfer seems to be overestimated at the beginning of the cool down for the two larger walls and underestimated when steady state is approached, the opposite seems to be true for the two smaller walls. Apart from the above mentioned restrictions of the radiant slab model, the two main reasons for the deviation are firstly that the whole air volume is assumed to be completely mixed. This is not the case in reality, where an uneven temperature distribution in the air and at the construction surfaces can be observed. Secondly, the simulated values are to be understood as an av-
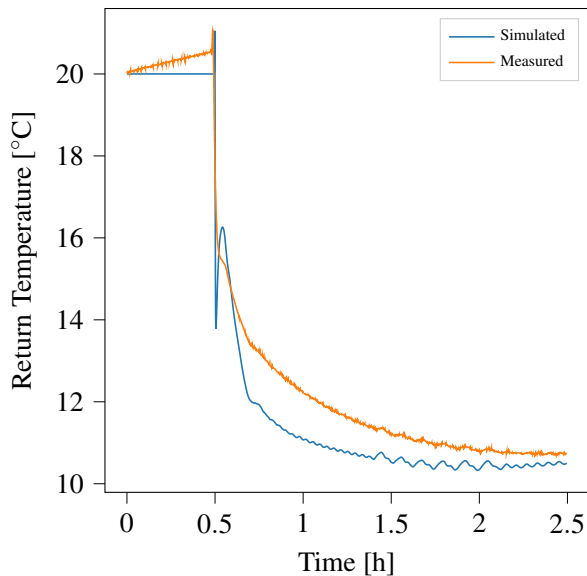
Figure 5. Simulated and measured return temperatures

erage over the whole surface area while the sensor measures the temperature at one point.
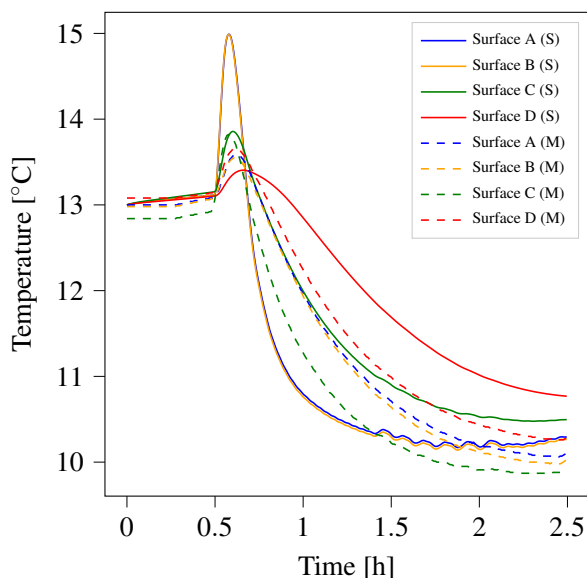

Figure 6. Simulated (S) and measured (M) inside surface temperatures

The results show that the *Buildings* model *ParallelCircuitsSlab* is reasonably well suited for an estimation of the behaviour of the considered type of capillary tube mats within the *Enclosure* model, e.g. for the capturing of temporally constant machine waste heat, keeping in mind the depicted limitations.

3.2 Evaluation of energy efficiency measures

Using a script with convenient plot settings provided in the TIL, an overview of the annual heating, cooling, electrical and total energy demands, energy costs and greenhouse gas emissions is given based on the user inputs. In

this case, the insulation of the floor leads to a reduction of the heating demand by 80%, but at the same time to an increase of the cooling demand by 350%. Therefore an increased ventilation of additional 1.5 h^{-1} is introduced when the room temperature exceeds a maximum value of 24 °C as well as the outside temperature. However, the effect is not high, as the heat capacity of the constructions is very low. The electricity costs and emissions decrease noticeably, but the relative effect on the overall energy costs and emissions is not high. It can be safely assumed that this would not be the case taking into account the electricity consumption of the machines. The results for the comparison of the total energy costs and emissions is shown in Figure 7. The overall costs and emissions are more than halved and more evenly distributed throughout the year in the refurbished building, due to the above described reasons.
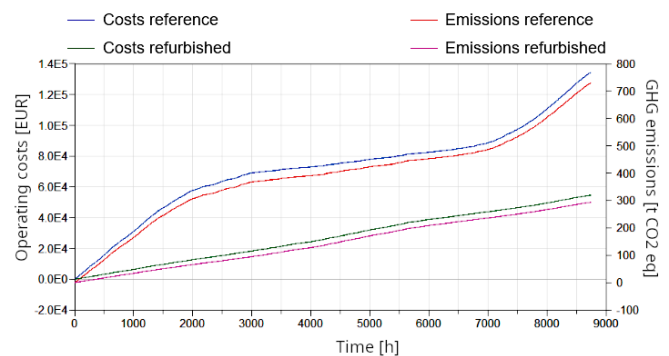

Figure 7. Results for the energy efficiency measures in *Dymola*

The assumptions made in this example are not representative for industrial buildings in general and are merely meant to depict the application of the *FactoryBuildings* package. As the utilization and boundary conditions for different industrial buildings are manifold, it is important for the user to make suitable assumptions for their specific case.

4 Conclusions and Outlook

The presented package enables the user to identify and evaluate energy efficiency measures especially in factory buildings. It relies largely on the *Buildings* library, but provides a simplified user experience by adding some functionalities and restricting the user's choice to a necessary minimum. The building model can either be simulated with simplified assumptions for machine waste heat to lay the focus on the building related efficiency measures, or act as an environment for the production equipment, typically simulated in a shorter time frame.

To propose and analyze more sophisticated energy efficiency measures than the ones presented in Section 2.3, it is important to have some knowledge about boundary conditions like the type of production equipment and details about the technical building equipment. Therefore, in future work a case study with a real factory will be per-

formed where all important parameters are known a priori and customized efficiency measures can be evaluated using the *FactoryBuildings* package. The application of the package as part of the *ThermalIntegrationLibrary* is intended to serve as a starting point for more in-depth energy system analyses.

Acknowledgements

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