Various door systems in industrial buildings considering
energetic, building climatologic and economic aspects

final report

Technische Universität München
Department of Building Climatology and Building Services

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Dipl.-Wirt.-Ing. Klaus Klimke
Dipl.-Ing. Jakob Schneegans
Dipl.-Ing. (FH) Timm Rössel, M.Sc.

student assistants:
Johannes Scholten
Christine Hans

Translation to English: Béatrice Müller

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1. Introduction

Sustainable buildings have become very important in Germany. The level of requirements with regard to energy-efficiency, thermal insulation and efficient supply technology of real estate has been rising steadily in the wake of amendments to the German "Energieeinsparverordnung" (engl. energy savings program) [EnEV 2009]. Especially the need for air-tight building envelopes and high thermal insulation became mandatory to reduce heat loss.

In contrast to residential and administrative buildings, industrial buildings are characterized by high heat loads and a wide range of uses resulting from the diversity of the processes taking place there [Rössel et al. 2012, 17]. Greenhouse gas emissions from industry and commerce, trade and services add up to approximately 50 % of the emissions in Germany. In the industrial sector around 40 % of the energy used is needed for space heating, process heat, mechanical energy and as well as for information and communication applications [Wietschel et al. 2010, 691].
A recent study has shown that about 215,000 conditioned industrial buildings were built between the years 1980 and 2009. An estimated 40 % of which are factory and workshop buildings. In this case, the total energy consumption for heating is about 61 billion kWh / year - equivalent to about 30% of the yearly end energy consumption of space heating for non-residential buildings [Oschatz et al. 2011, 42, 51].

Industrial doors are a common part of this building typology. These prevent air flows resulting from openings in the building envelope that are necessary for the supply and removal of goods. Industrial doors ensure that no unnecessary heat loss arise. Depending on the geographical location of the building – openings in the building envelope can have a negative impact on the energy balance and on the indoor climate conditions. Should the door be left open, various phenomena can arise such as high air flows with large temperature differences between inside and outside, especially during the cold season. This leads to an uncomfortable indoor climate and increases the heating demand of the building.

Significant energy savings are achievable by reducing heat loss through doors, e.g. by reducing the opening time, as shown in this study. Technical systems such as sensors can trigger automated door operation to prevent unwanted door openings and to limit the opening period to a minimum.

With the development of several practice-oriented scenarios in terms of door opening frequency and open state duration, it is possible to identify efficient door types under energetic and economical aspects.
In addition, various measures will be taken to increase energy efficiency and thermal comfort (e.g., an investigation of a needs-based, height-variable opening of the door).

The study is addressed primarily to designers, installers and operators of buildings to show the energetic impact of doors in the daily operation of a building.

2. Objective

Object of this study is the investigation of door systems and the associated energy, indoor climate and economic impact on the building.

Looking at the common door systems on the market, there are large differences in design, materials, insulation standard, opening and closing speeds and control techniques. The study examines these aspects and analyses their interactions with the building.

Simulation models with a thermal building simulation tool taking into account both building-specific parameters (e.g. different times of use, internal heat loads, thermal stratification) as well as door-specific properties (e.g. heat transition coefficient, leaks, opening and closing speed). This builds the basis of the research. In order to calculate the air flow through a single opening, a new ventilation model, taking into account both the thermally induced and the wind-induced air exchange in the calculation of the resulting air flow, was implemented in the simulation software.

Simulation results are energetic values such as heating and cooling demand of the building as well as transmission and ventilation heat loss by the doors.

In a first step, various door-specific parameters such as the heat transfer coefficient and different opening periods were studied on the basis of the defined building models (see Chapter 5) in order to determine their influence on the energy balance of the building, see Figure 1. The interdependencies of the technical processes are discussed in Chapter 6.
Once we have identified the influencing factors we include several practice-oriented scenarios with corresponding door opening cycles and opening periods in the simulations, see Chapter 7. The aim is to identify efficient door types for each scenario, see Figure 2.
In addition, appropriate measures to increase energy efficiency and thermal comfort are presented in Chapter 8, for example a reduction of ventilation heat loss through an object-size adapted door opening or shortening of the stay-open time by using a high-speed door.

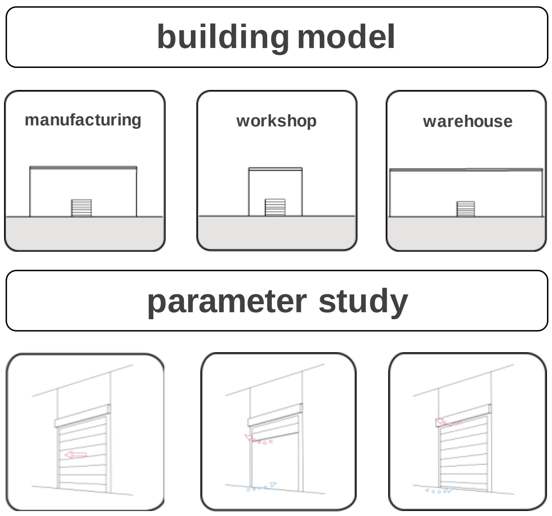


Figure 1: General approach of the parameter study: examination of different door-specific parameters, e.g. heat transition coefficient, opening duration and air permeability of the door.

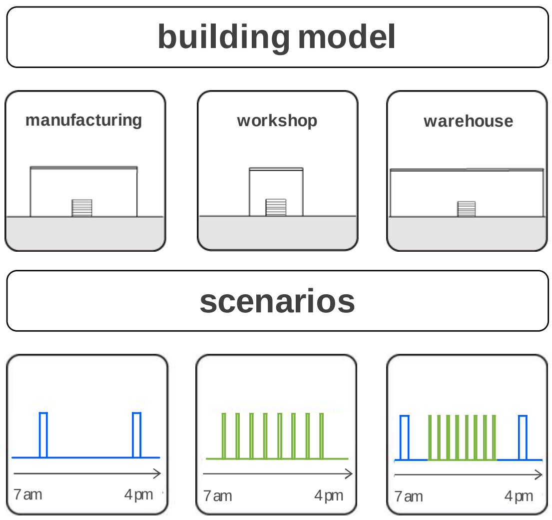


Figure 2: Development of scenarios for the defined building models manufacturing, workshop, warehouse.

3. Fundamentals

3.1 Heat loss through doors

Heat loss is caused by heat conduction (transmission) and leaks (leakages) with closed doors and by ventilation with opened doors. An open door leads to a natural air exchange. This air exchange is mainly influenced by the opening speed, the door dimensions and the temperature difference between inside and outside, the wind speed and wind direction.

3.1.1 Heat loss caused by transmission

The heat transition coefficient of the door is relevant in order to calculate the heat loss caused by transmission. This coefficient is determined for doors in accordance with [EN 12428] and depends on the particular types of doors and is situated between 0.5 W/(m²K) (highly thermally insulated sectional doors) and 5.9 W/(m²K) (flexible high-speed door), see Chapter 3.2.

It should be noted that the heat transition coefficient of doors from different manufacturers is limited to compare. It was found that there is no “standard size” for doors, on which the heat transition coefficient is based. However, the door size is an important factor in the specification of the heat transition coefficient, since the ratio of door leaf to frame changes with increasing size of the door and the door panel has a higher thermal resistance compared to the door frame.

3.1.2 Heat loss caused by leakages

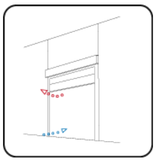
Doors like any multi-part constructions have joints (leakages), through which air can enter and escape. These leaks can vary depending on the door type. Therefore, the air permeability of doors is generally determined according to [DIN EN 12426]. The European standard specifies a classification of the resistance to the air permeability of doors in the closed state. The air permeability classes according to DIN EN 12426 are shown in Table 1. The air permeability values relate to a pressure difference of 50 Pa and are specifically expressed in cubic meters of air per m² door surface and hour.

Table 1: Air permeability classes of doors in accord. to [DIN EN 12426].

class	air permeability at 50 Pa [m³/(m²·h)]	specification
0		no performance determined
1	24	
2	12	
3	6	
4	3	
5	1.5	
6		exceptional

Generally speaking, the higher the air permeability class, the tighter the door. Regular, outside doors are situated in the air permeability classes 0-3, see Chapter 3.2.

3.1.3 Ventilation heat loss



Heat loss caused by an open door usually has a larger impact on the heat balance of the building as the heat loss caused by transmission or leaks. Therefore, there is no question that, especially during the cold season, a minimization of opening cycles and the respective opening time is recommended not only from an energetic point of view, but also for climatic and economic aspects. This can be done via a consistent closure of the door carried out manually according to the specific purpose of the door opening or on appropriate automate systems. In the case of an automated door closure, various sensory systems can be offered, which are described in Chapter 3.3.

3.2 Various doors for industrial buildings

The general definition of a door is in accordance with [DIN EN 12433-1, 2]:

“A device meant to close an opening provided for the passage of vehicles and the passage of people.”

The standard provides a list of existing types of doors. Here, the following door types can be distinguished:

- Swing doors
- Pendulum doors
- Folding joint doors
- Folding doors
- Sliding and folding doors
- Sliding doors
- Lift and falling doors
- Sectional doors
- Rolling doors
- Overhead doors
- Folding overhead doors.

At the beginning of the research, a variety of basic investigations were carried out. These investigations were carried out using a questionnaire, which was sent to various manufacturers of doors, drives and control systems. The so-created product database was further expanded by additional research, ensuring that this study is independent of the questioned manufacturers.
In the questionnaire, specific properties of doors, such as heat transition coefficient, opening speed or list price were queried (see Appendix). The manufacturers were asked to consider a wide range of doors.
Two workshops were conducted together with the participating companies of the Federal Association for Drives and Control Systems (BAS.T) in order to discuss the procedure and first results. It was decided to focus on the most used door types in industrial environments: sectional doors, roller doors and high-speed spiral doors. According to a study of [B + L 2010, 61, 67], these three door types cover a market share of over 90% in the industrial building sector.
An analysis of the questionnaires supplemented by our own research lead to the creation of a database of 28 doors, including sectional doors, high-speed spiral doors, and two types of rolling doors. Table 2 states the average values and the minimum and maximum values for property.
Furthermore, a door size of 4 x 4 m was adopted for further studies.

The Sections 3.2.1 to 3.2.3 give a more detailed description of the investigated door types.

Table 2: Specific characteristics of the investigated door types: sectional door, rolling door and high-speed spiral door after evaluation of the questionnaire.

	sectional door	**rolling door**		**high-speed spiral door**
		strips	film	
				
components	sections joints rollers guide rails	shutter curtain rollers guide rails winding shaft	film rollers guide rails winding shaft	slats rollers guide rails spiral
u-value [W/(m²·K)][1,2] **(weighted average)**	0.5-3.6 (1.8)	4.1-5.0 (4.7)	5.9 (5.9)	0.9-5.9 (1.9)
opening speed [m/s] **(weighted average)[1]**	0.2-0.44 (0.31)	0.2-0.3 (0.23)	0.8-3.0 (1.5)	0.5-2.5 (1.6)
closing speed [m/s] **(weighted average)[1]**	0.2-0.25 (0.21)	0.2-0.3 (0.23)	0.5-1.0 (0.6)	0.5-1.0 (0.75)
air permeability class[1,3] **(average class)**	2-3 (2)	0 (0)	0 (0)	0-3 (2)
maximum size[1] **(w·h) [m²]**	10 x 8	12 x 10	6 x 7	8 x 8
investment[3,4] [€] **(weighted average)**	2,900 – 6,500 (4,700)	2,500 – 4,100 (3,100)	4,600 – 5,500 (4,800)	8,000 – 16,000 (11,000)
maintenance interval[1] [a]	0.5	0.5		1

[1] The specific values were determined by the questionnaires and data sheets of different door manufacturers and thus represent a typical bandwidth.

[2] The u-value refers to a door size of 4 x 4 m according to [DIN EN 12428].

[3] Air permeability class according to [DIN EN 12426].

[4] The investment refers to a door size of 4 x 4 m and the manufacturer's list price including controls and default drive. The investment depending on the equipment may differ greatly (e.g. glazed surfaces in the door leaf).

3.2.1 Sectional doors

The most common used door type in industrial buildings is the sectional door [B+L 2010, 61]. It consists of several horizontally interconnected sections that result in the door leaf. The door is usually moved upwards when opening. In the upper opening position, the leaf can be moved upwards horizontally or folded [ASR A1.7, 6].

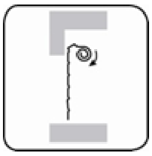
As far as sectional doors are concerned the sections are joined together by joints like a chain. These have side rollers which are guided in rails. Building the door with relatively few elements with up to 80 mm thick insulated sections allows to achieve high insulation levels and air tightness.

The sections can also be made of translucent elements. The advantage to non-transparent materials is a safety aspect, because the area behind the door is visible for operational staff. Furthermore, daylight entry can be increased.

3.2.2 Roller doors

The most common industrial doors beside sectional doors are roller doors. They can also be used both indoors as well as outdoors. These doors are designed as flexible high-speed doors or as rolling shutters with thermally insulated laths and as high-speed or slow running doors [Teckentrup 2012]. The roller shutter armouring, consisting of numerous narrow laths, or the metal structure can be rolled when opened by side mounted guide rails on a winding shaft. In contrast to the sectional doors, no additional space is required above the door by the retractor. Roller doors usually require less investment than the other two door types.

3.2.3 High-speed spiral doors



The high-speed spiral door is the latest door type that has been developed. In contrast to the sectional door, the door leaf does not consist of a few broad sections, but of fine-mesh laths. However, the laths are not rolled over each other when opening the door, as in the previously described roller door, but inserted into a fixed spiral, without rubbing against each other. Therefore, the design offers high opening and closing speeds, is sound insulated and long lived, even in highly frequented door operation [VDI 2409, 12].

A further advantage of this type of door lies in the combination of high opening speeds with the thermally insulated laths.

High-speed spiral doors are generally the most expensive of the three door types.

Figure 3: Sectional door

Figure 4: Flexible high-speed door

Figure 5: Rolling shutter

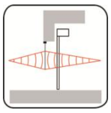
Figure 6: High-speed spiral door

3.3 Door control and sensory systems

The control of an opening and closing operation can be carried out by a dead man's switch, a manually traggered pulse and / or automatically by means of a sensory system. The various control possibilities are shown in Table 3.

In the following subsections, the individual control systems are explained in detail.

Table 3: Properties of possible door control systems upon analysis of the questionnaire.

	dead man's control	**manual activation**		**automatic drives**			
	button	**button**	**radio control**	**photocell**	**induction loop**	**radar**	**laser**
							
approach area monitoring	-	-	-	+[I]	+	-[II]	+
suppression of cross traffic	-	-	-	-	+[III]	+	+
persons and vehicle detection	-	-	-	-	+[IV]	+	+
object-size-adapted door opening	-	-	-	-	-	-	+

\+ Possible
\- Not possible

[I] only when used as a safety device
[II] only in combination with a suitable safety device
[III] in combination with several induction loops
[IV] only metallic objects are detected

3.3.1 Dead man's control / Push-pull switch

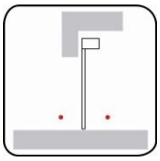
The dead man's control is a hold-to- run control, it requires a continuous operation for the opening and closing process and is done using a button.

A manual operation of the push-pull switch triggers the door opening or closing, the door opens and closes automatically after the impulse has been given.

3.3.2 Radio remote control

A radio control wirelessly transmits the signals by means of electromagnetic waves from a transmitter to a receiver. The receiver unit is placed at the door. An advantage of this manual control is the ability to open the door "from a distance". However, the range heavily depends on disturbance factors (e.g. high proportion of reinforced concrete in the area) [Litzmann 2012].

3.3.3 Photocells



The photocell is an electronic optical system, which detects the interruption of a light beam and comprises a light beam source (transmitter) and a sensor (receiver).
Normally, several photocells are used as safety device (safety light grid). The automatic closing of the door stops when a light beam is interrupted by persons or vehicles [Stricker 2012-1].
When using a photocell as automatic impulse emitter, the light beam source is installed at the door. The receiving unit in the area in front of the door initiates a door opening if the light beam is interrupted.

3.3.4 Induction loop

The induction loop uses the change of an electromagnetic field by metals for the registration of vehicles. So it is appropriate for automated door openings. When crossing the induction loop vehicles such as lift trucks, cars and trucks are registered.
This technology allows precise delineation of the sensing field and does not register people for technical reasons.
Induction loops must be laid in the ground. Therefore, the cable loops are embedded in a rectangular shape in the ground in front of the door, which is an additional expense and is not compatible with all floor coverings [BEA 2012-1], [Stricker 2012-2].

3.3.5 Radar

The radar detector sends microwaves at constant frequency in a defined area. When there is a movement caused by persons or vehicles in the detection area, waves with an altered frequency are sent back to the detector, triggering a registration.
The ability to distinguish between an approaching and departing movement combined with the detection of cross traffic allows avoiding unnecessary openings [BEA 2012-2].

3.3.6 Laser

Laser technology is based on the principle of transit time measurement. In this case, a light pulse is emitted and the time until the reflection returns is measured.
The presence of vehicles and pedestrians in the detection zone of the laser is monitored by the high resolution scan. The door closing mechanism is immediately triggered when neither persons nor vehicles or objects are in the detection area. This reduces the open dwell time of the door to a minimum.
The use of laser technology achieves an unprecedented level of safety in addition to the automated door opening or closing [BEA 2012-3], [2012-3 Stricker].

Note: The analysis of questionnaires described in Chapter 3.2 and expert interviews have shown that it is not necessarily possible to establish the connection between the reduction of the door-open period via a sensory system and the opening period without such a system. The “additional open time” after which the door is to be closed again can rather be determined by the property owner and the experiences in daily production operation. This time was indicated between 8 s and 200 s, that means there is a large temporal value range.

4. Research method

4.1 Thermal building simulation

Basis of the research is a thermal building simulation model using [IDA ICE 2012]. A new ventilation model was implemented in the simulation environment to calculate the air flow for one-side opened doors, taking into account both the thermally induced and the wind-induced air exchange, see Chapter 4.1.1.

Full-year simulations using the weather data from test reference years (location: Munich, Germany) were carried out [DWD 2011] in order to determine the energy consumption of the building as a result of transmission heat loss through the building envelope and ventilation heat loss through the building doors.

This requires comprehensive and validated simulation models covering both door-specific and building-specific parameters. Physical measurement is performed through a multi-zone model, see Figure 7. Advantage over a single-zone model is that the airspace is divided into several zones, between which air exchanges are calculated. Thus a homogeneous air climate prevails within a zone.

A flow network is integrated in the stationary building simulation to determine the local temperature field in the hall (air flow and temperature distribution), especially in the surrounding door zone,. This allows assessing the temperature distribution in the defined zones within an acceptable time-frame of one year. Energetic sizes such as the heating and cooling requirements of the building as well as transmission and ventilation heat losses of the doors can also be calculated and analyzed. Since vertical temperature stratification due to thermal lift is present especially in hall buildings, a vertical temperature gradient has been defined for each zone. This gradient depends on the height of the hall, the internal heat loads as well as the employed heating and air conditioning systems. Therefore, it varies from building to building. Reference values of typical temperature gradients for different types of buildings and plants technologies can be found in [FVLR 10, 6] and [Oschatz et al. 2011, 101].

Ambient air flows can also be analyzed via numerical simulation through Computational Fluid Dynamics (CFD). There is a discretisation of the volume to be examined into many small volumes applying the numerical approach of the finite element method (FEM).

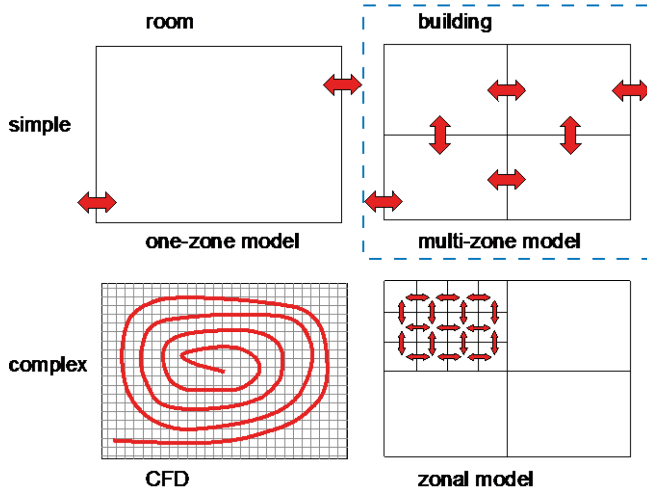


Figure 7: Different model types to calculate room air flows [Flieger et al. 2013].

The zone-based model also divides the space into small volumes, but in a smaller number than the CFD approach [Flieger et al. 2013].

The use of CFD as well as zone-based models is not recommended for this application because the high level of detail leads to a disproportionate computing effort. Consequently, these models are only recommended for specific case studies.

However, it should be pointed out that it is not possible to provide detailed information on local flow conditions in the building with the selected multi-zone model. Such local effects require a much more accurate computing approach, only involving CFD and zone-based models. As this research project has a time-frame of one year and energetic quantities such as the heating demand of the building are determined, the simulation model used can be considered as reasonably accurate.

4.1.1 Air flow calculation

A ventilation model taking into account both the thermally induced and the wind-induced air exchange was first integrated in the simulation software in order to calculate the air flow for a one sided open door. This computational approach was first developed through experimental investigations on window openings of [Phaff et al. 1982]. Various research using experimental tests and numerical methods were checked for validity and partly supplemented on other aspects such as a wind-direction-dependant calculation of the air flow [Larsen 2006], [Freire et al. 2009] or modified for other applications such as in [Maas 1995] for small window opening angle. This approach has also been used in the German standard "Ventilation for buildings" [EN 15242].

In the calculation method, it is assumed that, a bi-directional exchange of air takes place, for a single opening and the air enters through one half of the opening and escapes through the other half.

The calculation equation is as follows:

$$\dot{V}_{supply} = \dot{V}_{exhaust} = \frac{1}{2} \cdot A_{opening} \cdot \sqrt{C_1 \cdot v_{Wind}^2 + C_2 \cdot h_{opening} \cdot \Delta T + C_3} \tag{4.1}$$

with

$\dot{V}_{supply}$	Supply air flow rate [m³/s],
$\dot{V}_{exhaust}$	Exhaust air flow rate [m³/s],
$A_{opening}$	Opening area [m²],
v_{Wind}	Wind speed [m/s],
$h_{opening}$	Opening height [m],
ΔT	Temperature difference between inside and outside [K].

The coefficients C_1, C_2 und C_3 have been determined with the help of experimental measurements through [Phaff et al. 1982] as follows and applied in the works of [Larsen 2006, 28, 100f] and [Freire et al. 2009, 1043]:

$C_1 = 0.001$	Coefficient to consider the wind turbulence
$C_2 = 0.0035$	Coefficient to consider the thermal buoyancy [m/(s²K)]
$C_3 = 0.01$	Coefficient to consider the wind turbulence [m²/s²].

Figure 8 shows exemplary flow rates resulting in the application of equation (4.1) for a square opening area of 16 m² depending on the temperature difference at various wind speeds ranging from 0.5 to 10 m/s.

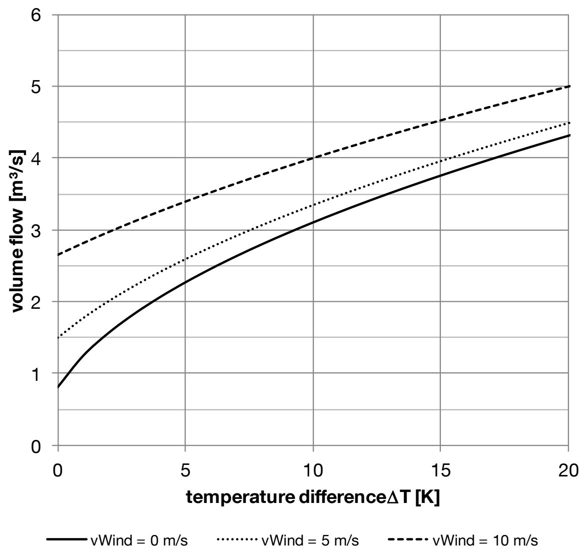


Figure 8: Air flows as a function of temperature difference and average wind speed at a square opening area of 16 m².

It becomes obvious that with increasing temperature difference, the influence of wind speed on the resulting air flow is smaller, the curves are converging.

In order to demonstrate the applicability of the calculation approach for large open areas and to examine the coefficients determined through [Phaff et al 1982] measurements were carried out at the Department of Building Climatology and Building Technology affiliated tool hall, see Chapter 4.2.

4.1.2 Calculation of air flow through leakage

For the calculation of leakage (joints) of the door the following approach according to [Hensen 1991, 4.18] is used in the simulation environment:

$$\dot{V}_{leakage} = \frac{c}{\rho_{air}} \cdot \Delta p^{n} \tag{4.2}$$

with

$\dot{V}_{leakage}$	air flow through leaks [m³/s],
c	Flow rate coefficient [kg/(sPa)],
ρ_{air}	Density of air [kg/m³],
Δp	Pressure difference between indoor and outdoor [Pa],
$n = 0.6$	Flow exponent [-].

Since the leakage of a door according to [DIN EN 12426] at a pressure difference of 50 Pa is known (see Chapter 3.1.2), the flow coefficient (the only unknown parameter) can be determined using the equation (mentioned in equation (4.2) and the simplification of ρ_{air} = 1.2 kg/m³. The link between pressure difference and resulting air flow shown in Figure 9 can be made for the different air permeability classes (LDK). It is shown that with increasing pressure difference Δp, the resulting air flow $\dot{V}_{leakage}$ does not increase as sharply. It becomes evident that with an LDK value > 3, the air flows only slightly differ from each other with increasing pressure difference.
In the simulation, the pressure difference Δp between inside and outside depending on the dynamic pressure due to the wind flow and to the temperature difference between inside and outside is dynamically calculated.

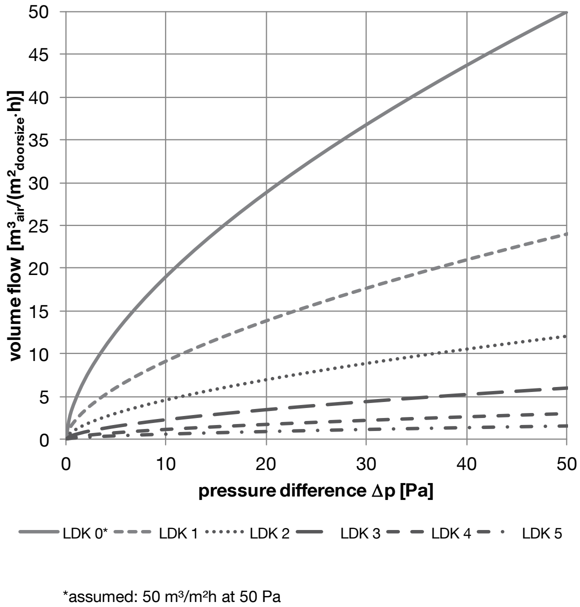


Figure 9: Relationship between pressure difference and air flow for different air permeability classes (LDK) according to [DIN EN 12426].

4.2 Verification of the calculation method based on measurement and simulation

In order to verify the simulations, temperature measurements are made and compared with a dynamic building simulation in one of the Department affiliated halls.

4.2.1 Department Tools Hall

The hall, shown in Figure 10, with a sectional door and a volume of about 320 m³ is appropriate to study the building door complex. The hall comprises three heated neighboring spaces and an outer wall which is indirectly heated by these neighboring spaces. Furthermore, the hall is only designed for tool storage. Neither internal heat loads nor air-conditioning are available.

4.2.2 Experimental set-up

Thermal elements of the K type are used for measurement set in space as shown in Figure 11. With this experimental set-up, the room temperature can be detected on three vertical levels: the floor area, at 1.4 m in height, and at the top of the door frame.
In order to show the influence of penetrating air flows in the room depth, a second measurement plane is located in the back hall area.

The outdoor temperature and wind speed are also determined by measurement. Further boundary conditions for the measurement are shown in Table 4.

Table 4: Boundary conditions of the temperature measurement.

temperature measuring device	thermocouples type K, Almemo data logger 2390-8
measuring points	1 sensor outside, 18 sensors inside
recording start	08 February 2013, 12:30 pm
recording end	08. February 2013, 02:40 pm
logging interval	10 s
∅ opening speed door [m/s]	0.2
∅ closing speed door [m/s]	0.2
∅ wind speed [m/s]	1.2
maximum wind speed [m/s]	4.8
∅ outside air temperature [°C]	1.7

Figure 10: View of the Hall of the Department of Building Climatology and Building Services used for the temperature measurements.

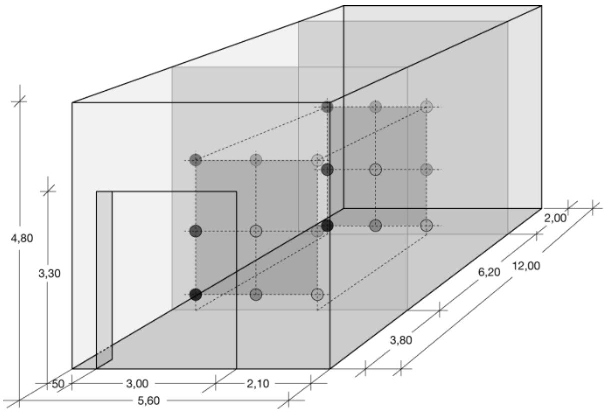


Figure 11: Experimental set-up for the temperature measurements with thermocouples.

4.2.3 Measurement results

In Figure 12, interior temperatures of the front measuring plane are shown as red lines, indoor temperatures of the rear measurement plane are shown as yellow lines and the average room temperature of the two measurement planes is depicted as a green line. The data points shown here are located at a height of 1.4 m.
The sectional door is opened at time t = 0 min. At the beginning the interior temperature is about 14 °C both in the front and in the rear. Obviously, the rapid temperature drop after the door opening is due to the cold weather. Within minutes the average room temperature, shown as a green line drops by about 8 K. It also becomes obvious that the temperature rises when the door is closed. The temperatures oscillate at approximately 11 °C in the room. The temperature rise is caused by the still warm surfaces of the room and the heated adjacent rooms.

4.2.4 Boundary conditions of the building for the simulation

The measured outdoor temperature and the wind speed are used as input parameters for the simulation calculation. Further boundary conditions of the building model are described in Table 5.

Table 5: Boundary conditions of the building for the simulation.

dimensions (h·w·d) [m]	4.8 x 5.6 x 12
floor area [m²]	67
volume [m³]	322
internal heat loads [W/m²]	-
u-value internal walls [W/(m²·K)]	1.6
u-value external walls [W/(m²·K)]	0.6
u-value ceiling [W/(m²·K)]	0.6
dimensions door (h·w) [m]	3.4 x 3
u-value door [W/(m²·K)]	5.8
adjacent room temperature [°C]	18
natural infiltration [1/h]	0.5 at 50 Pa
mechanical ventilation	-
zoning	one-zone model
simulation time step	dynamic (high resolution at door opening), ~1 s

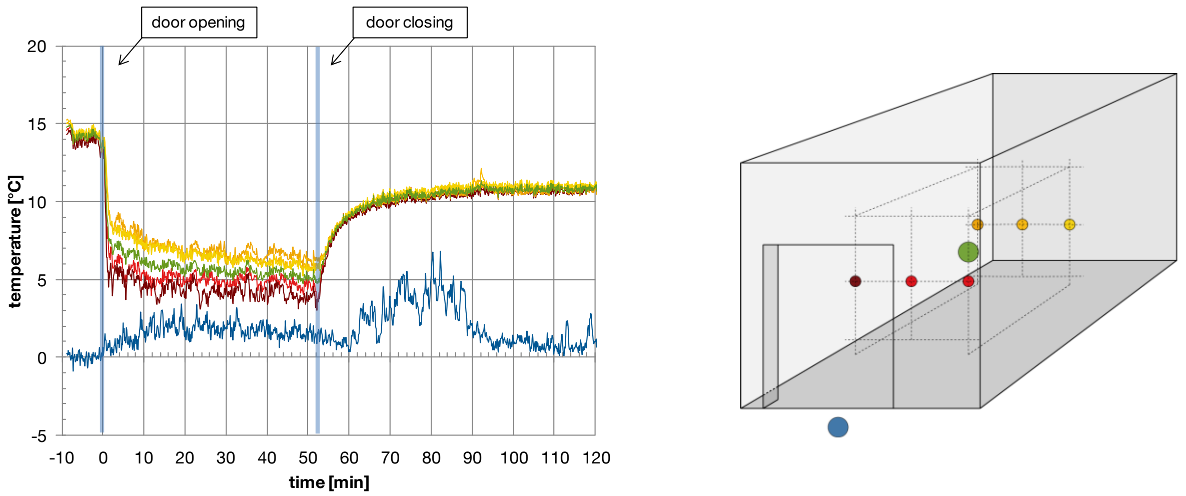


Figure 12: Temperature profile during door opening. The temperatures shown here refer to the measuring points in front (red lines) and rear (yellow lines) of the hall at a height of 1.4 m. Furthermore, an average interior temperature is calculated and shown as a green line. The measured outdoor temperature is represented as a blue line.

4.2.5 Results of the simulation

Figure 13 shows the average interior temperature of the measurement as a green line, the simulated room air temperature as a yellow line and the measured outdoor temperature as a blue line. To verify the simulation model with the method for flow calculation is described in Chapter 4.1.1, the average interior temperature (green line) is used in the measurement because the simulation model is simulated as a one-zone model.

It becomes obvious that the measurements match well with the simulation. Both the variation of the temperature drop at the opening of the door and the resulting temperature rise after closing the door by the warm walls and ceilings are correctly mapped in the simulation.

4.2.6 Summary

Both the type of simulation methodology and the implemented ventilation model could be reviewed and confirmed through the measurements of the survey followed by the simulation. Compared to the measurement the simulation provides good results and is suitable for further investigations focusing on the energetic interaction between door system and building.

As established in Chapter 4.1, the dynamic building simulation cannot replace numerical simulations (CFD) or a wind tunnel measurement. However, in terms of energy targets, such as the ventilation heat loss of a door or the heat demand of a hall, the simulation has to be seen as a target-oriented tool.

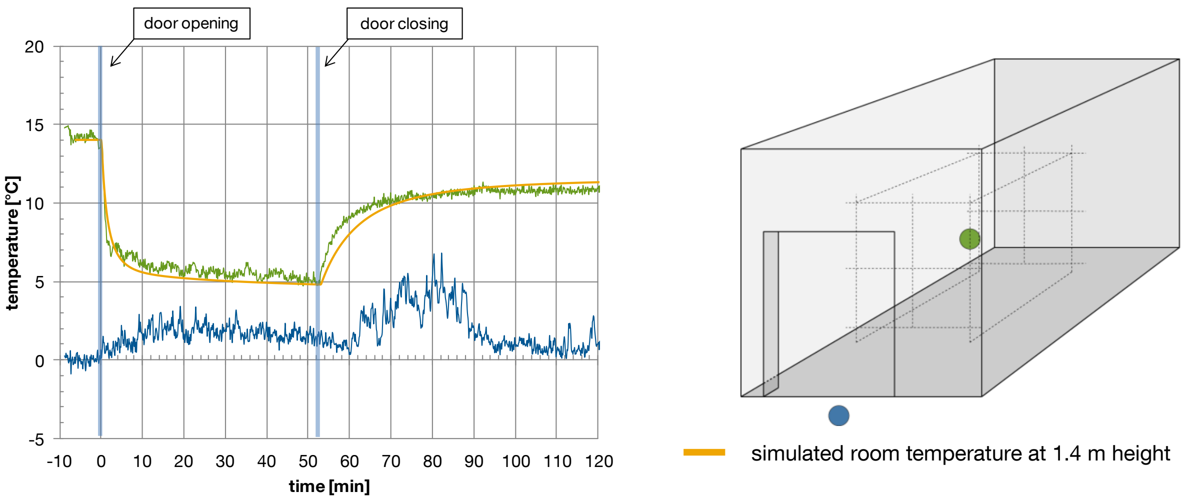


Figure 13: Comparison of the measured average interior temperature (green line) and the simulated interior temperature (yellow line).

5. Development of various building models

5.1 Versatility of industrial buildings

Industrial buildings hold a wide range of uses and production processes. In addition, the buildings differ in structural characteristics such as the building footprint, height, age and insulation standard or the installed system technology.
Three building models have been developed for the studies described in Chapter 6 and 7: manufacturing, workshop and warehouse. These models differ in dimensions, predominant use, internal heat loads, target temperature levels, and life span. Each building is typical within its category, see Figure 14.
The building models, along with different boundary conditions, allow to examine the doors influence on energy and indoor climate for many typical scenarios.

More details on the building models are described in Sections 5.2 to 5.4.

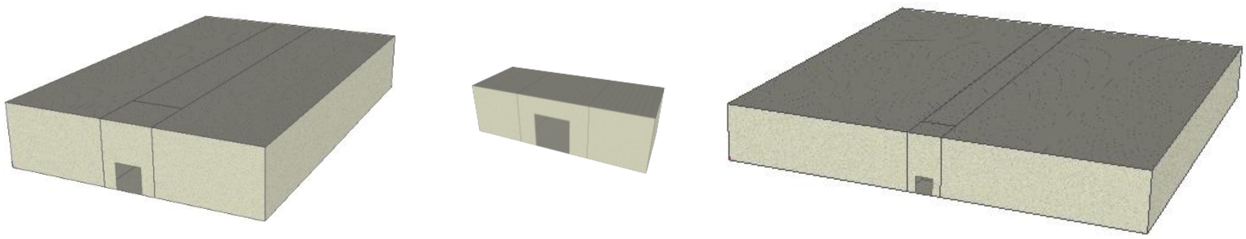


Figure 14: Manufacturing, workshop, *warehouse building model*s [IDA ICE 2012].

5.2 Manufacturing building model

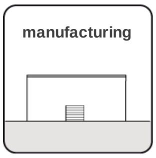


Figure 15 shows the *manufacturing building model*. The selected zoning can be seen in the sectional view of the horizontal plane. Due to a large number of simulations a 4-zone building model has been created to reduce the computation time.
In order to investigate the interior temperature drop caused by an open door described in Section 6.4, a finer zoning has been assumed so the simulation period only runs as long as it takes to open the door.

A “door zone” of 8 x 8 m located right behind the door has been defined, see Figure 15. This additional zone allows to register the temperature “directly behind” the door for further studies. It also allows to describe the temperature drop at different stay-open periods of the door.
According to [DIN V 18599-10, Table A 24] for commercial and industrial halls, a nominal room temperature of 20 °C for a light, mainly sedentary activity for manufacturing, production, installation as well as a daily usage time of 7 am till 4 pm from Monday to Friday has been set, see Table 6. The building is classified as a new building in compliance with the current [EnEV 2009] and is constructed using sandwich panels for the exterior walls and the roof. In order to not be limited to one heating system, an ideal heating system[5] with a specific power of 100 W/m² is used. This ensures that the minimum target room temperature is achieved (with closed doors).

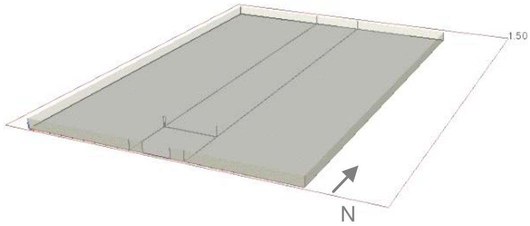


Figure 15: Section through the *manufacturing building model* given in [IDA ICE 2012] showing the zoning.

Table 6: Boundary conditions of the *manufacturing building model*.

dimensions (h·w·d) [m]	10 x 40 x 60
floor area [m²]	2,400
volume [m³]	24,000
internal heat loads (including lighting) [W/m²]	40
minimum target room temperature at a height of 1.4 m [°C]	20
maximum target room temperature at a height of 1.4 m [°C]	28
surface-to-volume ratio	0.28
vertical temperature gradient [1/m]	0.5
insulation standard	EnEV 2009, sandwich panels
natural building infiltration (at 50 Pa) [m³/(m²·h)]	8.2 (n_{50} = 1.5)
usage time	1-shift-operation: Mo-Fr, 7 am to 4 pm
climate data	TRY 13, Schwäbisch-fränkisches Stufenland und Alpenvorland[6]
pressure coefficients	exposed location (see Appendix 13.2)

[5] The building model was first simulated without internal heat loads and with an ideal heating system with unlimited power in order to determine the required power to maintain the target interior temperature of 20 °C at the coldest outside temperature.

[6] The test reference year (TRY) 13 was chosen as weather data input for the simulation [DWD 2011]. The climate is described in [DWD 2011, 52] as follows: Winter: cool; Summer: moderate to warm. Difference between lowest and highest monthly mean air temperature: - 1.1 °C to 18.1 °C.

5.3 Workshop building model

Figure 16 shows the *workshop building model*. Due to the relatively small dimensions, zoning of the building is carried out in three zones. The "door zone" already mentioned in the previous chapters has the same dimensions of 8 x 8 m, in order to ensure comparability in the analysis of temperatures between the building models. The specific power of the ideal heating system for this building has been adapted at 125 W/m² to maintain the target room temperature of 15 °C[7].

Various constraints such as usage time and target room temperature for “heavy work, standing activity” have been defined for the building according to [DIN V 18599-10, Table 22]. Significant differences to the *manufacturing building model* are the smaller size, the smaller volume, lower internal heat loads and a reduced target room temperature, see Table 7.

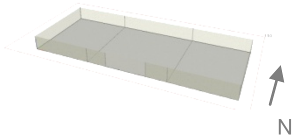


Figure 16: Section through the *workshop building model* given in [IDA ICE 2012] showing the zoning.

Table 7: Boundary conditions of the *workshop building model*.

dimensions (h·w·d) [m]	6 x 8 x 20
floor area [m²]	160
volume [m³]	960
internal heat loads (including lighting) [W/m²]	20
minimum target room temperature at a height of 1.4 m [°C]	15
maximum target room temperature at a height of 1.4 m [°C]	28
vertical temperature gradient [1/m]	0.5
surface-to-volume ratio	0.68
insulation standard	EnEV 2009, sandwich panels
natural building infiltration (at 50 Pa) [m³/(m²·h)]	8.2 (n_{50} = 4.2)
usage time	1-shift-operation: Mo-Fr, 7 am to 4 pm
climate data	TRY 13, Schwäbisch-fränkisches Stufenland und Alpenvorland
pressure coefficients	exposed location (see Appendix 13.2)

[7] As the *workshop building model* has a higher surface to volume ratio than the *manufacturing building model* therefore more power is necessary to maintain the target interior temperature of 15 °C despite the lower target temperature.

5.4 Warehouse building model

Figure 17 shows the *warehouse building model*. With the selected dimensions the building represents a typical flat-build warehouse. This building is not based on the [DIN V 18599-10, Table A.43] for logistics warehouses, as it is assumed that there are no permanent employees. Therefore, the heating temperature only amounts to 12 °C [HLH 2013]. On the basis of the research project “Carbon neutral logistics facilities - development of holistic recommendations for energy-efficient logistics facilities” at the Department of Building Climatology and Building Services in cooperation with the Department of Materials Handling, Material Flow and Logistics, the assumption is taken that the employees work throughout the building, and thus, a minimum target room temperature of 17 °C is set.
As warehouse buildings are rarely operated on a one-shift basis, but rather a 2-shift operation, the influence of different usage times on the heat loss through the doors is investigated in the developed scenarios, see Section 7.6.
The specific power of the ideal heating system for this building has been adapted to 65 W/m² in order to maintain the target room temperature of 17 °C[8]. The internal heat loads are only 6 W/m² by artificial lighting during the time of use. There are no further heat loads (e.g. industrial process waste heat).

Table 8 states more boundary conditions.

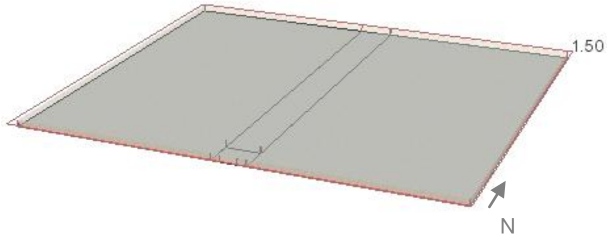


Figure 17: Section through the *warehouse building model* given in [IDA ICE 2012] showing the zoning.

Table 8: Boundary conditions of the *warehouse building model*.

dimensions (h·w·d) [m]	14 x 100 x 100
floor area [m²]	10,000
volume [m³]	140,000
internal heat loads (including lighting) [W/m²]	6
minimum target room temperature at a height of 1.4 m [°C]	17
maximum target room temperature at a height of 1.4 m [°C]	28
vertical temperature gradient [1/m]	0.5
surface-to-volume ratio	0.18
insulation standard	EnEV 2009, sandwich panels
natural building infiltration (at 50 Pa) [m³/(m²·h)]	8.2 (n_{50} = 0.9)
usage time	1-shift-operation: Mo-Fr, 7 am to 4 pm 2-shift-operation: Mo-Fr, 6 am to 10 pm
climate data	TRY 13, Schwäbisch-fränkisches Stufenland und Alpenvorland
pressure coefficients	exposed location (see Appendix Appendix 13.2)

[8] As the warehouse building model has a lower volume-to-surface ratio than the *workshop building model* less power is needed to maintain the target interior temperature of 17 °C although the target room temperature is 2 K higher than the room temperature of the *workshop building model*.

5.5 Heating and cooling demand of the building models without doors in the facade

In order to assess the influence of a door and the resulting additional heat demand in connection with the building, the building models without openings in the façade are simulated first. These studies are used as a reference for building models with doors.

Figure 18 shows the specific energy demand for heat (red bar) and cooling (blue bar) of the various building models.

As can be seen in Figure 18, the heat demand of the *manufacturing building model* without doors only totals15 kWh/m²a[9]. Furthermore, due to the resulting internal heat loads, a cooling demand of about 10 kWh/m² arises in order not to exceed the maximum target interior temperature of 28 °C.

The *workshop building model* has a specific heat demand of about 35 kWh/m²a[10]. This is more than twice as high compared to the *manufacturing building model*. This is caused by reduced internal loads as well as the adverse surface-to-volume ratio. Furthermore, there is almost no need for cooling, the maximum target interior temperature of 28 °C is not reached.

The *warehouse building model* has the highest heat demand of about 50 kWh/m²a[11], cooling is not necessary. The main difference is the barely existing internal heat load as there only is an artificial illumination of 6 W/m².

If we plan a 2-shift operation for the *warehouse building model* the annual heat demand only increases by 7 %. This relatively small increase of the heat demand can be explained by the highly insulated and sealed facade. Once the warehouse is heated to the target interior temperature, only a slight heat demand is needed to keep the interior temperature. This is achieved by lights permanently switched on (internal heat load) during the period of use.

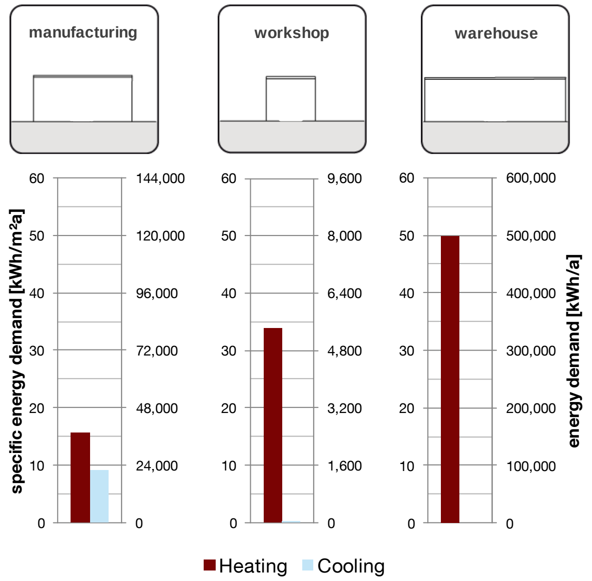


Figure 18: Specific and total energy demand for heating and cooling of the manufacturing, workshop and *warehouse building models* at 1-shift operation.

[9] If the *manufacturing building model* is simulated without internal heat loads, heat demand amounts to 80 kWh/m²a, cooling is not necessary. This shows the high influence of the internal heat loads on the energy demand of the building.

[10] If the *workshop building model* is simulated without internal loads the heat demand amounts to 65 kWh/m²a. The heat demand is thus halved by the internal heat loads.

[11] If the warehouse building model is simulated without internal loads the heat demand amounts to 60 kWh/m²a. As we only plan a lighting of 150 lx and 6 W/m² as internal load, the heat demand only drops by 20% taking into account the lighting heat.

6. Energy assessment of the door-specific variables

6.1 Introduction

This chapter deals with the quantification of door-specific variables related to the energy balance - especially the heat demand. The assessment is based on the building models described in Chapter 5. Individual parameters of a door (e.g. heat transition coefficient, opening duration) are varied and (unless otherwise stated) based on one door in the façade. Since the number of doors does not only depend on the building but also on the type of use of the building it is difficult to make general statements.

The area ratio of one door in relation to the façade surface for the investigated building models is:

	manufacturing	workshop	warehouse
Area ratio of door in relation to facade surface	16 m² / 2,000 m²	16 m² / 336 m²	16 m² / 5,600 m²
	0.8 %	4.8 %	0.3 %

If there are several doors in the façade, the heat loss and the additional heat demand increase according to the number of doors where the influence of a throughflow of air within the building (e.g. opposite opened doors) must be considered. This effect is studied for the *manufacturing building model* in Chapter 6.5.

6.2 Variation of the opening duration

In order to make an initial estimate of the heat loss through doors, an average opening time during the period of use is set. For this purpose, a 4 x 4 m large door with “standard technical features” is inserted in the south-facing façade of the building model.

The following values have been set: heat transition coefficient of 3 W/m²K, an air permeability class of 1 in accordance with [EN 12426] (see Chapter 3.1.2) and in a next step an opening time varying from 0 min/h (door remains closed) to 20 min/h (door stays open 20 min/h during the operation time of the building).

6.2.1 Heat loss and additional heat demand

Figure 19 shows the annual heat loss of the door by transmission, leakage and opening up and the additional heat demand related to the (global) door-open time (DOT) per hour. The percentage of additional heat demand related to the respective building model without doors is indicated in the diagrams above the red bar. The diagrams show the absolute additional heat demand in kWh/a.

If the door remains closed (opening time 0 min/h) the heat demand of the building rises compared to the building model without doors due to the poorer heat transition coefficient (3 W/m²K) compared to the façade (0.24 W/m²K) and the selected air permeability class. For the *manufacturing building model,* the additional heat demand totals 5 % or approximately 1,300 kWh/a, 19 % or approximately 1,000 kWh/a for the *workshop building model,* and 0.5 % or approximately 2,400 kWh/a for the *warehouse building model*[12].

An increase of the opening time results in high additional heat demand especially for the manufacturing and *warehouse building model*s. Opening the door 6 minutes per hour during the period of use leads to 27 % or approximately 10,200 kWh/a additional heat demand for the *manufacturing building model* (*warehouse building model* 1,9 % or 9,700 kWh/a). The heat loss through the open door is largely proportional to the opening time due to the large volume of both buildings.

[12] The low percentage impact of additional heat demand for the warehouse building model can be explained by the very small area ratio of doors in relation to façade surface. As the area ratio of doors in relation to the façade surface is quite considerable in warehouse buildings, the additional heat demand of the building increases in accordance with the number of doors. The warehouse building model has a higher additional heat demand with closed door than the two other building models, since the internal heat loads are lower (2,400 kWh/a compared to 1,300 kWh/a for the *manufacturing building model* and compared to 1,000 kWh/a for the *workshop building model*, respectively).

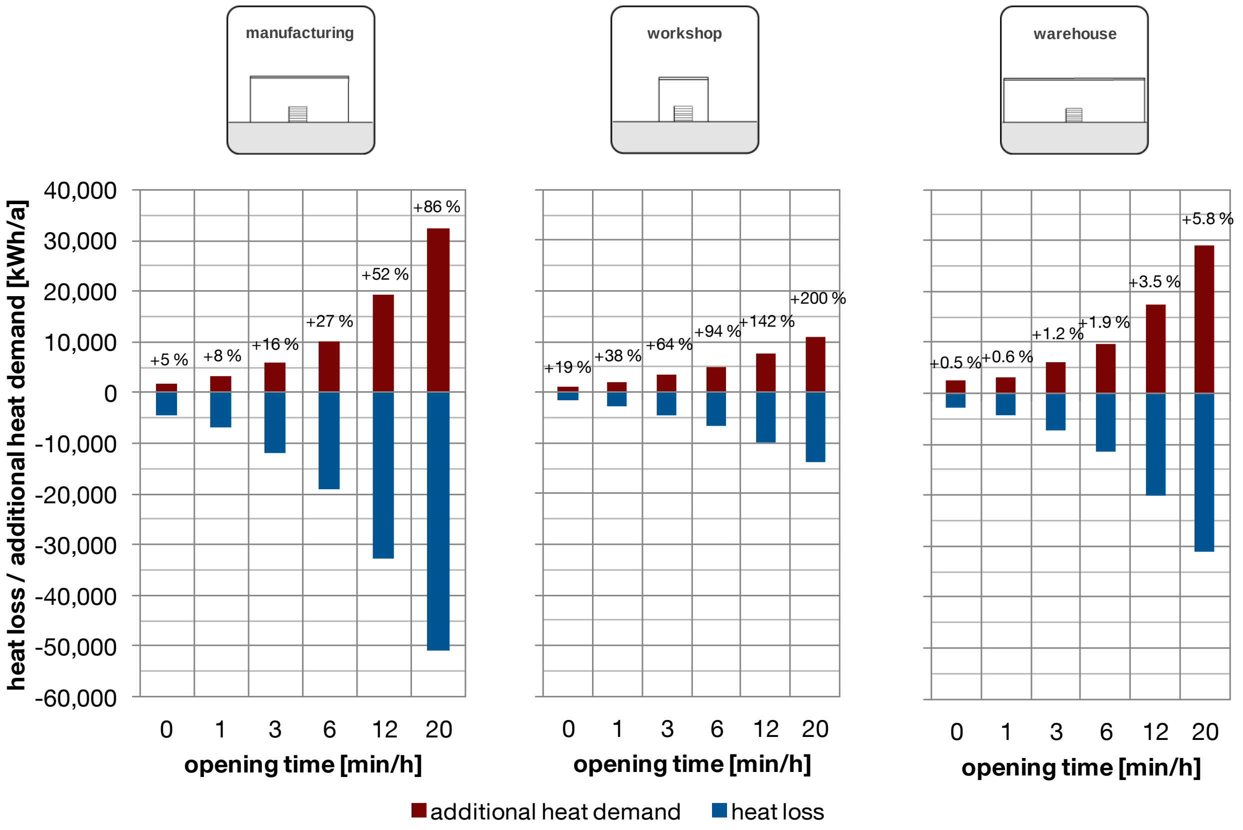


Figure 19: Heat loss through transmission, leakage and opening and additional heat demand related to the respective building models without doors for the building models manufacturing, workshop and warehouse.

For the *workshop building model*, the influence on the heat demand in absolute numbers is lower. This is due to the following differences in the types:

- The volume of the building model (960 m³) is substantially lower than in the *manufacturing* and *warehouse building model*. Therefore, it cools down faster.
- the target interior temperature is only 15 °C (manufacturing: 20 °C, warehouse: 17 °C), the thermal air exchange is less

Due to the small dimensions of the workshop building, however, the specific (percentage) effect of the door on the heat demand of the building is much higher.

Figure 20 shows the connection between the opening period and ventilation heat loss for the three building models. In the *manufacturing* and *warehouse building model,* the ventilation heat loss is largely proportional to the opening period due to the large volume. In the *workshop building model*, the ventilation heat loss does not rise as strongly due to the differences mentioned above.

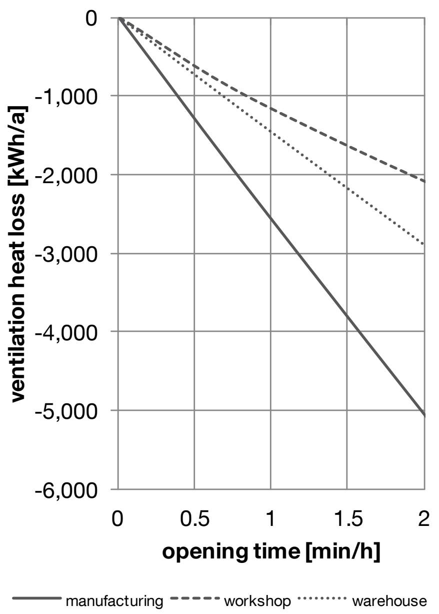


Figure 20: Ventilation heat loss in relation to opening time.

Furthermore, it is striking that in the *manufacturing building model* the heat loss through the door (blue bar) is significantly higher than the additional heat demand (red bar). This is due to a “compensation” of the heat loss by the internal heat loads. In a monthly comparison, this is shown as an example for an average door opening time of 6 min/h in Figure 21.

Particularly, in the transitional months, but also during summer months from June to August heat loss is caused by the door when the exterior temperature is lower than the interior temperature. The target interior temperature doesn’t fall below 20 °C, which is a prerequisite for turning on the ideal heating system. This effect can mainly be seen in the *manufacturing building model* as the internal heat loads result in extra heat up of the building.

6.2.2 Proportion of heat loss caused by transmission, leakage an opening of the door

Figure 22 shows the percentage distribution of heat losses by transmission, leakage and opening of the door in relation to the average opening time of the door as an example for the *manufacturing building model*.
With regard to boundary conditions chosen for the door and the building the transmission heat loss outweighs the heat loss through leakage if the door remains closed. However, even if the door is open only 3 minutes per hour the ventilation heat loss outweigh the heat losses through transmission and leakage.
This statement is also valid for the workshop and *warehouse building model*s. The percentage distribution of heat losses is similar to *manufacturing building model*.

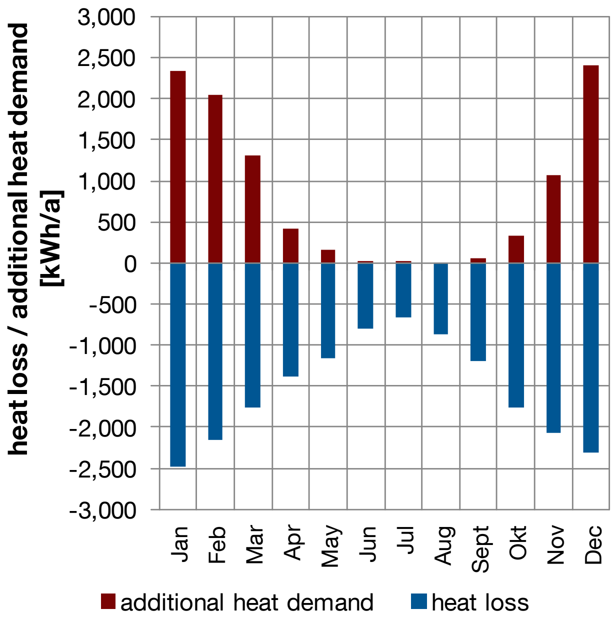


Figure 21: Heat loss through transmission, leakage and opening of the door and additional heat demand of one year with an average opening time of 6 min/h.

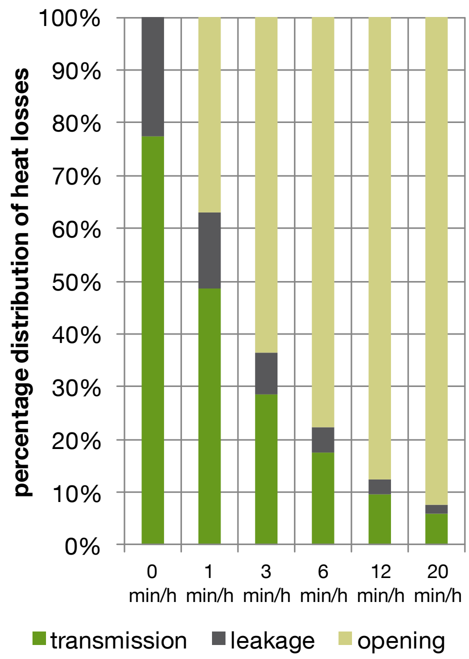


Figure 22: Percentage distribution of heat losses through the door by transmission, leakage and opening of the door in relation to the average opening time of the door as an example for the *manufacturing building model*.

6.3 Variation of heat transition coefficient and air permeability class

Since doors are closed over a longer period of time (e.g. on weekends), the influence of heat loss by transmission and leaks is examined independently.
The heat transition coefficient is a parameter for heat loss due to transmission, see Chapter 3.1.1. The lower the heat transition coefficient, the lower the transmission heat loss. The tightness of a door is specified by the air permeability class, see Chapter 3.1.2. The following principles can be applied here: the higher the permeability class, the tighter the door.

Since both types of losses only occur when the door is closed the "worst case" chosen for the following investigation is a door that remains closed the whole year.

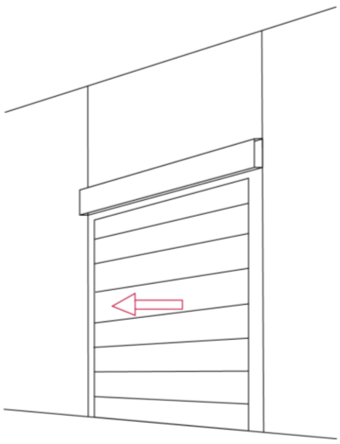


Figure 23: Transmission heat loss.

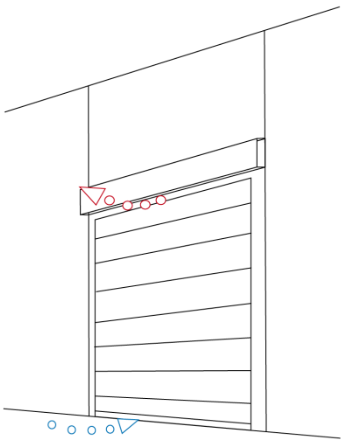


Figure 24: Heat loss caused by leakages.

6.3.1 Variation of the heat transition coefficient

The influence of the heat transition coefficient ranging from 1 W/m²K (high thermally insulated door) to 5 W/m²K (door with low thermal insulation) can be seen in Figure 25.

In the *manufacturing building model*, the additional heat demand increases by 5 % or 1,700 kWh/a, when the heat transition coefficient varies from 1 W/m²K to 5 W/m²K. Similar to the previous investigation on variation of the door´s stay-open time, the heat loss by transmission is greater than the resulting additional heat demand. When the interior temperature is higher than the minimum target temperature (20 °C), a transmission heat loss results but does not lead to an additional heat demand.

In the *workshop building model*, varying the heat transition coefficient results in an additional heat demand of 18 % or 1,000 kWh/a. The transmission heat loss and the additional heat demand are lower compared to the *manufacturing building model*. The main reason is the lower minimum target temperature of 15 °C (*manufacturing building model*: 20 °C). In addition, the absolute difference between heat loss and additional heat demand is smaller than in the *manufacturing building model*. This is due to the reduced internal heat load, so the ideal heating system has to compensate the transmission loss by the door to a greater extent.

In the *warehouse building model*, a variation of the heat transition coefficient results in an additional heat demand of 0.4 % or 1,870 kWh/a. Although the heat loss by transmission is lower than for the *manufacturing building model,* the additional heat demand is slightly higher. The low internal heat load in the *warehouse building model* (artificial lighting 6 W/m² only) does not compensate the transmission loss caused by the door. The ideal heating system must compensate the transmission loss of the door to a greater extent.

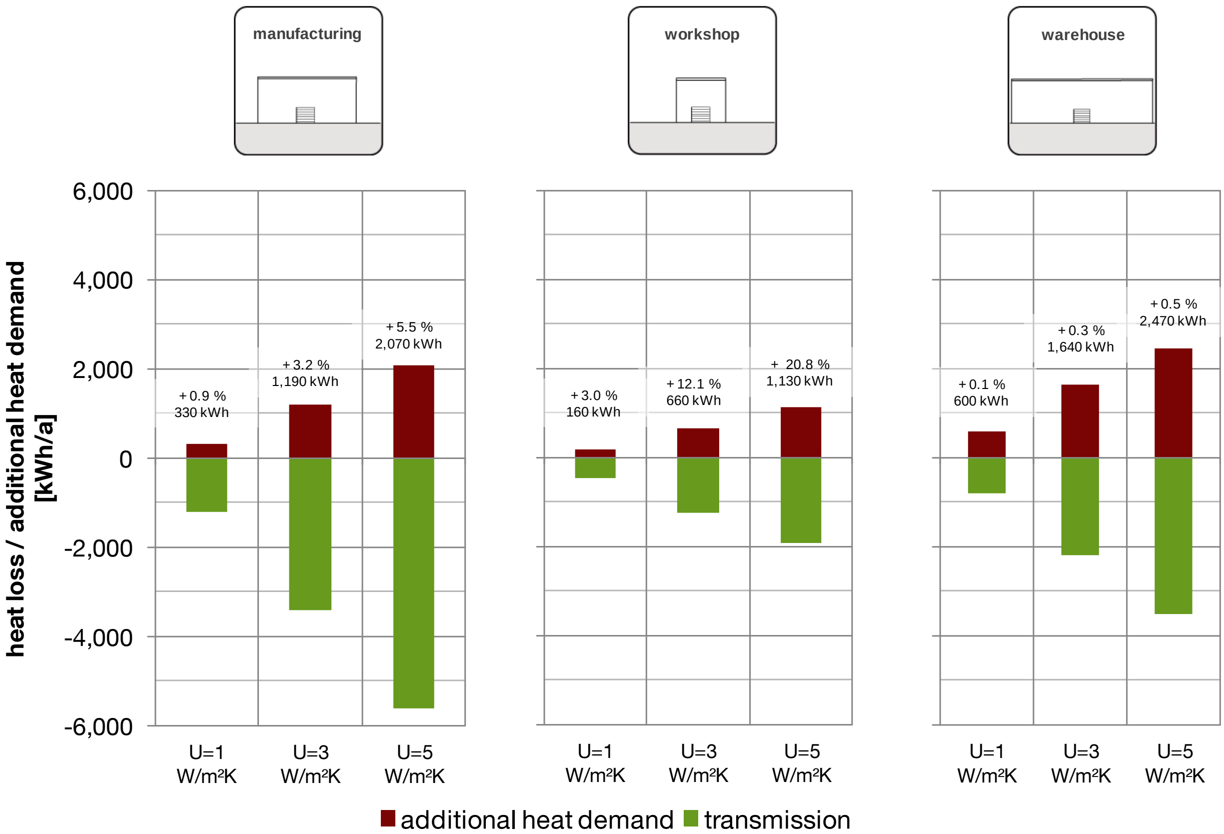


Figure 25: Variation of the u-value of the door.

6.3.2 Variation of the air permeability class

An always closed door is a prerequisite to analyze the heat loss caused by leakages. Since no corresponding value of air permeability is specified for the “air permeability class 0” in [EN 12426], an air permeability of 50 m³/m²h at 50 Pa pressure difference is set. The air permeability is more than twice as high as of a door with the “air permeability class 1”.

Figure 26 shows the influence of different air permeability classes of the door for the manufacturing, workshop and *warehouse building models*.

Taking into account the boundary conditions of the building models, the heat loss through leakage has less impact than the transmission heat loss through the door (previous Section). If the door has a higher level of air-tightness (air permeability class > 3) an additional heat demand cannot be explicitly calculated by the simulation due to the complex structure within the building model.

In the *manufacturing building model,* a variation of the air permeability class from 0 to 3 leads to an additional heat demand by 3 % or 1,100 kWh/a. Again, the heat loss is greater than the resulting additional heat demand, since the heating system is activated only if the temperature drops below the minimum target temperature.

In the *workshop building model,* a variation of the air permeability class leads to an increase of the additional heat demand by 14 % or 800 kWh/a. The heat loss through leakage of the door as well as the additional heat demand is lower than in the *manufacturing building model* due to the lower minimum target temperature of 15 °C.

In the *warehouse building model,* a variation of the air permeability class leads to an increase of the additional heat demand of 0.3 % or 1,550 kWh/a. Due to the reduced minimum target temperature of 17 °C, the heat loss through leakage is lower compared to the *manufacturing building model* (minimum target temperature 20 °C). However, the additional heat demand is slightly higher. This shows that the low internal heat load set in the *warehouse building model* (artificial lighting only 6 W/m²) hardly contributes to a compensation of the heat loss through leakages of the door. The ideal heating system must compensate the heat loss through the door to a greater extent, unlike in the *manufacturing building model*.

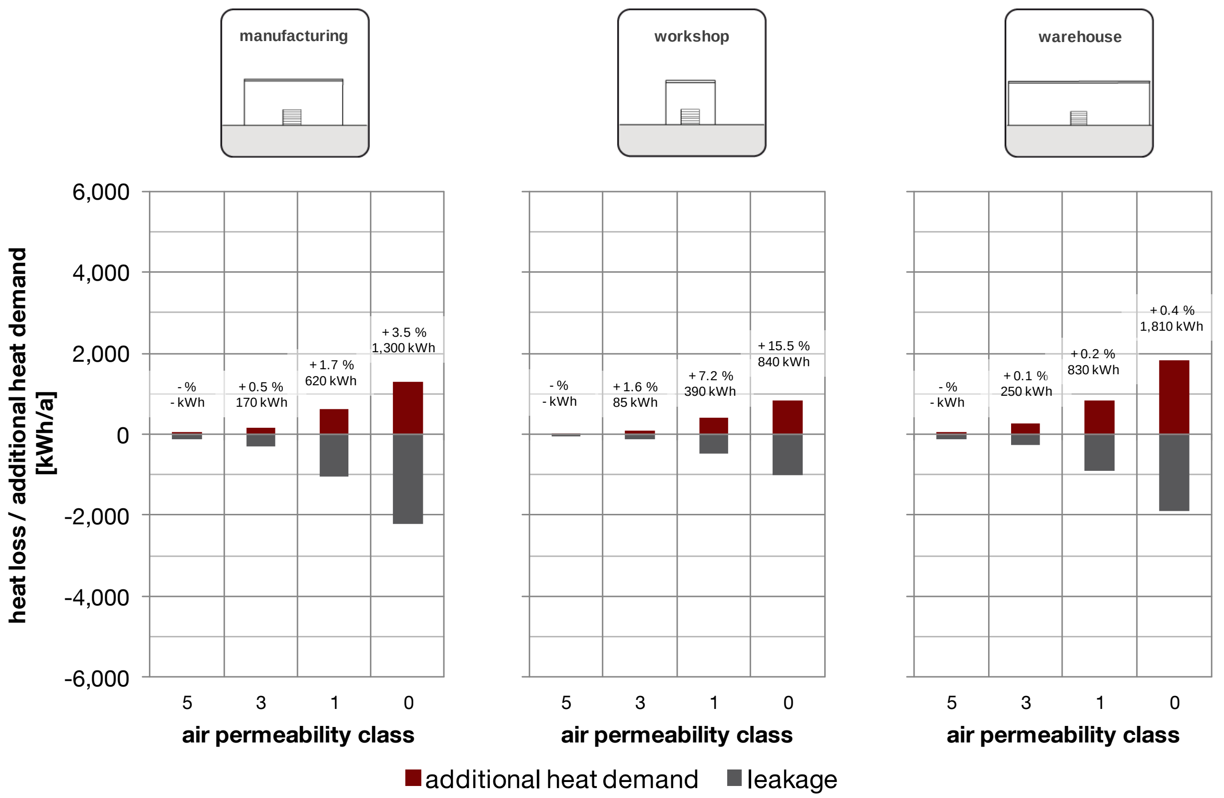


Figure 26: Variation of the air permeability of the door.

6.4 Drop of room temperature when door is opened

In the following chapters the temperature drop is investigated as a function of the opening time of the door. For this purpose, a finer zoning (8 x 8 m) of the building models has been defined, as the simulation period is limited to a few minutes.

The investigation of the temperature drop is done exemplarily for a cold winter day. Before the opening operation (t = 0 min), there is a uniform temperature distribution in the building.

6.4.1 *Manufacturing building model*

Figure 27 shows the interior temperature distribution for the manufacturing building model at a height of 1.4 m as a function of the opening period. To this end, the building model is divided into 35 zones, between which air exchange processes are simulated. According to the laws of the zone-based simulation model, homogeneous air conditions prevail within a zone with a vertical temperature gradient of 0.5 K/m. The selected zoning pattern is 8 x 8 m. The exterior temperature is -8.1 °C, the interior temperature at t = 0 min is 20.2 °C. The average wind speed is 0.5 m/s.

As expected, Figure 27 shows the largest drop of temperature in the zone in which the door is inserted ("door zone"). The boundary conditions chosen for this building model (internal heat loads, power of the ideal heater, temperature gradient over the height of the building, etc., see Chapter 5.2) and the investigation period lead to an effective penetration depth of the cold air of about 24 m when the door is open. After about 10 minutes, the temperature drops only slightly in all zones.

However, it should be noted that the simulation model can only provide an initial assessment for the temperature distribution, as many flow-relevant aspects such as local turbulence effects within the multi-zone model (see Chapter 4.1) cannot be considered.

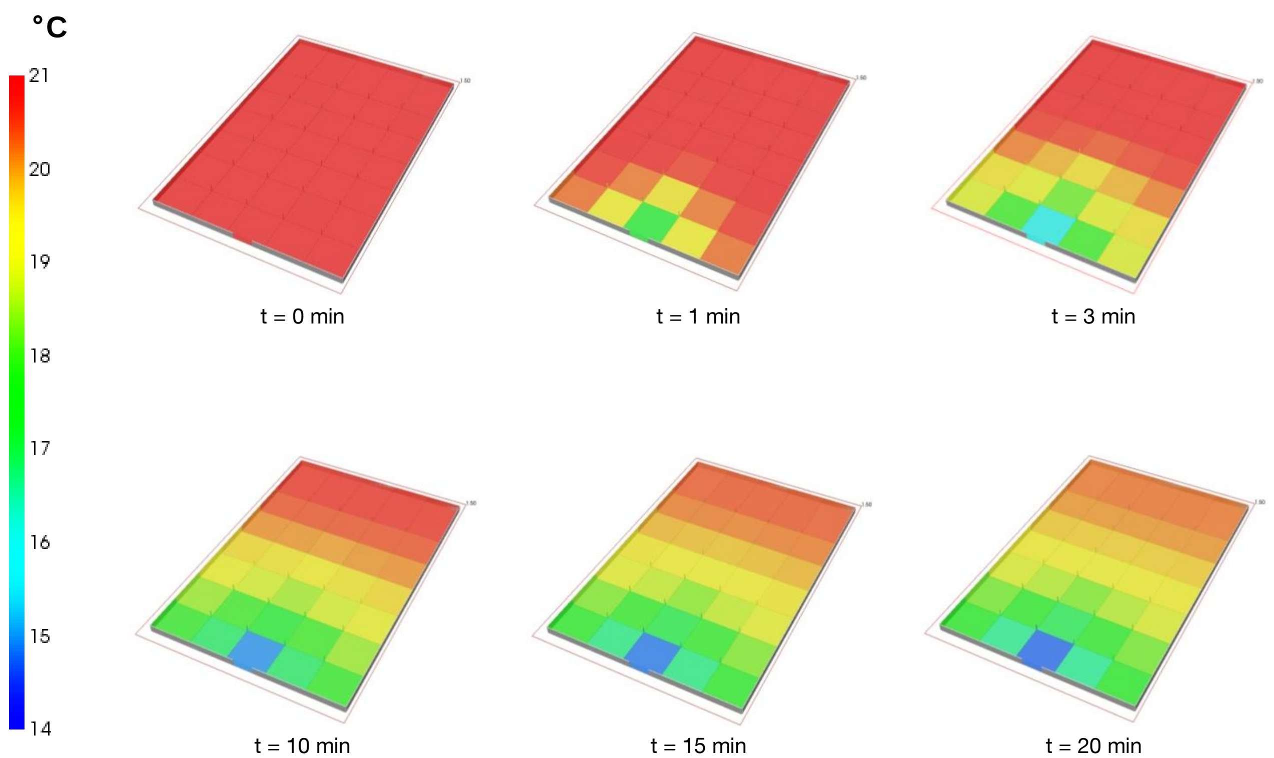


Figure 27: Simulated drop of interior temperature at opened door of the *manufacturing building model* on January 16 from 8:00 am to 8:20 am.

6.4.2 *Workshop building model*

For the *workshop building model,* a temperature profile is created for the same period as well. Due to the small footprint of this building model, the number of zones is limited to three only, see Figure 28. The following parameters have been chosen: temperature at a height of 1.4 m, exterior temperature -8.1 °C, interior temperature at t = 0 min 15.0 °C, average wind speed 0.5 m/s.
Due to the low volume of the building model, the drop of temperature is much higher when the door is open than for the *manufacturing building model* (a similar rapid temperature drop was observed in the measurement under real conditions, see Chapter 4.2). The interior temperature drops very quickly in the first minutes when the door is open, after 3 minutes the temperature drop is about 7 K. Therefore, the opening time should be reduced to a minimum in order to prevent rapid temperature drops of the hall.

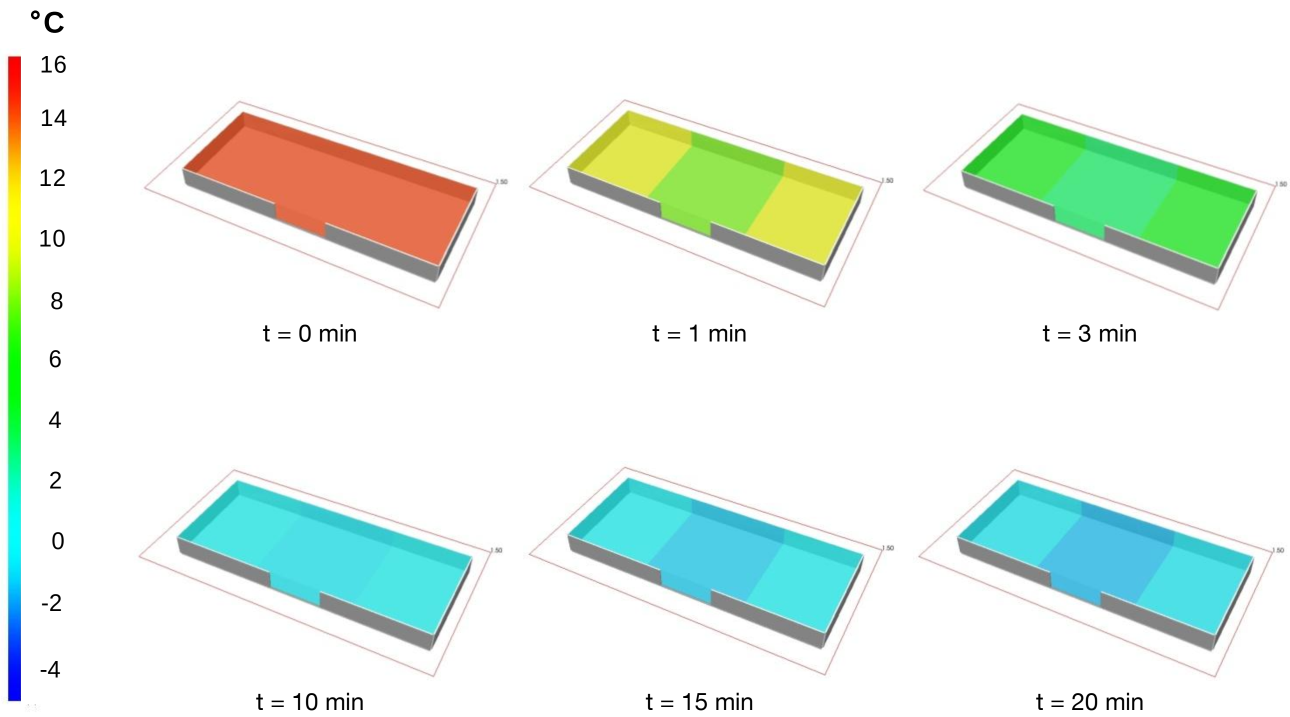


Figure 28: Simulated drop of interior temperature at opened door of the *workshop building model* on January 16 from 8:00 am to 8:20 am.

6.4.3 *Warehouse building model*

For the *warehouse building model*, the building footprint is divided into 169 zones, see Figure 29. The temperature is shown at a height of 1.4 m. The selected zoning pattern is 8 x 8 m. The exterior temperature is -8.1 °C, the interior temperature at t = 0 min 17.0 °C, the average wind speed 0.5 m/s.

It can be stated that the influence of the open door is highest at the beginning of the opening period, similar to the *manufacturing* and *workshop building model*. Furthermore, it is apparent that the temperature-effective penetration depth of the cold air (see Chapter 5.4) is about 24 m (similar to the *manufacturing building model)*. The temperature drop in the “door zone” after 10 minutes of opening time is around 4 K, the temperature at 1.4 m height drops to about 13 °C.

The investigation shows that a high temperature drop arises in the door area which influences the energy demand as well as the interior climate negatively. Therefore, optimization measures to reduce cold air entry should already be taken into account during the planning process of an industrial building, see Chapter 8.

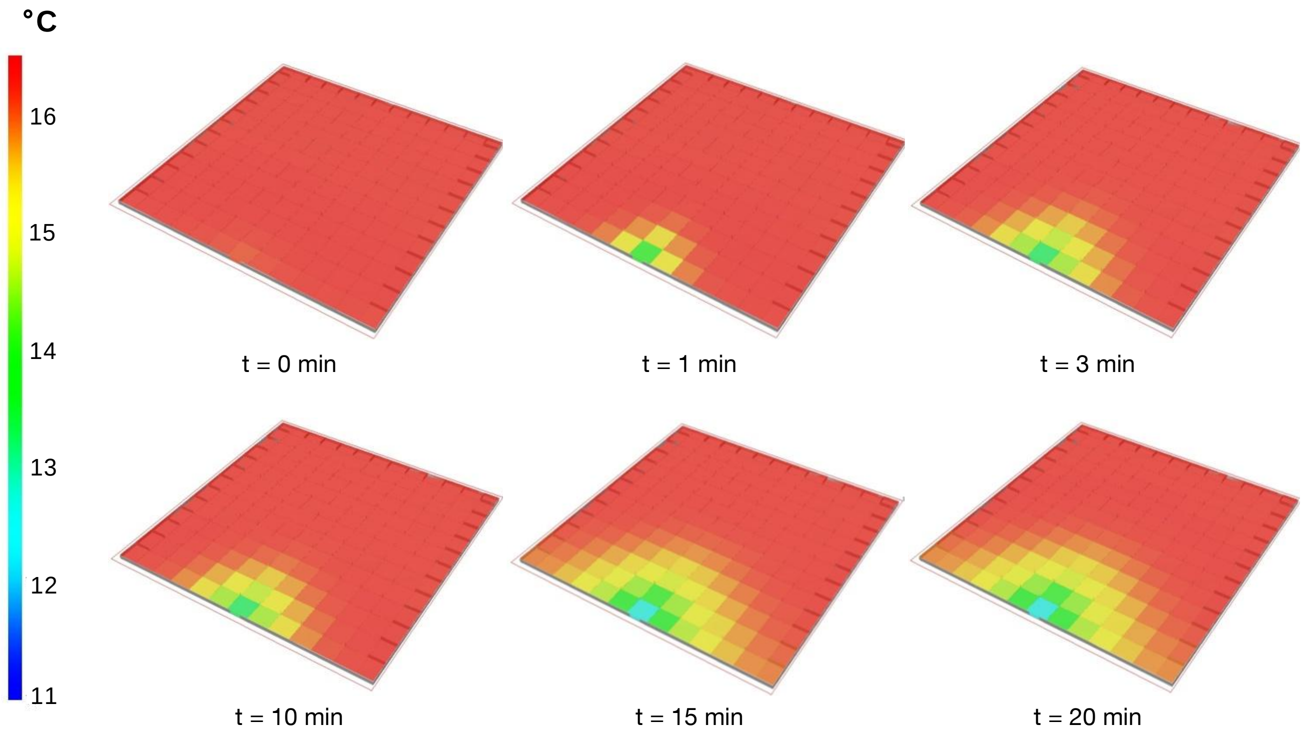
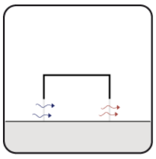


Figure 29: Simulated drop of interior temperature at opened door of the *warehouse building model* on January 16 from 8:00 am to 8:20 am.

6.5 Influence of multi-sided open doors



The influence of open doors on opposite sides of the building will be examined in this chapter as an example for the *manufacturing building model*. In this respect, an additional “door zone” with a second door is inserted into the 4-zone building model described in Chapter 5.2, see Figure 30.

It should be mentioned that the ventilation model for a single-sided, bidirectional air exchange, described in Chapter 4.1.1, is no longer appropriate. Instead, the ventilation model implemented in [IDA ICE 2012] is used to calculate the influence of simultaneously opened doors.

The calculation determines the air flow rates via a flow network within the building zones with flow coefficients and pressure coefficients of the façade (see Appendix). Based on the research methodology in Chapter 6.2, the comparison between two simultaneously opened doors and a delayed opening is simulated. For this purpose, average stay-open times of 1, 3 and 6 min/h have been set during the period of use. Opening and closing speeds are not considered. Both doors have the same properties as described in Chapter 6.2.

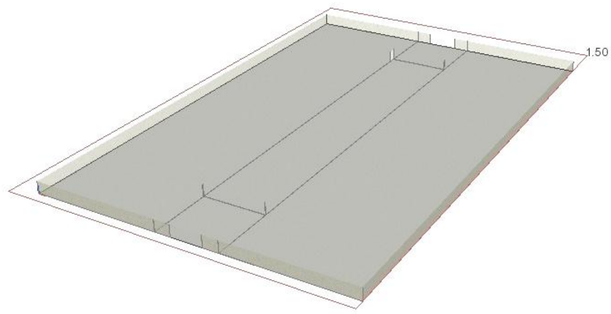


Figure 30: Section through the *manufacturing building model* in [IDA ICE 2012] showing the zoning and 2 doors on opposite sides.

Figure 31 shows the heat loss of the doors and the additional heat demand in case of "doors opened in succession" (left diagram) and "simultaneously opened doors" in the north-south orientated façade (middle diagram) and the east-west orientated façade (right diagram).

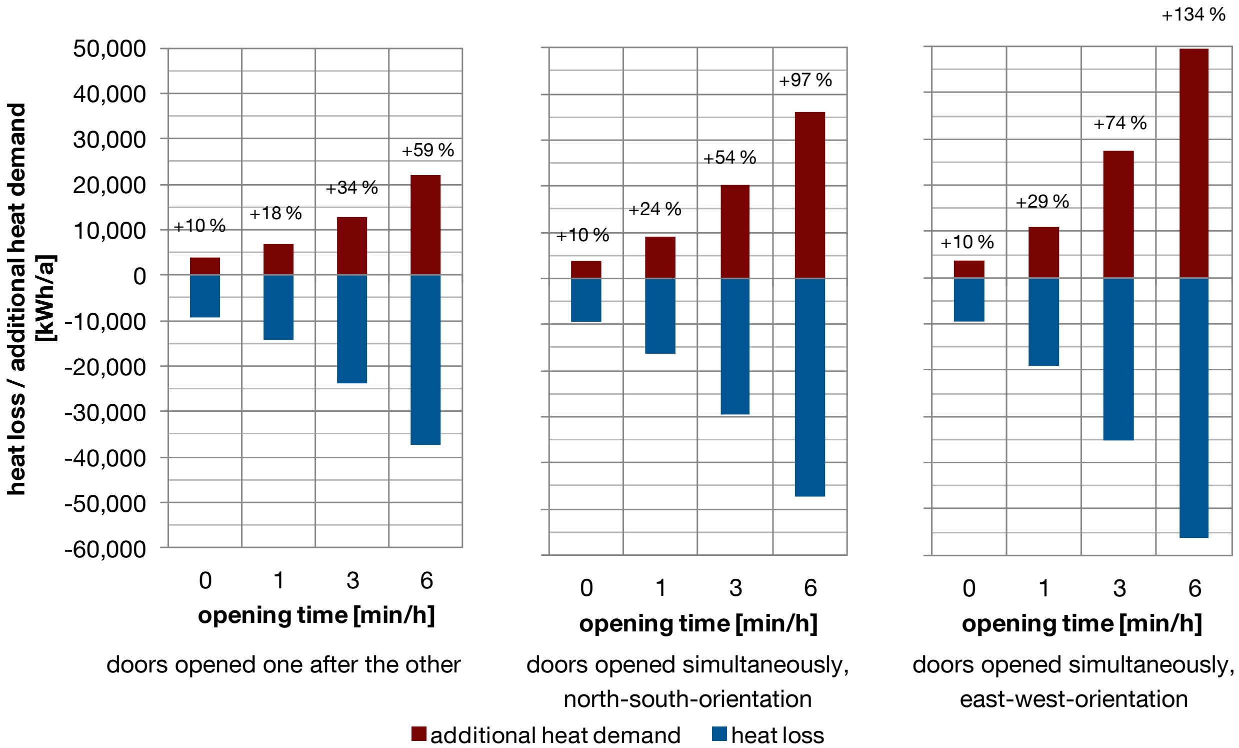


Figure 31: Additional heat demand and heat loss related to the respective building models without doors. Left diagram: doors opened one after the other. Middle diagram: doors opened simultaneously, north-south-orientation. Right diagram: doors opened simultaneously, east-west-orientation.

As expected, it can be seen that a much higher heat loss as well as a higher heat demand arise when the doors are opened simultaneously. The following initial assessment can be stated: the additional heat demand per 1 minute opening duration increases with north-south orientated doors by about 6 %, compared to the building model with successively opened doors. The high influence of simultaneously opened doors on the heat demand is even more obvious, when the doors are east-west orientated. The additional heat demand sums up to more than 11 % per 1-minute opening period, compared to the building model with successively opened doors. The considerable difference between north-south and east-west orientation is due to the main wind direction from east to west of the selected test reference year, see Figure 32.

The results show that there are many reasons to avoid opposite doors staying open simultaneously: not only for reasons of thermal comfort due to high air velocities in the building, but also in terms of energy. The wind direction is a non-negligible factor. If doors on opposite sides of the building are necessary (e.g. due to logistical reasons) a simultaneous opening should be avoided, e.g. using a barrier function of the door control or a traffic light system.

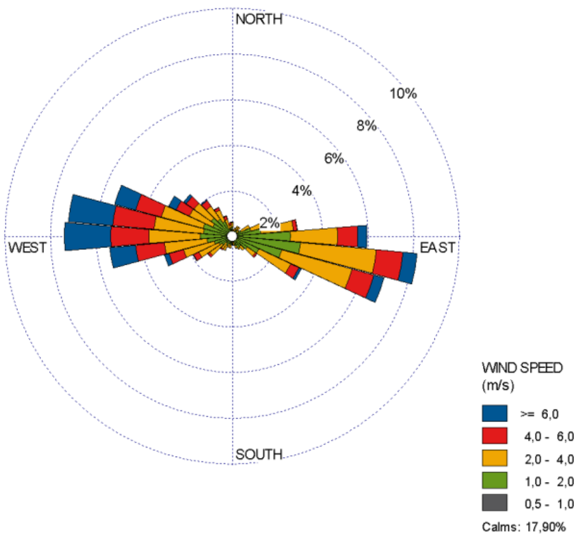


Figure 32: Wind rose of the test reference year 13 [DWD 2011], [WRPLOT 2011].

6.6 Electrical energy demand of door control, sensor and drive

Door operation differ in design and function, depending on the door type, door size and weight, the number of opening cycles as well as fast or slow-driven door system.

In accordance with [VDI 2409, 16], the following door operations are available

- Pneumatic door operators
- Hydraulic drives
- Electrical drive systems
- (Manual operation).

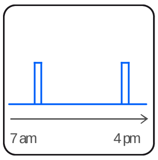
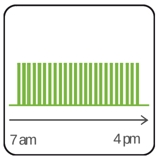
As the focus of the study is on the investigation of door systems and their energetic impact to the building, the various drive systems are not investigated.

The following two calculations give an initial estimation of the electrical energy consumed by control, sensor and drive in relation to the annual heat loss through door openings. For this, the scenarios *truck loading / unloading* and *regular forklift traffic* for the *manufacturing building model* are used. A detailed description of the scenarios is described in Chapter 7.4. The boundary conditions of the comparative energy considerations are summarized in Table 9.

Door control and sensory systems cause permanent stand-by energy consumptions. According to manufacturers, the power consumption sums up to 10 to 20 W, depending on the installed system. For the following calculations, a standby power of 15 W is calculated (5 W door control and 10 W sensor system, such as laser scanners on both sides of the door). This results in an annual electric energy demand of 131 kWh, assuming that these devices are not switched off outside the operation time.

The drive of the door is the second source of power consumption that must be considered in the calculation. The two following applications relate to the drive of the door.

Table 9: Comparison of energy consumption of door drive, controls, sensors and additional heat demand for the scenarios *truck loading / unloading* and *regular forklift traffic* in the *manufacturing building model*.

	truck loading / unloading	***regular forklift traffic***
scenario (see Chapter 7.4)		
	ST	**SST**
door type (see Chapter 7.1)		
operating time	261 working days 9 hours/day	
opening periods / day	2	270
∅ opening speed [m/s]	0.25	1.5
∅ closing speed [m/s]	0.25	0.8
door control and sensory system		
power [W]	15	
useable energy (8,760 h stand-by) [$kWh_{electric}$/a]	131	
primary energy (factor 2.6 in accord. with [ENEV 2009]) [$kWh_{electric}$/a]	342	
drive		
power [W]	550	2,200
useable energy [$kWh_{electric}$/a]	2.6	330
primary energy (factor 2.6 in accord. with [ENEV 2009]) [$kWh_{electric}$/a]	6.6	858
heating		
additional heating demand [$kWh_{thermal}$/a]	5,970	14,130
primary energy (factor 1.1 in accord. with [ENEV 2009] / 0.85 efficiency heat (gas boiler)) [$kWh_{thermal}$/a]	7,726	18,286

6.6.1 1st application: Sectional door and scenario *truck loading / unloading*

The first use case to examine the energy demand has low opening times of doors. In this application, the sectional door is opened in the morning and evening for 15 min. Considering the boundary conditions from Section 7.4.2, the additional heat demand totals 5,970 kWh/a, compared with a door that is always closed.

The electrical power of a typical drive for sectional doors was determined at 550 W using the results of the questionnaire mentioned in Chapter 3.2. To simplify the calculation, the drive has a constant power consumption during the opening and closing operation of 16 seconds each. This results in an energy consumption of about 5 Wh per door cycle. Due to the low number of cycles, the electric annual energy demand of the drive only sums up to 2.6 kWh.

Drive, control and sensor systems require electrical power. However, the heat loss caused by an open door must be balanced with thermal energy. For a comparison, the power consumption is calculated in primary energy. In accordance with [ENEV 2009], a primary energy factor of 2.6 has been chosen.

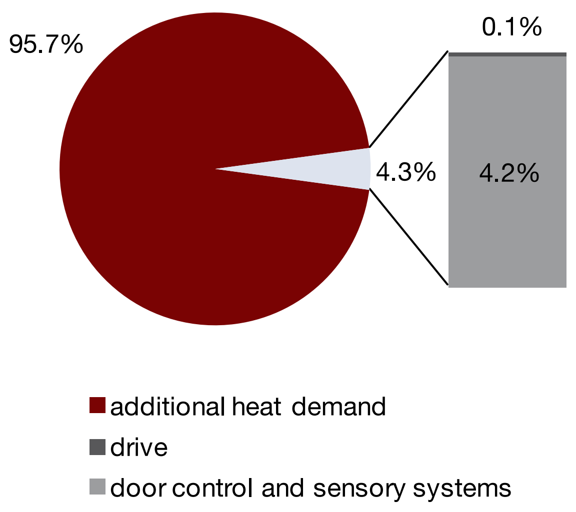


Figure 33: Comparison of energy consumption for heating, drive, door control and sensory systems. 1st application: sectional door and scenario *truck loading / unloading*.

The primary energy factor of heat generation is 1.1. Furthermore, an efficiency of 0.85 is taken into account for a gas boiler. In this application, the additional heat demand needed to compensate the ventilation heat loss totals 7,726 kWh/a, calculated in primary energy. The primary energy-equivalent of drive, control, and sensor sums up to 350 kWh/a. If the primary energy demand for heating is compared to the electric consumers (control, sensor and drive), the power consumption of the drive (0.1%) is negligible, see Figure 33. The comparison shows that two openings per day cause an additional heat demand of around 96 % of the total energy consumption, which is higher than the electric power consumption for control, sensor and drive.

6.6.2 2nd application: High-speed spiral door and scenario *regular forklift traffic*

The second use case represents a frequent opening and closing of the door (scenario *regular forklift traffic)*. The boundary conditions for this scenario are described in detail in Chapter 7.4.3. In such applications, mostly high-speed doors are used. To compare the energy consumption, a high-speed spiral door with a drive power of 2,200 W has been chosen. With the simplification of a constant drive power described in use case 1, the energy requirement of one door opening cycle is calculated at 4.7 Wh (power 2,200 W, opening time 2.7 s, closing time 5.0 s). This calculated value was compared to measurements on six high-speed spiral doors in a factory of a major automotive manufacturer. Due to the significantly higher number of cycles, the annual energy demand of the drive of 330 kWh is significantly higher than in the 1st application.

However, the frequent opening and long stay-open duration of the door leads to high ventilation heat loss. This increases the heat demand compared to an always closed door up to 14,130 kWh/a.

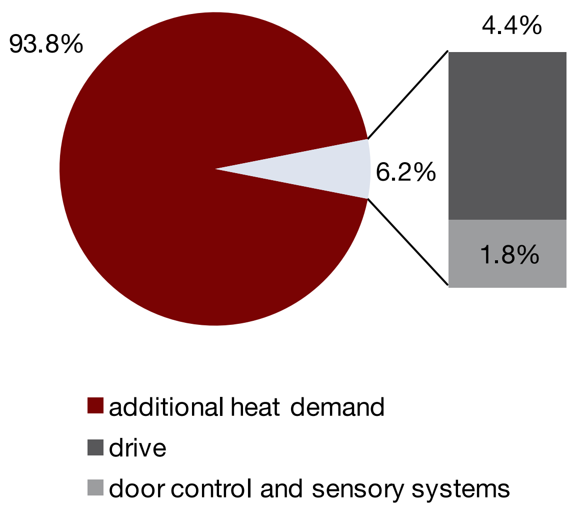


Figure 34: Comparison of energy consumption for heating, drive, door control and sensory systems. 2nd application: High-speed spiral door and scenario *regular forklift traffic*.

Just like the first use case, both the electrical and the thermal energy demand are converted in primary energy for a comparison.

The comparison illustrates that the percentage of electric consumers sums up to 6.2 %, which is of little importance, see Figure 34. It can be seen that the drive has a higher energy consumption than the control and sensor systems. However, the drive is of little importance compared to the heat demand caused by ventilation loss.

The calculation shows that the power consumption for drive, control and sensor only represent a small percentage of the energy balance. Furthermore, a replacement of high-speed doors with slow running doors leads in both applications (*truck loading / unloading* or *regular forklift traffic*) to largely identical results. The observations show that the energy consumption of the drive and the permanent stand-by mode of control and sensor is of little importance compared to the heat demand caused by ventilation heat loss.

6.7 Summary

This chapter deals with the energy assessment of door-specific factors. Considering the assumptions made in Chapter 4 and 5 the following results can be noted:

- The specified values for heat loss or additional heat demand relate to one door. Therefore, the percentage effect on the heat demand of the building must always be seen in relation to the facade surface. With several doors in the façade the calculated heat loss and the resulting additional heat demand increases according to the number of existing doors. Air flow rates can influence each other depending on the building geometry and spacing of the doors. Simultaneously open doors on opposite sides of buildings causes an additional increase in heat demand.
- Even at a 3-minute opening period per hour during the period of use the ventilation heat loss exceeds the heat loss by transmission and leakage of the door, regardless of the building model.
- The heat loss through the door, consisting of transmission, leakage and ventilation is higher than the resulting additional heat demand to keep the building at the required temperature level. The effect is enhanced by internal heat loads.
- The influence of the air transition coefficient and air permeability can be significant especially with a large number of doors in the façade, more particularly when the doors are rarely opened. The difference between a super-insulated and a poorly insulated door respectively a highly leak-proof door versus a door with poor tightness can be up to 1,900 kWh / a.
- Heat loss caused by transmission has a higher impact on heat demand than heat loss caused by leakage of the door.
- Due to the large volume of the manufacturing and *warehouse building model*s, heat loss caused by an open door is largely proportional to the opening period. In contrast the *workshop building model* cools down very quickly and has the greatest temperature drop as a result of its small volume. When the door is open, interior temperature decrease is greatest within the first few minutes. Due to the decreasing difference between interior and exterior temperature the air flow decreases with increasing opening duration. This shows that there is potential for optimizing comfort (avoiding noticeable drop in temperature and drafts) and energy savings by keeping stay-open periods as short as possible with a suitable sensor.
- The depth of penetration of outside air when the door is open can only be calculated on an individual basis and is influenced by many building and site-related factors. Based on the previously mentioned simplified assumptions this depth of penetration has been calculated at around 24 m depth of room.
- When opposite situated doors are simultaneously open, heat loss and additional heat demand are higher than successively open doors. A reference value for additional heat demand of around 6 % can be specified for a building flow-through in north-south direction and by approximately 11 % in east-west direction compared to the successive opening of the doors.
- The electrical energy demand required for door operation, consisting of drive, control and sensor system is of little importance compared to the heat loss of the door.

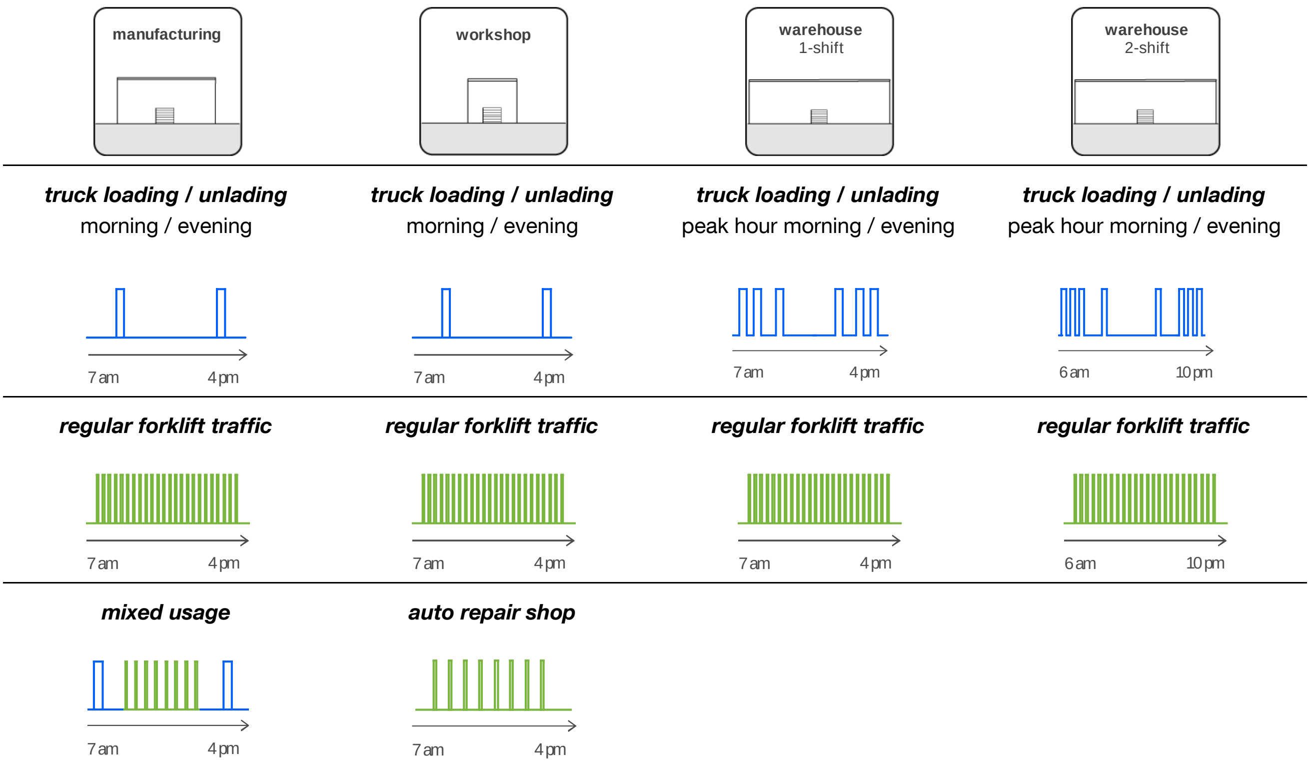
7. Development of scenarios and use-case related door opening characteristics

7.1 Overview of scenarios and procedure

This chapter deals with the development of several practice-oriented scenarios for the building models *manufacturing*, *workshop* and *warehouse* with corresponding door opening cycles and opening periods. By means of the developed scenarios, it is possible to investigate various applications in practice. Different user groups and operators of real estate, but also manufacturers of door systems can easily find themselves in the scenarios. The scenarios were developed by visits at a major automotive manufacturer as well as with the help of a questionnaire (see Appendix). The aim is to identify the best door types for each scenario in terms of energy efficiency and economic aspects.

A schematic overview of the scenarios is shown in Table 10. Detailed information on the opening cycles of doors and opening periods are given in the Chapters 7.4 to 7.6. Various door types are examined for each scenario: a fictitious “ideal door” serves as a reference for the evaluation of the real doors. The ideal door is characterized by ideal characteristics, e.g. no opening and closing time, the same heat transition coefficient as the building facade and absolute tightness when the door is closed. The specific characteristics of the simulated door types are summarized in Table 11.

Table 10: Schematic overview of the scenarios developed for the building models manufacturing, workshop and warehouse.

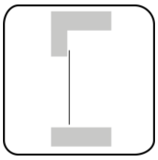


The following parameters have been chosen for the real doors:

- The heat transition coefficients of the real doors correspond to the average results from the evaluation of the questionnaire (see Chapter 3.2).
- The air permeability classes of the real doors represent averages of the results of the questionnaire (see Chapter 3.2). As [DIN EN 12426] does not give any value for the air permeability class 0, an air permeability of 50 m³/(m²h) at a pressure difference of 50 Pa has been assumed for both rolling doors. For the sectional door and high-speed spiral door the air permeability is 12 m³/(m²h) at a pressure difference of 50 Pa.
- As the opening and closing speed depend on the individual door and its drive, average opening and closing speeds have been set: opening speed of the high-speed spiral door and flexible high-speed door: 1.5 m/s (closing speed: 0.8 m/s); sectional door and rolling shutter 0.25 m/s (closing speed: 0.25 m/s).

Furthermore, a continuous operation of the ideal heating system is assumed in times of the opening operation, since in reality the heating system is not switched off.

Table 11: Specific characteristics of the simulated door types "ideal door" (iT), sectional door (ST), high speed spiral door (SST), rolling shutter (RT-L) and flexible high-speed door (RT-F).

	ideal door (iT)	**sectional door** (ST)	**high-speed spiral door** (SST)	**rolling shutter** (RT-L)	**flexible high-speed door** (RT-F)
					
u-value [W/m²K]	0.24	1.8	1.9	4.7	5.9
air permeability class [-]	tight	2	2	0	0
∅ opening speed [m/s]	∞	0.25	1.5	0.25	1.5
∅ closing speed [m/s]	∞	0.25	0.8	0.25	0.8
investment [€]	-	2,900 – 6,500	8,000 – 16,000	2,500 – 4,100	4,600 – 5,500

7.2 Explanation of the “scenario energy graphic”

Figure 35 illustrates the “scenario energy graphic” which shows the influence on the energy demand of each door for each scenario. The heat loss caused by transmission, leakage and opening is shown as a negative bar, the additional heat demand as a positive bar. The values above the bar indicate the percentage of additional heat demand compared to the “ideal door”. Above, the percentage and absolute additional heat demand compared to the building model without doors is shown. The white, not color filled area at the bar of the “real doors” corresponds to the heat loss and the additional heat demand of ideal door. Thus the energy influence of the respective door compared to the ideal door can be seen at a glance.

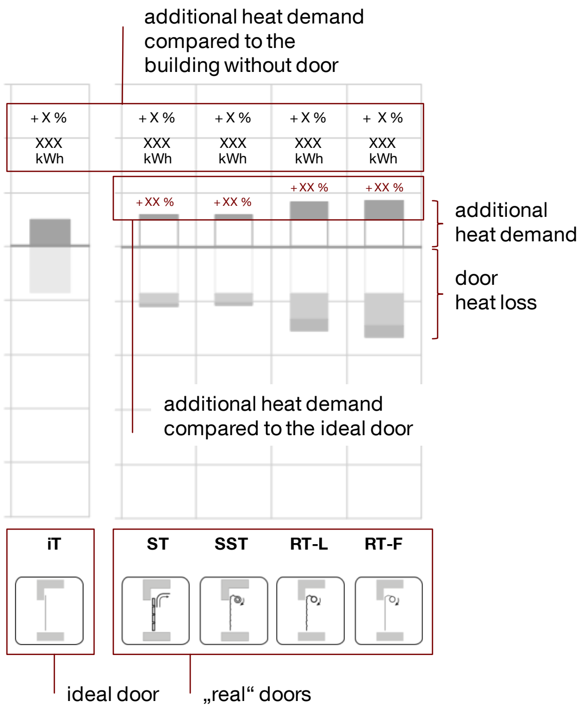


Figure 35: Explanation of the “scenario energy graphic”.

7.3 Explanation of the “scenario cost graphic”

Figure 36 shows the “scenario cost graphic”. The list price of the investigated door types and the resulting door-specific heat costs are the basis for the cost calculation.

To give an idea of the cumulated costs of the doors the following boundary conditions are specified:

- It is not possible to determine an average price of each door type because the research project is carried out vendor- and product-independently. Also the list prices can fluctuate significantly depending on the equipment (e.g. high proportion of glazing in the door leaf). Therefore, a range of the minimum and maximum investment is provided. The values were determined on the results of the questionnaire in Chapter 3.2 and refer to list prices for a door size of 16 m² including control and standard drive for each door type.
- The investment is made at time “0”.
- The development of costs is analyzed during an observation period of 20 years.
- The scenario does not change during the observation period.
- A typical gas boiler has been chosen for heat generation, the efficiency is defined between 90 and 95 % in [Hausladen et al. 2011]. Because of further system-related losses (pipes, etc.) a system efficiency of 85 % is assumed.
- The gas price for the industry differs significantly towards households and depends on the order quantity and the contractual framework between suppliers and industrial customer. For the cost analysis, a gas price for small industrial customers of about 4 cents/kWh is set [Frontier 2010, 118]. The average price increase of gas can be stated of approximately 7 % from 1998-2008 per year, so a yearly increase of 7 % during the observation period is assumed as well [Frontier 2010, 118].
- Maintenance costs for doors, consisting of inspection, maintenance and repair depend on the individual type of use, number of door openings and conditions individually determined between operator and door manufacturer. For this reason maintenance costs are not considered.
- The electrical energy demand of door control, sensor and drive is neglected due to the relatively minor influence compared to the heat loss of the door (see Chapter 6.6).

The illustrated “scenario cost graphic” shows the development of costs during a period of 20 years with the initial investment as minimum / maximum price range and the annual door-specific heating costs, assuming a price increase of gas of 7 %/a.

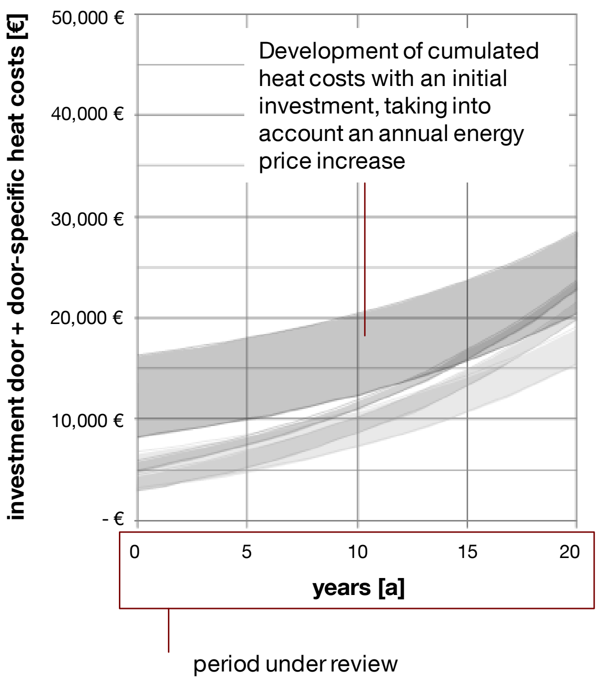
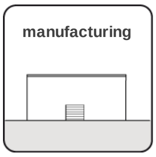


Figure 36: Explanation of the “scenario cost graphic”.

7.4 Scenarios of the manufacturing building model



This section deals with the analysis of three different scenarios in terms of opening periods for the *manufacturing building model*.

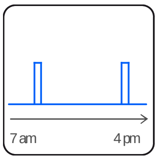
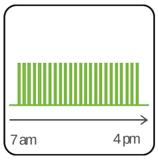
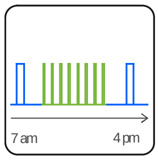
The scenario *truck loading / unloading* is characterized by a very low door opening frequency with only 2 openings / day in the morning and evening and a stay-open time of 15 min / opening.

In the scenario *regular forklift traffic* a frequent opening and closing of the door is simulated. The door opening frequency totals 30 / hour, with a stay-open time of 15 seconds / opening.

The scenario *mixed usage* is characterized by a *truck loading / unloading* with occasional forklift traffic with two longer openings in the morning and evening and a moderate door opening frequency of 6 openings per hour during the operation period.

Table 12 summarizes the 3 scenarios.

Table 12: Overview of the simulated scenarios for the *manufacturing building model*.

	truck loading / unlading morning / evening	***regular forklift traffic***	***mixed usage***
			
opening characteristics	2 openings morning / evening	Frequent openings due to forklift traffic	2 openings of 15 min morning / evening, during the remaining operation period occasional forklift traffic
opening times	8:00 - 8:15 am, 3:00 - 3:15 pm	regularly from 7:00 am till 4:00 pm, 30 openings per hour	8:00 - 8:15 am, 3:00 - 3:15 pm, between 9:00 am and 3:00 pm 6 openings per hour
stay-open time per opening	15 min	15 s	15 min (morning/evening),15 s (remaining operation period)
openings/ Day	2	270	38

7.4.1 Comparison of the scenarios using the "ideal door", *manufacturing building model*

In a first step, the three scenarios will be compared using the "ideal door" (iT). Figure 37 shows the annual heat loss of the door (here: only ventilation heat loss caused by the ideal door) and the resulting additional heat demand for the scenarios *truck loading / unloading*, *regular forklift traffic* and *mixed usage*.
As shown in Chapter 6.2 and 6.3, the heat loss due to doors is higher than the resulting additional heat demand. This result can also be seen in the scenarios. For the scenario *truck loading / unloading* the additional heat demand totals 13 % respectively 5,000 kWh/a using the ideal door with the chosen boundary conditions compared to the building model without door (see Chapter 5.5). Regular forklift traffic results in a much higher additional heat demand. The additional heat demand rises by 27 %, or approximately 10,200 kWh/a. For a *mixed usage* of the door with two longer openings in the morning and evening and occasional forklift traffic the additional heat demand totals 17 % and approximately 6,400 kWh/a.
If the summed opening periods per day were compared, it can be noticed that the scenario *regular forklift traffic* has a longer opening period (67.5 min/d) than the other scenarios (*truck loading / unloading*: 30 min/d, *mixed usage*: 39 min/d).

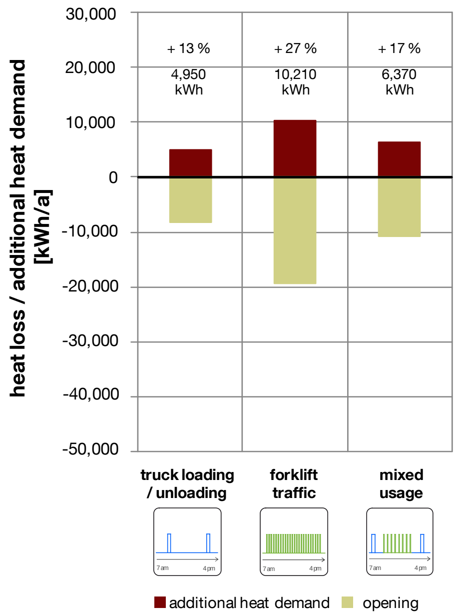


Figure 37: Comparison of the scenarios *truck loading / unloading*, *regular forklift traffic* and *mixed usage* in terms of additional heat demand and heat loss for the "ideal door", *manufacturing building model*.

This explains the higher additional heat demand in this scenario compared to the other two scenarios when using the ideal door.
As mentioned in the building model description in Chapter 5.2 a "door zone" of 8 x 8 m is defined "behind" the door. With this "door zone" the local temperature near the door can be determined for various scenarios. Thereby a first statement about the temperature distribution at different door opening periods over one year can be made, see Figure 38.

The first bar represents the temperature distribution in the "door zone" of the *manufacturing building model* with closed door, here 1 % represents around 24 hours operation time[13]. The “comfortable temperature range” is set between 20 °C and 26 °C at a height of 1.4 m.
When the door is closed, it can be seen that temperatures above 26 °C prevail in approximately 40 % of the usage time, primarily on warm summer days. Furthermore, internal heat loads result in higher temperatures. When the temperature is above 28 °C the hall is cooled by an ideal cooling system, see Chapter 5.2. Furthermore, it is evident that the required minimum target temperature of 20 °C is always maintained.
As an “average temperature” is calculated in the “door zone” (see Chapter 5.2), the temperature rarely falls below 18 °C in the examined scenarios. In a finer resolution of the zone significantly colder temperatures would prevail near the door.
Due to two door openings per day with stay-open times of 15 min (scenario *truck loading / unloading*) temperatures below the target temperature in the “door zone” arise 10 % of the year respectively 240 h/a. In the scenario *regular forklift traffic*, temperatures below 20 °C prevail at 30 % of the year respectively 720 h/a. The proportion of temperatures below 18 °C is lower compared to the scenario *truck loading / unloading* because of the shorter stay-open time per opening. In the scenario *mixed usage* the proportion of temperatures below the target temperature only rises slightly compared to the scenario *truck loading / unloading*, because there are only 6 short openings of 15 s per hour in addition to the two longer openings of the door in the morning and evening.

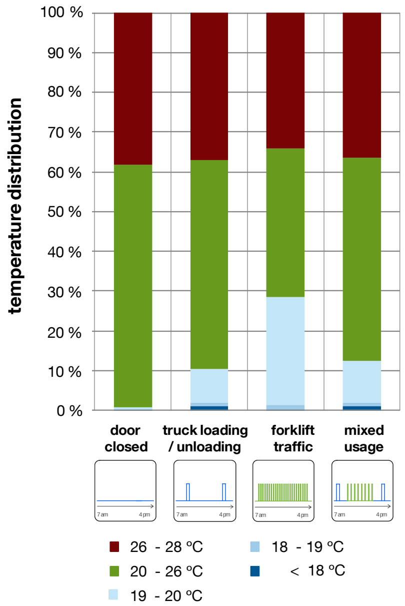


Figure 38: Temperature distribution of the scenarios of the *manufacturing building model* in the “door zone” using the “ideal door” at a room height of 1.4 m during the operation time. Simulation time step: 30 s. Observation period: 1 year.

Hereinafter the real door types are examined in terms of energy and from an economic point of view for each scenario.

[13] The simulation is based on a daily usage time of the building of 9 h from Monday till Friday, see Chapter 5.

7.4.2 Scenario *truck loading / unloading*, *manufacturing building model*

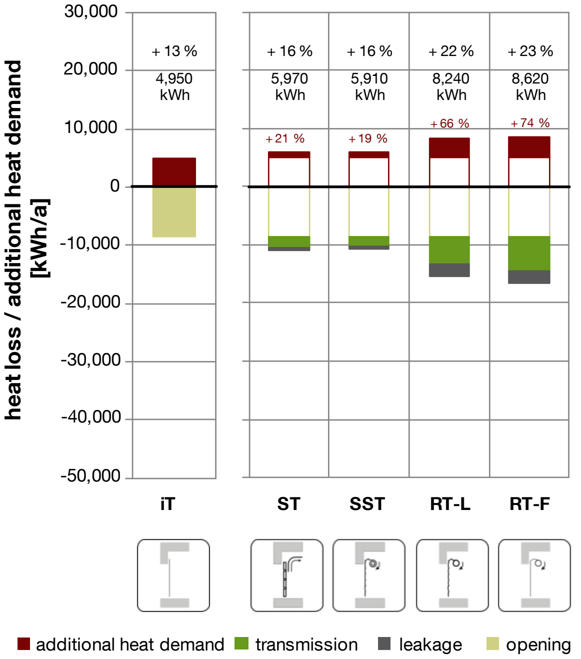


Figure 39: Additional heat demand and heat loss of each door in the scenario *truck loading / unloading*.

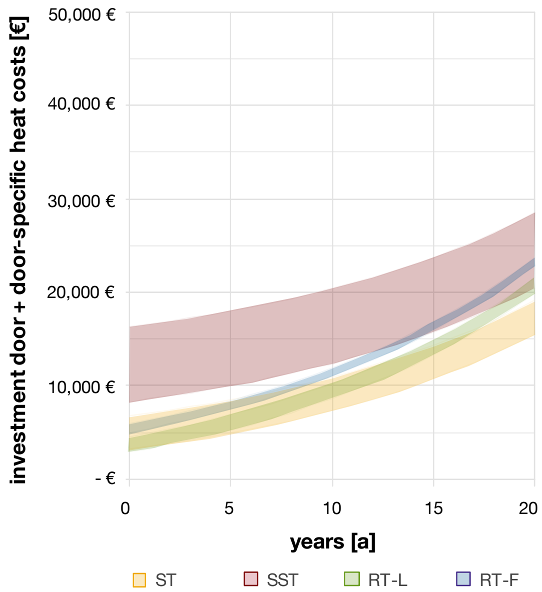


Figure 40: Door-specific investment and cumulated costs over 20 years in the scenario *truck loading / unloading*.

The scenario *truck loading / unloading* is characterized by a very low door opening frequency with only two openings in the morning / evening per day. The stay-open time is 15 min per opening.
Figure 39 shows the energetic impact of the various door types for the scenario *truck loading / unloading* of the *manufacturing building model*.
When using the ideal door the additional heat demand totals 13 % respectively around 5,000 kWh/a compared to the building model without doors. The door types ST (sectional door) and SST (high-speed spiral door) perform better than the two roller doors in terms of energy in this scenario due to a higher insulation standard and higher tightness. Due to the low door opening frequency, additional ventilation heat losses during opening and closing operation have no significant impact compared to the ideal door. The additional heat demand increases by 21 % for the sectional door and by 19 % or approximately 1,000 kWh/a for the high speed-spiral door. Therefore, it can be seen that the high-speed spiral door is only marginally more energy efficient than the sectional door, as the higher opening and closing speed has no energy advantage in two openings per day. The additional heat demand increases by 66 % respectively around 3,300 kWh/a for the rolling shutter and by 74 % respectively around 3,700 kWh/a for the fast running, but uninsulated flexible high-speed door (RT-F), which represents the most unfavorable door type in terms of energy in this scenario.
Figure 40 shows the cumulated costs of the doors, consisting of the investment and door-related heating costs (see explanation in chapter 7.3). Due to its high insulation and tightness the sectional door has the lowest cumulated costs over the years. The rolling shutter requires the lowest investment than the other door types. The higher annual heating costs, however, lead to higher cumulated costs than the sectional door after 10 years. Both high-speed doors have the highest cumulated costs in this scenario – the high-speed spiral door due to the high initial investment – the flexible high-speed door due to its additional heat costs resulting from the low insulation respectively air tightness.

Chapter 8.3 explains how to increase the energy efficiency of the high-speed spiral door (SST) and flexible high speed door (RT-F) by repeatedly opening and closing the door during a *truck loading / unloading* process.

7.4.3 Scenario *regular forklift traffic*, *manufacturing building model*

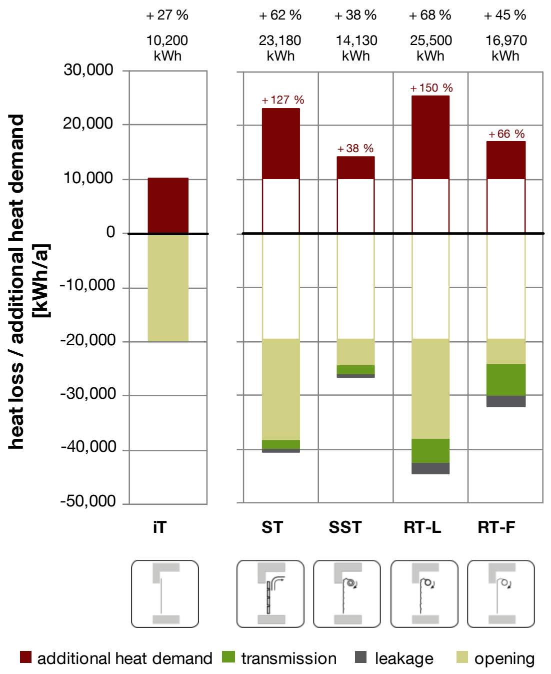


Figure 41: Additional heat demand and heat loss of each door in the scenario forklift traffic.

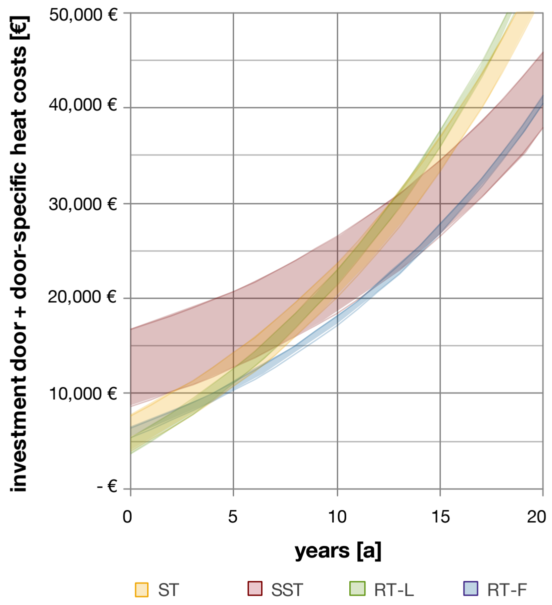


Figure 42: Door-specific investment and cumulated costs over 20 years in the scenario forklift traffic.

The scenario regular truck traffic describes a frequent opening and closing of the door with short stay-open periods.

Figure 41 shows the energetic impact of each door for the scenario *regular forklift traffic*. When using the ideal door the additional heat totals 27 % respectively around 10,200 kWh/a compared to the building model without doors. High opening and closing speeds of the high-speed spiral door (SST) and flexible high-speed door (RT-F) lead to significant energy savings compared to the slow running sectional door (ST) and the rolling shutter (RT-L). The additional heat demand increases for the SST by 38 % respectively around 3,900 kWh/a and by 66 % respectively around 7,800 kWh/a for the RT-F compared to the ideal door. When using the ST or RT-L the ventilation heat loss which occurs during the opening and closing operation in addition to the necessary stay-open time of 15 s leads to a substantial increase of the heat demand: compared to the ideal door, the additional heat demand increases by 127 % respectively around 13,000 kWh/a (ST) and by 150 % respectively around 15,300 kWh/a (RT-L).

If the additional heat loss of the SST are considered compared to the ideal door, the heat losses arising during opening and closing operation appear relatively low. A further improvement of the insulation standard (heat transition coefficient) is only partially advisable due to the low energy savings compared to the ventilation heat loss during the stay-open time. To increase the energy efficiency for this scenario it should be focused on a reduction of the necessary openings of the door and an object-size adapted door opening, see Chapter 8.5.

Figure 42 shows the cumulated costs of the doors, including investment and door-specific heat costs. Due to low heat costs the fast running doors SST and RT-F have significantly lower cumulated costs than the ST and RT-L.

It should be noted that high-speed doors are recommended for this scenario especially from a logistic point of view. The opening and closing duration (16 s) of the slow running ST and RT-L is more than twice as high as the stay-open time of 15 s per opening. This may affect the operational process greatly.

7.4.4 Scenario *mixed usage*, *manufacturing building model*

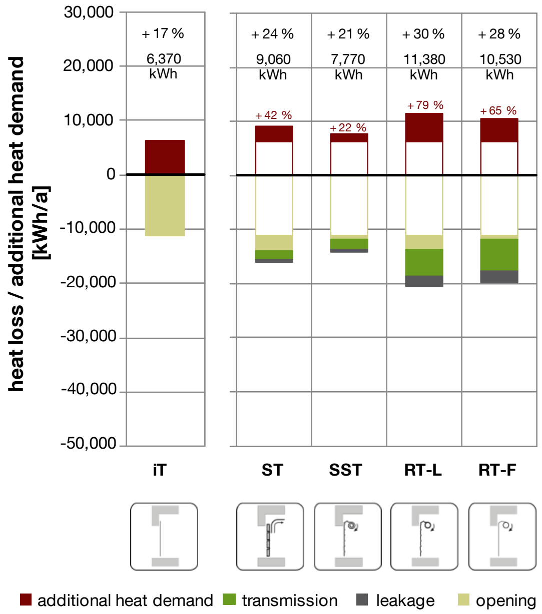


Figure 43: Additional heat demand and heat loss of each door in the scenario *mixed usage*.

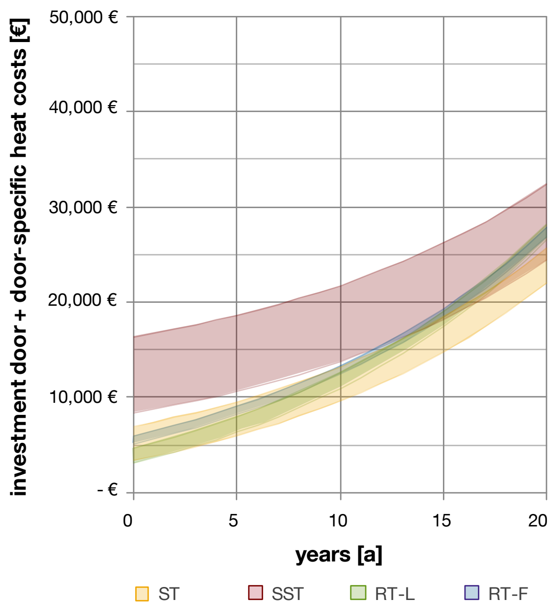


Figure 44: Door-specific investment and cumulated costs over 20 years in the scenario *mixed usage*.

The scenario *mixed usage* (*truck loading / unloading* with occasional forklift traffic) is characterized by two longer openings in the morning and evening and a moderate opening frequency of 6 openings per hour during the operation period.

Figure 43 shows the energetic impact of the investigated door types. Compared to the building model without doors the ideal door has an additional heat demand of 17 % respectively about 6,400 kWh/a. The high-speed spiral door (SST) is recommended from an energy perspective due to its high insulation and tightness as well as high opening and closing speeds. The additional heat demand totals 22 % respectively about 1,400 kWh/a compared to the ideal door. The additional heat loss of the SST is mainly caused by transmission losses when the door is closed. It can also be seen that the sectional door (ST) only performs slightly worse than the SST due to a good insulation and tightness in this scenario. The additional ventilation heat loss of the ST during opening and closing operations can be stated as relatively low compared to the ventilation heat loss during the stay-open time. The rolling shutter (RT-L) and the flexible high-speed door (RT-F) perform worse due to a lower insulation and tightness in this scenario,.

In Figure 44 it can be seen that the ST is recommended due to a low investment and low heating costs compared to the other doors.

7.5 Scenarios of the workshop building model

This chapter deals with the analysis of three different scenarios in terms of opening durations for the *workshop building model*.

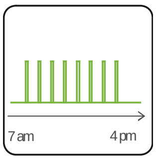
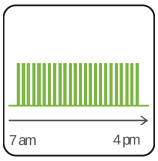
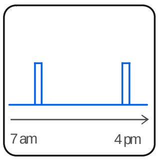
The scenario *auto repair shop* represents typical opening characteristics for car repair shops with 4 openings per hour. As an example, a general inspection of a vehicle is estimated at approximately 15 min. A stay open-time of 30 s is assumed for the entry and exit of one car.

The scenario *regular forklift traffic* complies with the scenario of the *manufacturing building model*. The opening frequency of the door totals 30 openings per hour in the operation time, the stay-open time has been set at 15 s per opening.

The scenario *truck loading / unloading* reflects a longer stay-open period of the door with two openings in the morning and evening.

Table 13 summarizes the three scenarios.

Table 13: Overview of the simulated scenarios for *workshop building model*.

	auto repair shop	***regular forklift traffic***	***truck loading / unlading*** morning / evening
			
opening characteristics	frequent openings	frequent openings due to forklift traffic	2 openings morning / evening
opening times	7:00 am till 4:00 pm, 4 openings per hour	regularly from 7:00 am till 4:00 pm, 30 openings per hour	8:00 - 8:15 am, 3:00 - 3:15 pm
stay-open time per opening	30 s	15 s	15 min
openings/ Day	36	270	2

7.5.1 Comparison of the scenarios using the "ideal door", *workshop building model*

Figure 45 shows the annual heat loss of the door and the resulting additional heat demand for the scenarios *auto repair shop*, *regular forklift traffic* and *truck loading / unloading*.

As described in the scenario comparison of the *manufacturing building model* in Chapter 7.4.1, different opening characteristics lead to different heat losses and additional heat demands.

The high influence of door openings on the energy demand of the building model workshop has already been described in Chapter 6.2.1. A frequent door opening (scenario *regular forklift traffic*) results in an additional heat demand of 160 % respectively about 8,700 kWh/a compared to the building model without doors (see Chapter 5.5). The heat demand is thus more than doubled in this scenario. The resulting heat demand of the building totals about 88 kWh/m²a (building model without doors: approx. 35 kWh/m²a).

The scenario *regular forklift traffic* shows a significantly higher summed opening period compared to the other scenarios (*regular forklift traffic*: 67.5 min/d, *auto repair shop*: 18 min/d, *truck loading / unloading*: 30 min/d). This explains the higher additional heat demand when using the ideal door.

Although the summed opening period in the scenario *auto repair shop* is lower by almost half compared to the scenario *truck loading / unloading*, a higher additional heat demand results. This is caused by a very rapid temperature drop at the beginning of an opening period due to the small building volume (see Chapter 6.4.2 for an opening period of up to 20 min).

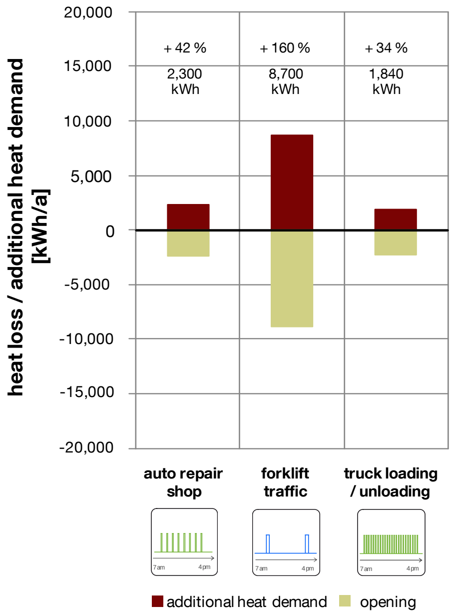


Figure 45: Comparison of the scenarios *auto repair shop*, forklift traffic and *truck loading / unloading* in terms of additional heat demand and heat loss for the "ideal door", *workshop building model*.

Figure 46 shows the temperature distribution in the "door zone" (see Chapter 5.3) expressed as a percentage over one year when using the "ideal door".

The first bar represents the temperature distribution in the “door zone” of the *workshop building model* with closed door, here 1 % represents around 24 hours usage time. The “comfortable temperature range” is set between 15 °C and 26 °C at a height of 1.4 m.

When the door is closed, it can be seen that the comfortable temperature range is maintained during almost the whole usage time. Temperatures above 26 °C prevail at about 4 % of the usage time.

Due to four openings per hour with stay-open times of 30 s (scenario *auto repair shop*), temperatures below the target temperature in the “door zone” arise 10 % of the year respectively 240 h/a. However, the temperature only slightly decreases by about 1-2 K.

In the scenario *regular forklift traffic*, the percentage of temperatures below the 15 °C prevail at 25 % of the year or approx. 600 h/a. However, the temperature decreases in most opening periods by about 1 K when using the ideal door[14].

The scenario *truck loading / unloading* show the lowest temperatures of all scenarios. The proportion of temperatures below 12 °C is significantly higher compared to the other two scenarios due to the two long opening periods in the morning / evening.

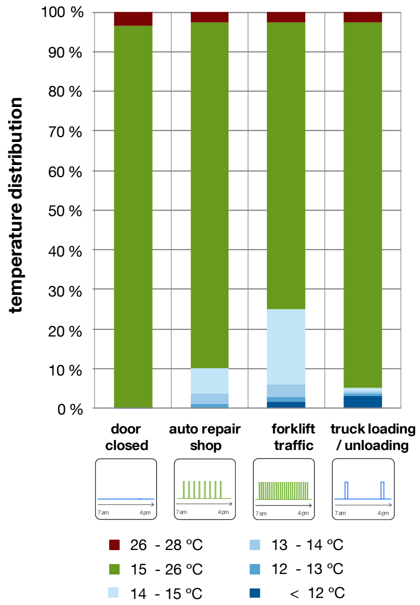


Figure 46: Temperature distribution of the scenarios of the *workshop building model* in the “door zone” using the “ideal door” at a room height of 1.4 m during the operation time. Simulation time step: 30 s. Observation period: 1 year.

Hereinafter the real door types are examined for the three scenarios.

[14] At this point it should be noted that the particular type of door has a non-negligible impact on the temperature drop within the “door zone” due to different opening and closing speeds. A separate analysis of the temperature distribution with the real door types showed that the proportion of temperatures below 12 ° C significantly increases about 6% when using the slow running doors (sectional door and rolling shutter).

7.5.2 Scenario *auto repair shop*, *workshop building model*

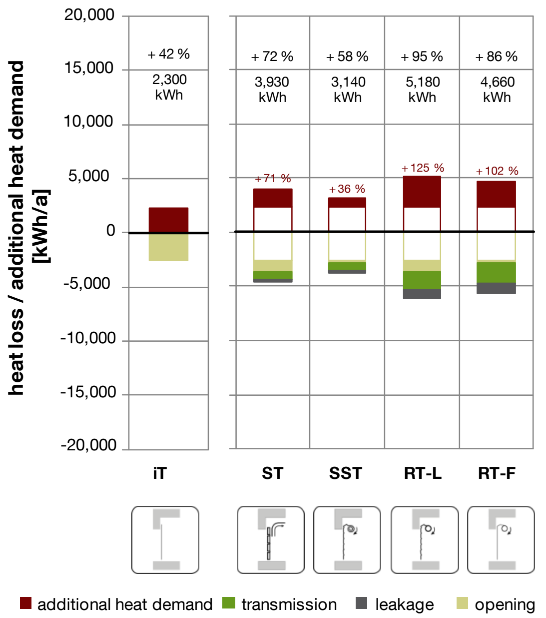


Figure 47: Additional heat demand and heat loss of each door in the scenario *auto repair shop*.

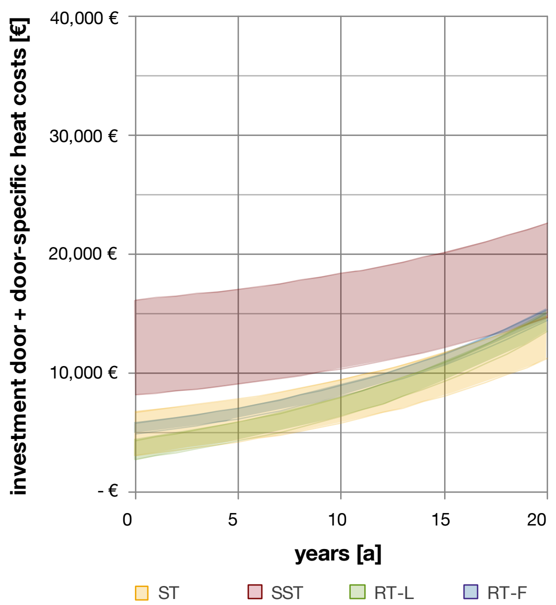


Figure 48: Door-specific investment and cumulated costs over 20 years in the scenario *auto repair shop*.

The scenario auto repair shop represents typical opening characteristics for *auto repair shops* with 4 openings per hour.

Figure 47 shows the energetic impact of the various door types. The high-speed spiral door (SST) performs best from an energy point of view. The additional heat demand of approx. 840 kWh/a (36 %) is relatively low compared to the ideal door. The sectional door (ST) has higher ventilation heat loss than the SST due to the slower opening and closing speed. The additional heat demand amounts to approx. 800 kWh/a compared to the SST. Both roller doors show the highest heat loss. However, the flexible high speed door (RT-F) is more advantageous than the rolling shutter (RT-L) in terms of energy savings despite a poorer insulation standard. In this case, the ventilation heat loss of the slower RT-L is higher than the transmission heat loss of the uninsulated RT-F.

Figure 48 shows the cumulated costs of the doors, consisting of the investment and door-specific heating costs. Due to its high insulation and tightness within a moderate investment the ST is recommended. Furthermore, the RT-F offers an alternative due to the low investment. Despite its good result in the energy calculation the SST can only be partly recommended due to the high investment.

The RT-L is preferable compared to the RT-F due to the lower investment despite a slightly higher additional heat demand.

7.5.3 Scenario *regular forklift traffic*, *workshop building model*

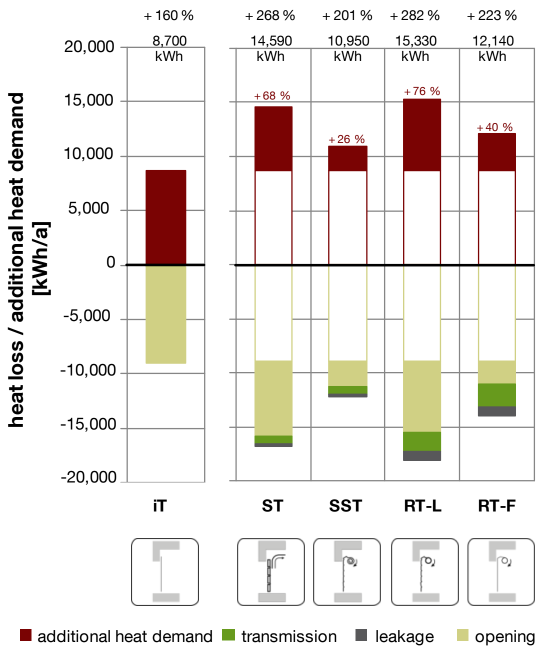


Figure 49: Additional heat demand and heat loss of each door in the scenario forklift traffic.

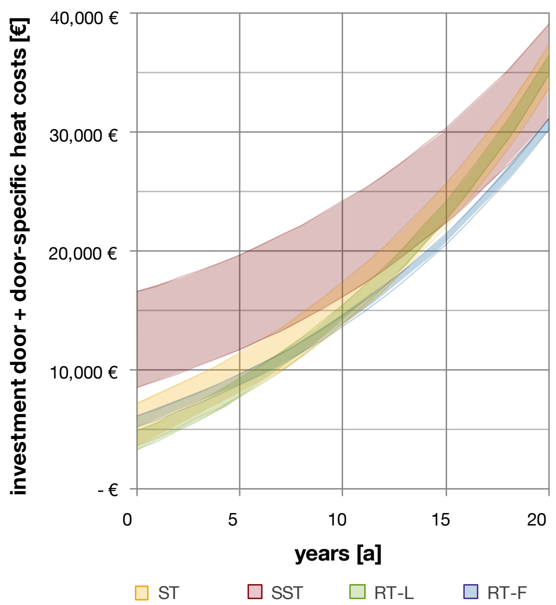


Figure 50: Door-specific investment and cumulated costs over 20 years in the scenario forklift traffic.

The scenario *regular forklift traffic* is characterized by a frequent opening and closing of the door with short stay-open periods.

Figure 49 shows the energetic influence of the doors for the scenario *regular forklift traffic*.

When using the ideal door, the heat demand corresponds to 160 % and approx. 8,700 kWh/a, compared to the building model without doors. With frequent and short opening periods, the high-speed spiral door (SST) and the flexible high-speed door (RT-F) perform better than the slow running sectional door (ST) and rolling shutter (RT-L) from an energy perspective. By using the ST, the additional heat demand increases by 26 % or approximately 2,300 kWh/a compared to the ideal door (RT-F: 40% or approximately 3,400 kWh/a). In accordance with the results of the same scenario in the *manufacturing building model* in Chapter 7.4.3 the ventilation heat loss leads to a high additional heat demand when using the two slow running doors ST and RT-L. Compared to the ideal door the additional heat demand increases by 68 % or about 5,900 kWh/a (ST) respectively by 76 % or approximately 6,600 kWh/a (RT-L).

Regardless of the door type it can be seen that the influence of the stay-open period per opening (15 s) is higher than the heat loss by transmission, leakages and additional ventilation heat loss during the opening and closing operations. Therefore, it seems advisable to reduce the ventilation heat loss, e.g. by merging of short openings to a few, but longer openings. However, it must be noted that the work flow may be significantly impaired by such a measure.

Figure 50 shows that over the years the RT-F is a suitable choice due to a balanced relationship between investment and resulting heat costs.

Due to its high initial investment the SST is only partly recommended in this building model.

An object-size-adapted opening of the door represents another measure to reduce the heat demand. This measure will be examined in Chapter 8.5.

7.5.4 Scenario *truck loading / unloading*, *workshop building model*

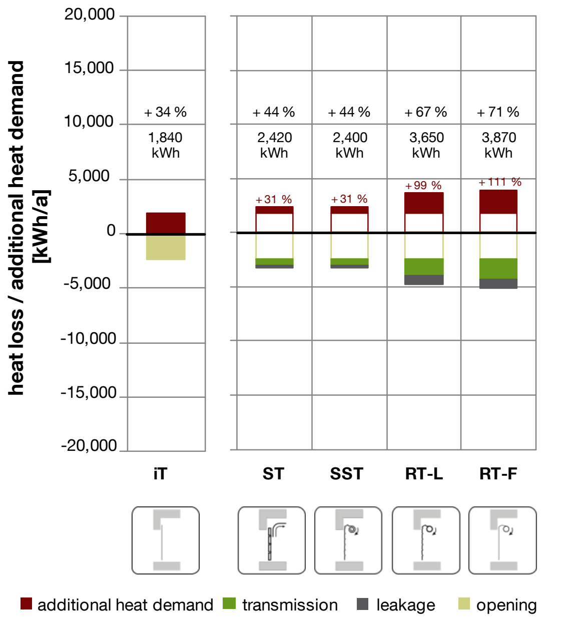


Figure 51: Additional heat demand and heat loss of each door in the scenario *truck loading / unloading*.

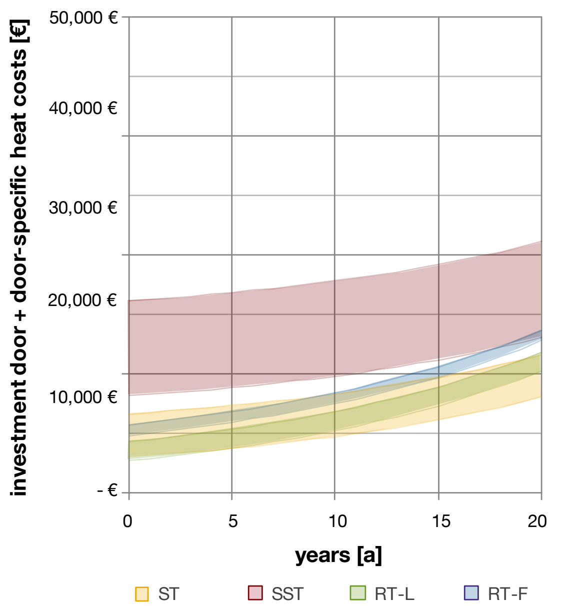


Figure 52: Door-specific investment and cumulated costs over 20 years in the scenario *truck loading / unloading*.

The scenario *truck loading / unloading* is characterized by a very low door opening frequency with only two openings in the morning and evening per day. The stay-open period per opening is 15 min.

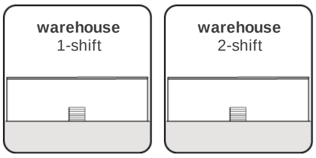
Figure 51 illustrates the energetic impact of the various door types for the scenario *truck loading / unloading* of the *workshop building model*.

Due to a better insulation standard and air tightness, the sectional door (ST) and high-speed spiral door (SST) are more energy efficient than the two rolling doors in this scenario. The additional heat demand increases by 31 % or approximately 560 kWh/a compared to the ideal door. As already described in Chapter 7.4.2 the high-speed spiral door (SST) has no significant energetic improvement compared to the ST so this door type is advisable from an energy perspective. Due to lower insulation standards and air tightness, the two rolling doors have the highest additional heat demand in this scenario.

Figure 52 shows the cumulated costs of the doors. It can be seen that the ST and RT-L have the lowest cumulated costs – the ST due to low annual heating costs – the rolling shutter due to the low investment. The two fast running doors (SST and RT-F) perform worse in this scenario – the SST due to the high initial investment – the RT-F due to high heating costs resulting from the low insulation and air tightness.

Chapter 8.3 explains how to increase the energy efficiency of the high-speed doors by repeatedly opening and closing during the *truck loading / unloading*.

7.6 Scenarios of the warehouse building model



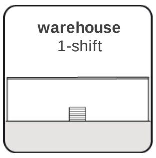
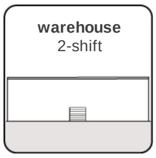
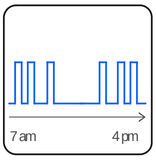
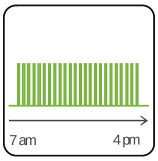
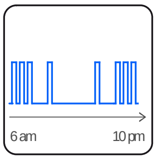
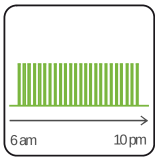
The scenarios of the *warehouse building model* were examined for two operation modes: 1-shift and 2-shift operation. According to the ongoing research project “Carbon neutral logistics facilities - development of holistic recommendations for energy-efficient logistics facilities” at the Department of Building Climatology and Building Services in cooperation with the Department of Materials Handling, Material Flow and Logistics, two different scenarios of door opening characteristics can be classified: *truck loading / unloading* with peak times usually in the morning (truck unloading) and evening (truck loading) as well as *regular forklift traffic* during the period of use.

Modern warehouses are usually characterized by a high number of loading doors in the façade e.g. via dock levelers: trucks can dock directly at the dock levelers, whereby the ventilation heat loss is reduced compared to a just stand-open door [Häußler 2012]. However, industrial doors are used in case of a lateral *truck loading / unloading*. The loading and unloading process is then carried out by forklifts. A lateral loading / unloading is assumed for the following examined scenario *truck loading / unloading*. The opening characteristics of this scenario were determined from a survey on the number of incoming and outgoing goods in various warehouses (project mentioned above).

The scenario *regular forklift traffic* corresponds to the scenario of the *manufacturing building model*. The opening frequency of the door totals 30 openings per hour in the operation time, the stay-open time has been set at 15 s per opening.

Table 14 summarizes the scenarios for the *warehouse building model*.

Table 14: Overview of the simulated scenarios for *warehouse building model*.

				
	truck loading / unloading peak time morning / evening 	***regular forklift traffic*** 	***truck loading / unloading*** peak time morning / evening 	***regular forklift traffic*** 
opening characteristics	several door openings per day with peak time morning / evening	Frequent openings due to forklift traffic	several door openings per day with peak time morning / evening	Frequent openings due to forklift traffic
opening times	7:00-7:15 am, 7:30-7:45 am, 9:00-9:15 am, 2:00-2:15 pm, 3:00-3:15 pm, 3:30-3:45 pm	regularly from 7:00 am till 4:00 pm, 30 openings per hour	6:00-6:15 am, 6:30-6:45 am, 7:00-7:15 am, 8:00-8:15 am, 10:00-10:15am,12:00-12:15am, 4:00-4:15 pm, 6:00-6:15 pm, 7:00-7:15 pm, 8:00- 8:15 pm, 9:00-9:15 pm, 9:30-9:45 pm	regularly from 6:00 am till 10:00 pm, 30 openings per hour
stay-open time per opening	15 min	15 s	15 min	15 s
openings/ day	6	270	12	480

7.6.1 Comparison of the scenarios using the ”ideal door“, *warehouse building model*

1-shift operation

First, the scenarios of 1-shift operation are compared to each other. Figure 53 shows the annual heat loss of the ideal door as well as the resulting additional heat demand for the scenarios *truck loading / unloading* and *regular forklift traffic*.

As already described in Chapter 6, the door-specific impact on the heat demand of the building is significantly lower than in the building models manufacturing and workshop due to the relatively low door area compared to the enveloping surface. In the scenario *truck loading / unloading* the annual heat loss by the ”ideal door” results in an additional heat demand of 2.6 % or about 13,000 kWh/a respectively. The additional heat demand is higher than in the scenario *regular forklift traffic* (1.8 %, about 8,700 kWh/a). Looking at the total opening time per day, it is clear that the scenario *truck loading / unloading* opening time adds up to 90 min/d which is significantly higher than the scenario *regular forklift traffic* (67.5 min/d).

Figure 46 shows the temperature distribution in the “door zone” expressed as a percentage over one year when using the “ideal door”.

The first bar represents the temperature distribution in the “door zone” of the *warehouse building model* when the door is closed. Here 1 % represents around 24 hours usage time. The comfortable temperature range is set between 17 °C and 26 °C at a height of 1.4 m. As already shown in Chapter 5.5, the building model warehouse has no cooling demand due to low internal heat loads (only artificial lighting). The comfortable temperature range is maintained almost throughout the annual period of use.

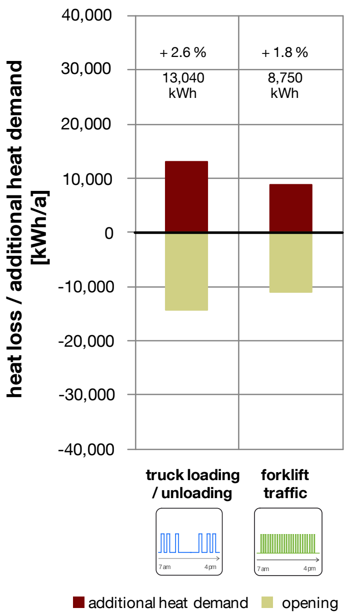


Figure 53: Comparison of the scenarios *truck loading / unloading* and forklift traffic in terms of additional heat demand and heat loss for the “ideal door”, *warehouse building model* at 1-shift operation.

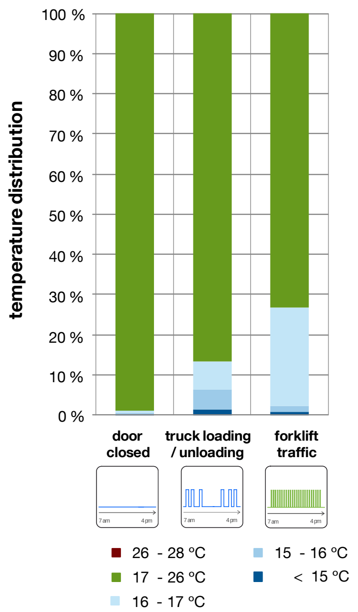


Figure 54: Temperature distribution of the scenarios of the *warehouse building model* at 1-shift operation in the “door zone” using the “ideal door” at a room height of 1.4 m during the operation time. Simulation time step: 30 s. Observation period: 1 year.

In the scenario *truck loading / unloading* the interior temperature falls below the target temperature of 17 °C during 12 % or about 290 h of the usage time.
In the scenario *regular forklift traffic* the percentage of temperatures below the target temperature amounts to 28 % respectively about 670 h/a. The temperature drops by about 1 K in most opening operations.
Note: with regard to the “door zone” (8 x 8 m), only an “average temperature” is calculated in the door zone. Therefore, significantly colder temperatures can arise near the door.

2-shift operation

Figure 55 shows the annual heat loss of the door as well as the additional heat demand for the scenarios *truck loading / unloading* and *regular forklift traffic* for a 2-shift operation. The calculation of the additional heat demand is based on the *warehouse building model* without doors with a 2 shift-operation, see Chapter 5.5.

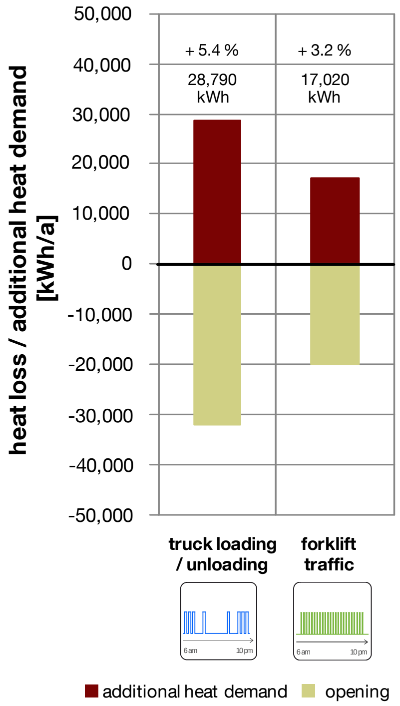


Figure 55: Comparison of the scenarios *truck loading / unloading* and forklift traffic in terms of additional heat demand and heat loss for the “ideal door”, *warehouse building model* at 2-shift operation.

A doubling of the truck loading and unloading operations of the one-shift operation is assumed for the scenario *truck loading / unloading*, the summed opening time amounts to 180 min/d. The additional heat demand totals 5.4 % respectively about 28,800 kWh/a by using the ideal door. The additional heat demand increases by approx. 120 % respectively approx. 15,800 kWh/a compared to the scenario with one-shift operation. This shows that the additional heat demand increases disproportionately to the number of door openings. This is due to re-timing of opening processes in the early morning or late evening hours when the outside temperature becomes colder, see Table 14.
In the scenario *regular forklift traffic* the additional heat demand increases by approx. 94 % respectively approx. 17,000 kWh/a compared to the scenario with one shift operation.

Hereinafter the real door types are examined in the scenarios.

7.6.2 Scenario *truck loading / unloading*, *warehouse building model*

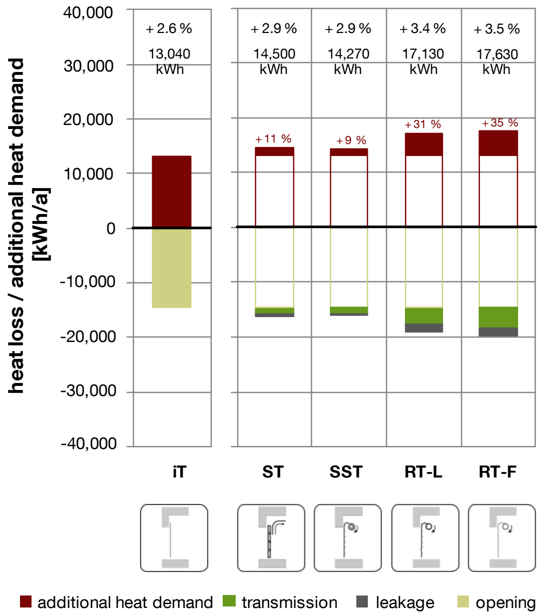


Figure 56: Additional heat demand and heat loss of each door in the scenario *truck loading / unloading*, 1-shift operation.

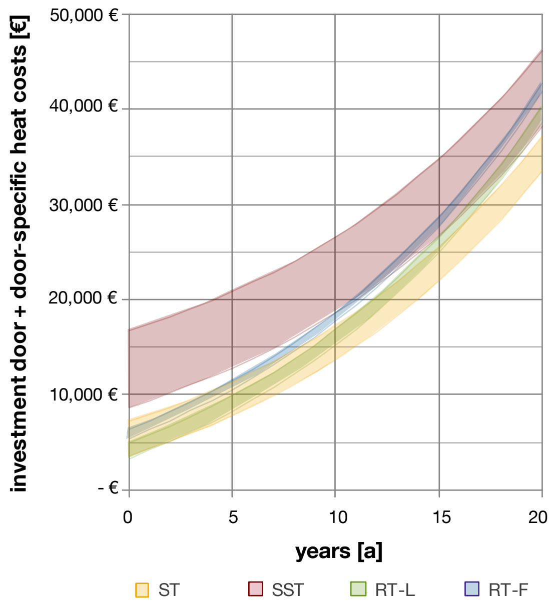


Figure 57: Door-specific investment and cumulated costs over 20 years in the scenario *truck loading / unloading*, 1-shift operation.

Note: since the evaluation of this scenario based on 1-shift or 2-shift operation tends to result in the same statements, the results of the 2-shift operation are given in brackets.

The scenario *truck loading / unloading* is characterized by several openings per day with peak times in the morning and evening. The stay-open period is 15 min per opening.

Figure 56 shows the energetic influence of the various door types for the scenario *truck loading / unloading* with one-shift operation. The additional heat demand increases by 11 % or approx. 1,500 kWh/a (9 %, ~2,500 kWh/a) when using the sectional door (ST) compared to the ideal door. When using the high-speed spiral door (SST) the additional heat demand increases by 9 % or about 1,200 kWh/a (7 %, ~2,000 kWh/a). Both rolling doors have higher heat losses. The additional heat demand increases by 31 % or approximately 4,100 kWh/a (22 %, ~6,300 kWh/a) when using the rolling shutter (RT-L) compared to the ideal door and by 35 % or approximately 4,600 kWh/a (23 %, ~6,700 kWh/a) when using the flexible high-speed door (RT-F). Despite a higher number of door openings in this scenario, the results are similar compared to the scenarios of the other building models (see Chapter 7.4.2 and 7.5.4): using the ST or SST results in a lower additional heat demand compared to the rolling doors (RT-L / RT-F) due to a higher insulation standard and air tightness.

Figure 57 shows the cumulated costs of the doors, consisting of the investment and door-related heating costs. The ST has the lowest cumulated costs over the years. The RT-L has the lowest initial investment. However, higher annual heating costs lead to higher cumulated costs after 10 years of operation compared to the ST. Both high-speed doors perform worse in this scenario – the SST due to the high initial investment – the RT-F due to higher heating costs resulting from the lower insulation and air tightness.

Chapter 8.3 explains how to increase the energy efficiency of SST and RT-F by repeatedly opening and closing the door during a truck loading and unloading. Chapter 8.4 examines how a truck passage (loading / unloading inside the building) can reduce the stay-open time and the associated ventilation heat loss as an advanced scenario.

7.6.3 Scenario *regular forklift traffic*, *warehouse building model*

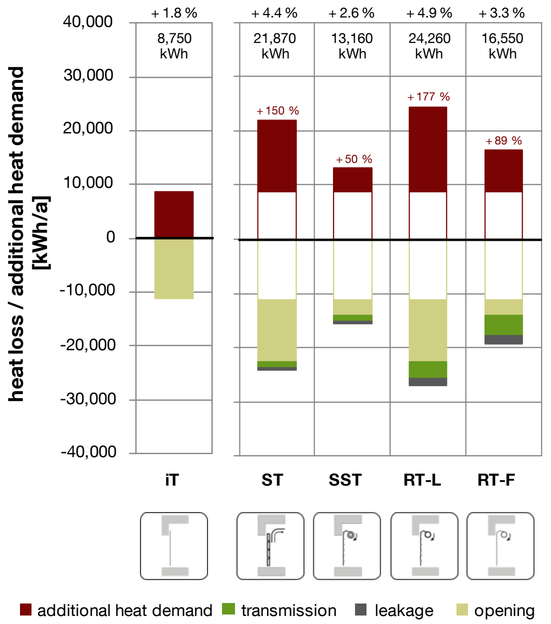


Figure 58: Additional heat demand and heat loss of each door in the scenario forklift traffic, 1-shift operation.

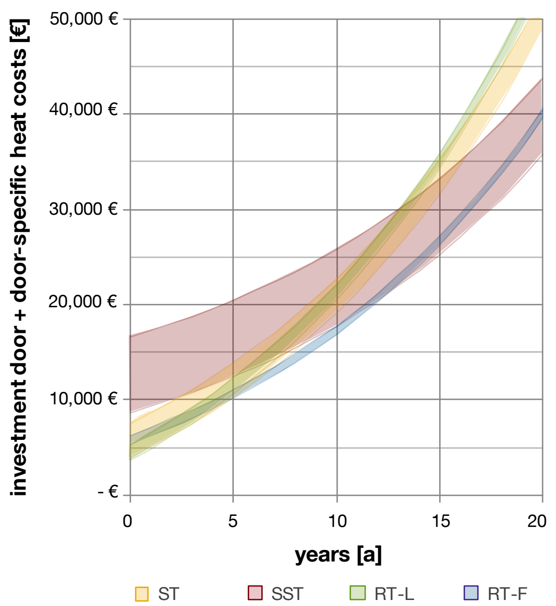


Figure 59: Door-specific investment and cumulated costs over 20 years in the scenario forklift traffic, 1-shift operation.

Note: since the evaluation of this scenario based on 1-shift or 2-shift operation tends to result in the same statements, the results of the 2-shift operation are given in brackets.

The scenario *regular forklift traffic* describes frequent openings and closings with short stay-open times.
Figure 58 shows the energetic influence of the doors for the scenario *regular forklift traffic*.
When using the ideal door the additional heat demand totals 1.8 % or about 8,800 kWh/a compared to the building model without doors. As expected, the high-speed spiral door (SST) and the flexible high-speed door (RT-F) perform best for this scenario. However, the door-specific influence is higher than in the previous scenario: when using the SST, the additional heat demand increases by 50 % or about 4,400 kWh/a (42 %, ~7,000 kWh/a) compared to the ideal door due to the additional ventilation heat loss during opening and closing operations. Higher heat losses by transmission and leakages lead to an additional heat demand of 89 % or about 7,800 kWh/a (69 %, ~11,700 kWh/a) when using the RT-F.
Looking at the slow running doors (ST and RT-L), the additional ventilation heat loss during the opening and closing operations is as high as the entire ventilation heat loss during the stay-open time.
Figure 59 shows that the SST and the RT-F are the most appropriate choice due to high opening and closing speeds.

Note: if high-speed doors are used the ventilation heat loss during the stay-open time (15 s) is significantly higher than the additional ventilation heat loss during the opening and closing operations. Reducing this ventilation heat loss by an object-size adapted door opening will be examined in Chapter 8.5.

7.7 Summary

In this chapter, several practice-oriented scenarios for the building models *manufacturing*, *workshop* and *warehouse* were examined using different door types. The following results can be summarized:

Results which are independent from the building model

- In almost all scenarios the ventilation heat loss is higher than the heat loss through transmission and leakage, regardless of the door type.
- Temperatures below the minimum indoor temperature can arise in up to 30% of the time of use in the "door zone", depending on the particular scenario and building model.
- At low opening cycles, a high insulation standard and air tightness is recommended from an energy perspective, especially if there are many doors in the facade.
- At high opening cycles, the opening and closing speed of the door is relevant, insulation and air tightness of the door have less influence in terms of energy. The slow running doors investigated here (sectional door, rolling shutter) are unsuitable both in terms of energy and costs. The opening and closing process needs more time than the stay-open period, which causes high additional ventilation heat loss.
- Given a high insulation standard as well as a high opening and closing speed, the high-speed spiral door has the lowest additional heat demand in the scenarios. However, the high-speed spiral door is not recommended in all scenarios due to its high investment.

Manufacturing building model

- At low to moderate opening cycles (scenarios *truck loading / unloading*, *mixed usage*), the sectional door is recommended in terms of energy and costs.
- At high opening cycles (scenario *regular forklift traffic*), high-speed doors are recommended in terms of energy and costs. By using high speed doors, energy savings up to 11,000 kWh/a or about 30 % can be achieved compared to slow running doors).

Workshop building model

- Due to the low building volume, cold temperatures occur, especially in long stay-open times of the door (e.g. scenario *truck loading / unloading*).
- The door-specific additional heat demand is lower compared to the *manufacturing building model* due to a regressive relationship between heat loss and opening duration as well as the lower interior target temperature. However, the building-specific influence of the various door types on the heat demand is much higher.
- At low to moderate opening cycles (scenario auto-repair shop, *truck loading / unloading*), the following door types are advisable when considering the cumulated costs: the sectional door due to the low door-specific heat costs and the rolling shutter due to the low investment. The sectional door and the high-speed spiral door are recommended from an energy perspective.
- At high opening cycles (scenario *regular forklift traffic*), the high-speed spiral door and the flexible high-speed door are recommended. Considering the development of costs, the flexible high-speed door is recommended due to the low investment.

Warehouse building model

- The door-specific additional heat demand as well as the associated heating costs are highest in this building model due to low internal heat loads, which would partly compensate heat losses (e.g. when the door is open).
- At low opening cycles (scenario *truck loading / unloading*), the sectional door is recommended in terms of energy and costs due to its high insulation standard and air tightness.
- At high opening cycles (scenario *regular forklift traffic*), high speed doors are recommended from an energy and cost perspective.

8. Measures to increase energy efficiency and thermal comfort

8.1 Overview of measures and procedure

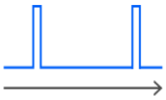
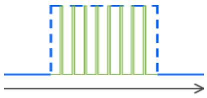
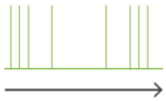
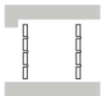
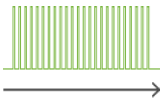
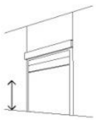
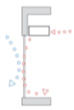
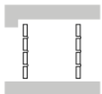
This chapter deals with different measures to increase energy efficiency and thermal comfort. The measures are evaluated on the basis of the scenarios developed in Chapter 7.

For long opening periods (e.g. scenario truck loading) it is investigated how a high-speed door with frequent opening intervals can contribute to the reduction of the stay-open time and the reduction of concomitant ventilation heat loss. Furthermore, the use of an airlock is analyzed in order to reduce the air exchange and the cold air feed. A *truck loading / unloading* within the building is another option to reduce the stay-open time of a door.

For frequent brief opening processes (e.g. scenario *regular forklift traffic*) an object-size-adapted door opening is investigated to reduce the ventilation heat loss. Air curtain systems or air wall systems can also contribute to a reduction of the ventilation heat loss. The use of an air wall system is examined through a sample calculation.

A schematic overview of the different measures is shown in Table 15.

Table 15: Schematic overview of the different measures to improve the energy efficiency or the thermal comfort for the various scenarios.

scenario	***measures***		
truck loading / unloading 	***frequent opening / closing*** (Chapter 8.3) 	***truck passage*** (Chapter 8.4) 	***lock*** (Chapter 8.6) 
regular forklift traffic 	***object-size adapted opening*** (Chapter 8.5) 	***air curtain/ air wall*** (Chapter 8.7) 	***lock*** (Chapter 8.6) 

8.2 Explanation of the “energy saving graphic”

Figure 60 explains the “energy saving graphic”, which shows the energy saving potential of each door for each measure. Since the energy saving potential of the various measures is examined on the basis of the initial scenarios from Chapter 7, the initial energy (see Chapter 7.2) is shown as grayed-out. For each door type the reduced heat loss (by transmission, leakage and opening) is shown by a bar in the negative values, the resulting heat demand of the energy saving measure is shown in the positive values. Above the bar graph the percentage and absolute reduction in heat demand is shown compared to the original scenario.

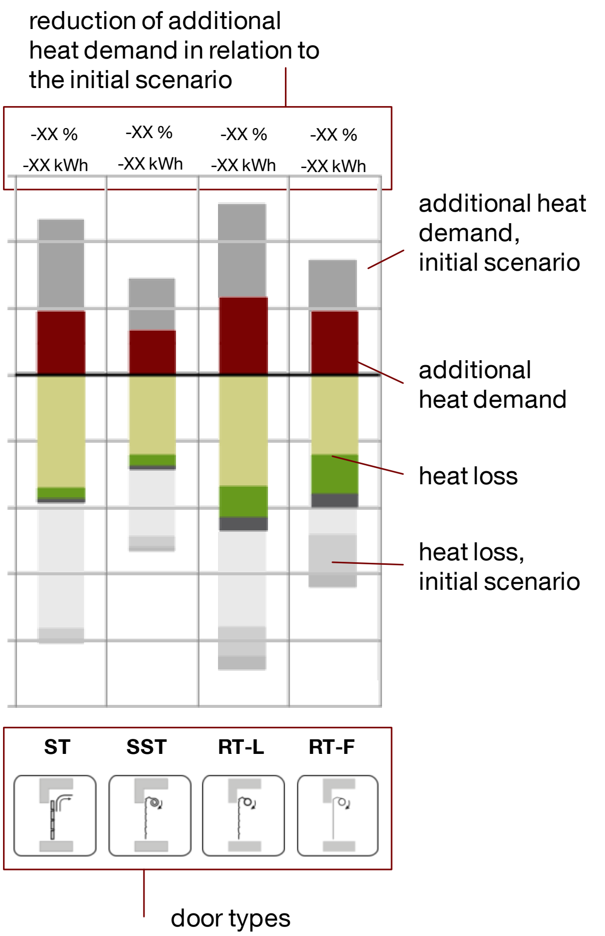
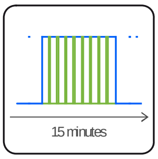


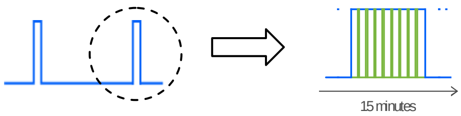
Figure 60: Explanation of the “energy saving graphic”.

8.3 Reduction of stay-open times through the use of fast running doors



The following chapter examines the influence of reducing stay-open times through the use of high-speed doors in two scenarios. For the truck loading scenario the manufacturing and workshop models are analyzed, whereas the *warehouse building model* is examined for the scenario truck loading with peak times in the morning and evening. The initial stay-open time per opening is 15 minutes.

The loading and unloading process, e.g. by forklift, is assumed to be continuous with two door openings per minute for smooth operation. The stay-open time per opening is 15 seconds. In the continuous initial stay-open time of 15 minutes there are 30 openings in total. Such high opening frequency is to be operated reasonably using high-speed doors only. Therefore, in this study the high-speed spiral door and the flexible high-speed door are utilized.



8.3.1 *Manufacturing building model*

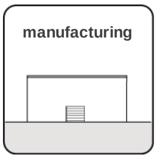


Figure 61 shows the reduction of heat demand through the frequent opening of a door for the scenario truck loading of the *manufacturing building model*.

Both the ventilation heat loss (resulting from door opening) and the resulting additional heat demand can be significantly reduced by a frequent opening of the door resulting in a shortening of the stay-open time. The additional heat demand can be reduced by 28 % (high-speed spiral door SST) or 19 % (flexible high-speed door RT-F) and about 1,600 kWh/a compared to a permanent staying-open of the door.

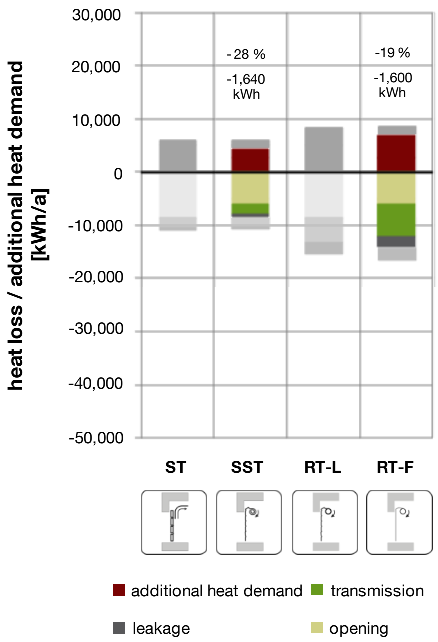


Figure 61: Reduction of the additional heat demand through frequent opening and closing of the door for the scenario *truck loading / unloading*, *manufacturing building model*.

8.3.2 *Workshop building model*

Figure 62 shows the reduction of the additional heat demand through the measure in the *workshop building model*.

Compared to the initial *manufacturing building model*, the reduction of heat loss and resulting additional heat demand is much lower. The saving is 10 % or approximately 230 kWh/a when using the high-speed spiral door (SST), 8 % or approximately 220 kWh/a when using the flexible high-speed door (RT-F). As explained in Chapter 6.2, the heat loss does not increase as much as the opening duration, that is to say the heat loss is higher at the beginning of the door opening than at the time of door closure. If the door stays open for 15 min (initial scenario) the room temperature drops significantly lower compared to several short door openings. Due to higher interior temperatures (than if the door is permanently opened as in the initial scenario), the air exchange and ventilation heat loss are increased, despite the stay-open time being shortened in total. A frequent opening and closing of the door can reduce the mentioned temperature drop, which leads to an increase in thermal comfort.

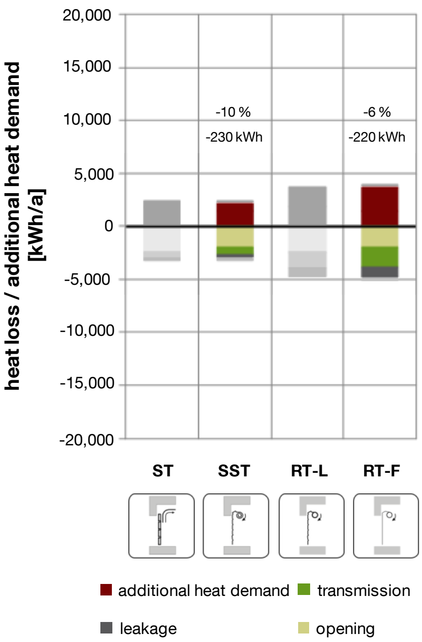


Figure 62: Reduction of the additional heat demand through frequent opening and closing of the door for the scenario *truck loading / unloading*, *workshop building model*.

8.3.3 *Warehouse building model*

Note: since the evaluation of this scenario based on 1-shift or 2-shift operation tends to result in the same statements, the results of the 2-shift operation are given in brackets.

Figure 63 shows the reduction of additional heat demand through frequent opening and closing of the door for the scenario truck loading of the *warehouse building model* with 1-shift operation.

Compared to the two previous building models the frequent opening and closing of the two high-speed doors SST and RT-F results in the highest savings in additional heat demand. The saving effect is increased due to the higher number of door openings: 6 opening processes in the 1-shift operation and 12 openings in the 2-shift operation, compared to only two opening processes in the other two building models. The additional heat demand can be reduced by 30 % or approximately 4,300 kWh/a (30 %, ~9,100 kWh/a) when using the SST and by 27 % or approximately 4,700 kWh/a (25 %, ~8,900 kWh/a) when using the RT-F.

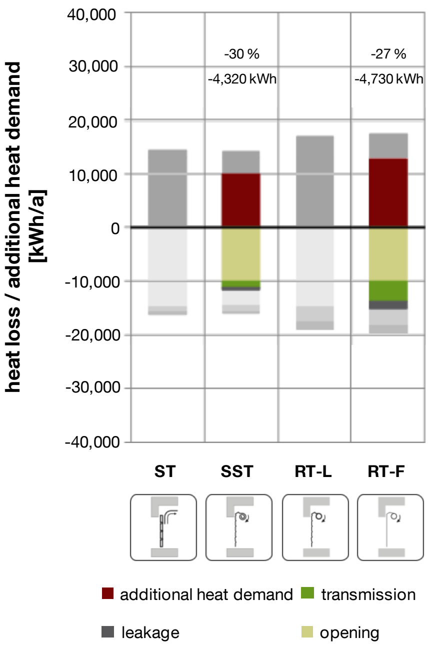
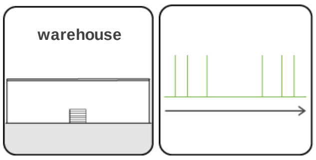


Figure 63: Reduction of the additional heat demand through frequent opening and closing of the door for the scenario *truck loading / unloading*, *warehouse building model* at 1-shift operation.

8.4 Reduction of long stay-open times through loading / unloading in the building



Note: since the evaluation of this scenario based on 1-shift or 2-shift operation tends to result in the same statements, the results of the 2-shift operation are given in brackets.

According to the ongoing research project “Carbon neutral logistics facilities - development of holistic recommendations for energy-efficient logistics facilities” a *truck loading / unloading* operation can also be carried out inside the building. This leads to a significant reduction of the stay-open time, as the door is opened only for the entry and departure of the truck. It should be noted that this measure for the increase of efficiency is not door-related but construction-related.
For the investigation the scenario *truck loading / unloading* with peak hours in the morning / evening from Chapter 7.6.2 has been chosen. The stay-open time in this scenario is 15 min per door opening.
A stay-open time of 30 s is assumed per door opening at the entry and departure of the truck.

Figure 64 shows the reduction of additional heat demand through loading / unloading in the building for the *warehouse building model* with one-shift operation.

Reducing the stay-open time of 15 min to two short openings for truck entry and departure enables a significant reduction of the additional heat demand of circa 12,500 kWh/a (~26,000 kWh/a). Depending on the door type these savings range from 72 % to 89 % (75 % and 87 %). Therefore, this measure results in higher energy savings than the use of high-speed doors described in the previous chapter.

However, it must be noted that a *truck loading / unloading* inside the building requires a high quantity of additional space. Furthermore, the indoor air quality can be significantly impaired by the introduction of contaminants, such as exhaust fumes of the truck. When the outside temperatures are cold, the incoming truck is an additional source of cold in the building, which is not considered in the simulation model. Therefore, the above mentioned savings may be less, depending on the temperature of the truck and of the transported cargo.

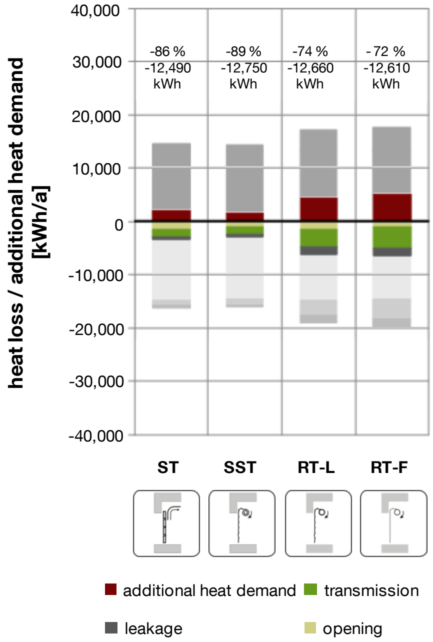


Figure 64: Reduction of the additional heat demand through *truck loading / unloading* in the building, *warehouse building model*, 1-shift operation.

8.5 Reduction of ventilation heat loss through object-size adapted door opening

In this chapter, the reduction of ventilation heat loss is examined through an object-size adapted door opening. By means of sensor systems such as laser scanner, the object (e.g. person, car, truck) can be detected and the door can be opened according to the required height, see Chapter 3.3.

The scenario *regular forklift traffic* is used as a sample scenario with the following building models: manufacturing (Chapter 7.4.3), workshop (Chapter 7.5.3) and warehouse (Chapter 7.6.3). This scenario describes a frequent opening and closing of the door with short stay-open periods. The opening characteristic of the scenario is shown in Table 16.

A typical height of a forklift is approximately 2.2 m. With an additional safety margin an opening height of 2.5 m is assumed for the simulation. Since the door is not opened to the full opening height, the opening and closing period is also decreased.

Table 16: Boundary conditions of scenario *regular forklift traffic* with reduced opening height.

opening characteristic	frequent door openings due to forklift traffic
opening times	regularly from 7 am till 4 pm, 30 openings per hour
stay-open time	15 s
openings / day	270
opening height	2.5 m (height of the door: 4 m)

8.5.1 Manufacturing building model

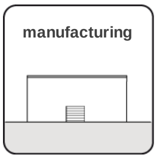


Figure 65 shows the reduction of additional heat and heat loss through an object-size adapted opening of the door for the scenario *regular forklift traffic* of the *manufacturing building model*.

The air exchange and the related ventilation heat loss can be significantly decreased due to the reduced opening height of 2.5 m. The saving is higher for the slow running doors (sectional door ST: 59 % or approximately 13,700 kWh/a, rolling shutter RT-L: 54 % or approximately 13,800 kWh/a), since the opening and closing time is also reduced through the lower opening height.

For the high-speed doors, the additional heat demand can be reduced by 52 % or approximately 7,300 kWh/a for the high-speed spiral door (SST) and by 44 % or approximately 7,400 kWh/a for the flexible high-speed door (RT-F).

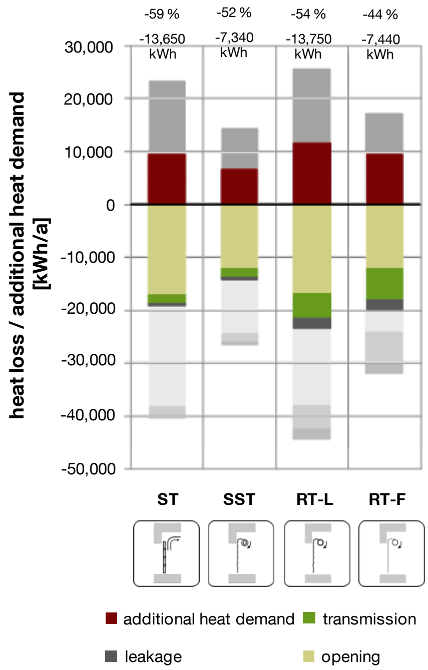


Figure 65: Reduction of additional heat demand through an object-size adapted opening, scenario *regular forklift traffic*, *manufacturing building model*.

8.5.2 *Workshop building model*

Figure 66 shows the reduction of additional heat demand for the scenario *regular forklift traffic* of the *workshop building model*.

It is shown that an object-size adapted opening of the door can significantly reduce the ventilation heat loss in this building model. Due to the mentioned regressive correlation between heat loss and opening duration as well as a lower target room temperature the savings in heat are lower than for the previous *manufacturing building model*. Nevertheless, the additional heat demand can be lowered by 39 % or approximately 4,800 kWh/a (flexible high-speed door) and 45 % or approximately 6,600 kWh/a (sectional door).
The reduced opening area can decrease the high temperature drop of this building model and thus causes an improvement in thermal comfort.

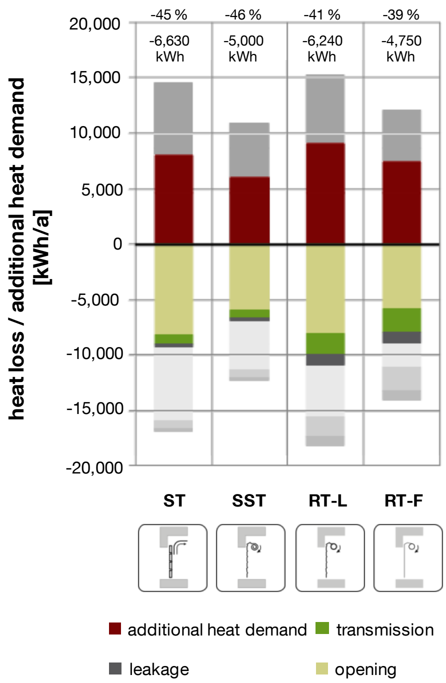


Figure 66: Reduction of additional heat demand through an object-size adapted opening, scenario *regular forklift traffic*, *workshop building model*.

8.5.3 *Warehouse building model*

Note: since the evaluation of this scenario based on 1-shift or 2-shift operation tends to result in the same statements, only the results of the 1-shift operation are given.

Figure 67 shows the reduction of additional heat demand through the measure for the *warehouse building model* with one-shift operation.
If we compare the reduced additional heat demand of the respective door type (achieved through the reduced door opening height) with the corresponding values from the *manufacturing building model*, similar savings are shown in percentage and absolutely. The reduced opening area causes an improvement in thermal comfort, especially when using the slow running doors ST and RT-L.

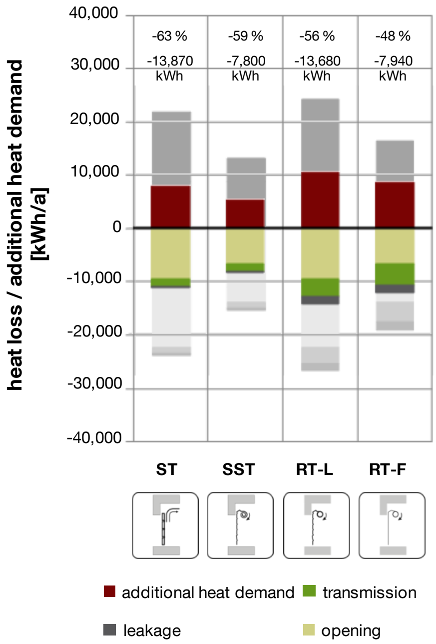
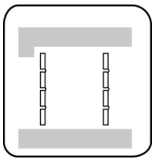


Figure 67: Reduction of additional heat demand through an object-size adapted opening, scenario *regular forklift traffic*, *warehouse building model*, 1-shift operation.

8.6 Reduction of ventilation heat loss through a lock



The following Chapter deals with a reduction of ventilation heat loss through the use of a lock in the scenarios *truck loading / unloading* and *regular forklift traffic* for the building models *manufacturing* and *warehouse*. Due to the low building dimensions, this measure is not investigated for the *workshop building model*.

A second door, which allows a lock function, is inserted in the respective building model for the investigation. Three interior walls (heat transition coefficient 2.9 W/m²K) are added to the "door zone" (see Chapter 5.2 and 5.4) in order to build an intermediary space of 8 x 8 m. This "lock zone" is not conditioned. However, there is an air flow from the lock zone to outside when the outside door is open, and an air flow from inside to the lock zone when the inner door is open.

Another "additional door zone" is inserted in order to detect the temperatures behind the lock, see Figure 68. The "real doors" described in Chapter 7.1 are examined as outside doors in the simulations. A flexible high-speed door is used as inner door.

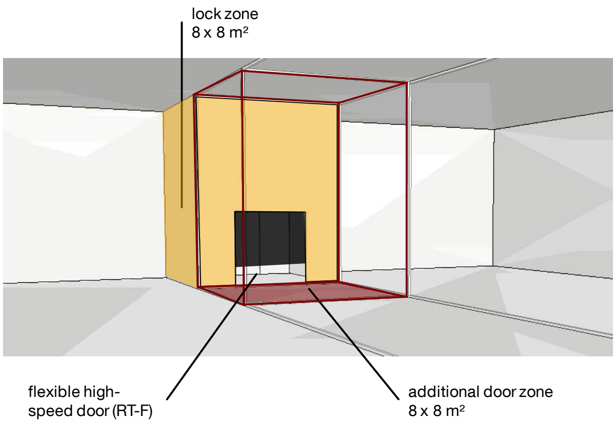


Figure 68: Interior view of the *manufacturing building model* in [IDA ICE 2012], showing the lock and the "additional door zone".

For the scenario *truck loading / unloading*, the lock is used as an unloading or a loading zone. The boundary conditions of the scenario are described in Chapter 7.4 (*manufacturing building model*) and 7.6 (*warehouse building model*).

First, an opening of the outer door is scheduled for 15 min for a morning truck unloading process. After closing the outer door, the interior door is opened for 15 min. Thus, the lock provides a buffer zone. For a truck loading in the evening, the inner door is opened first for 15 minutes. Then the exterior door is opened, see Figure 69.

During the remaining usage time both doors are closed.

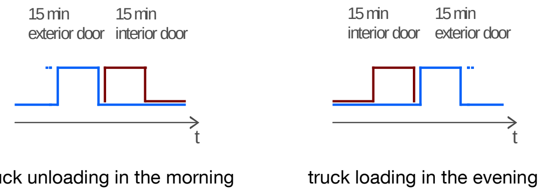


Figure 69: Lock function, truck unloading in the early morning (left), truck loading in the evening (right).

In the scenario *regular forklift traffic*, the lock is used as a "transit zone". Again, the interior door and the exterior door are not opened simultaneously. An exchange of air takes place either through the exterior door to the outside or inwardly through the interior door.

The boundary conditions in this scenario are also discussed in Chapter 7.4 and 7.6.

It is assumed that the transport is carried out by lift trucks alternately from inside to outside or from outside to inside. The stay-open time for each door is 15 s, see Figure 70.

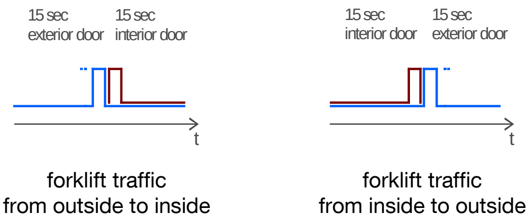


Figure 70: Lock function, regular alternating forklift traffic.

8.6.1 *Manufacturing building model*

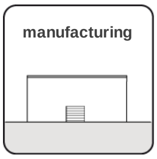


Figure 71 shows the reduction of heat demand through the use of a lock for the scenario *truck loading / unloading* of the *manufacturing building model*.

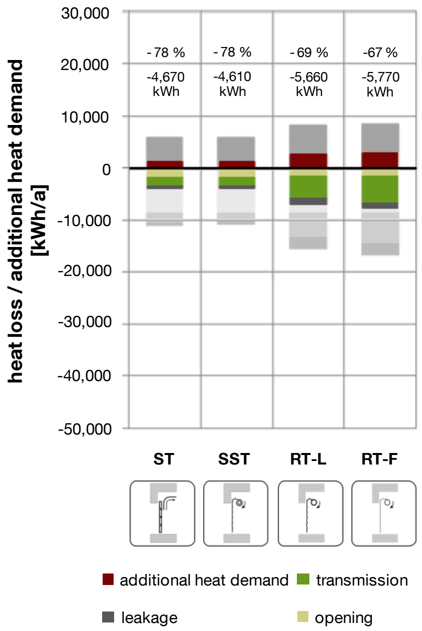


Figure 71: Reduction of additional heat demand through using a lock, scenario *truck loading / unloading*, *manufacturing building model*.

The additional heat demand can be significantly reduced through the use of the lock. This is due to the thermal separation of outside air and inside air. The air change is limited to the space volume of the lock zone. Thereby, the ventilation heat loss is reduced. The energy saving is between 67 % or approximately 5,800 kWh/a (flexible high-speed door RT-F) or 78 % and approximately 4,600 kWh/a (sectional door ST, high-speed spiral door SST) compared to the initial scenario without lock.

In addition to energy savings, thermal comfort is enhanced through the use of a lock. As an example, Figure 72 shows the air temperature in the door zone during a truck unloading operation (stay-open time of the door: 15 minutes) without using a lock. It can be seen that the temperature falls below the minimum target temperature (20 °C) by 2 K during the stay-open time. This temperature drop can be significantly reduced through the use of a lock, see Figure 73. The drop of air temperature behind the lock zone (“additional door zone”) can be seen as almost negligible. Due to the limited volume of the lock area, the not-conditioned air drops by 8 K when opening the exterior door. After closing the exterior door and opening the interior door the room temperature increases at about 16 °C.

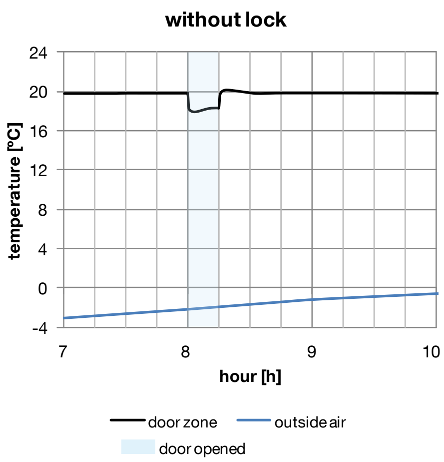


Figure 72: Outside temperature (blue line) and inside temperature at 1.4 m height (black line) in the door zone, *manufacturing building model* without lock, simulation period 01/23. 7 am – 10 am, scenario *truck loading / unloading*.

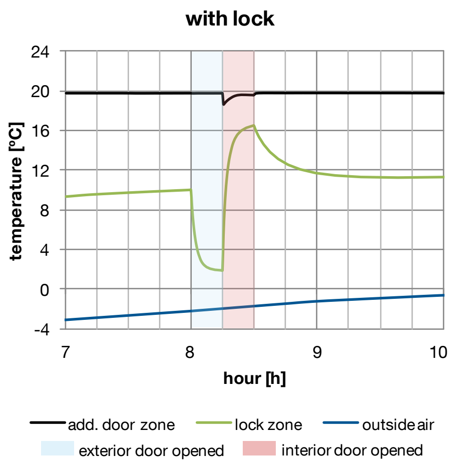


Figure 73: Outside temperature (blue line), inside temperature at 1.4 m height of the additional door zone (black line) and inside temperature at 1.4 m height of the lock zone (green), *manufacturing building model* with lock, simulation period 01/23 7 am – 10 am, scenario *truck loading / unloading*.

Figure 74 shows the reduction of additional heat through the use of a lock for the scenario *regular forklift traffic* in the *manufacturing building model*.

The additional heat demand can be significantly reduced through the “transit-zone function” of the lock. Depending on the door type, energy savings approximately amount to 60 % when using the high-speed spiral door (SST) and flexible high-speed door (RT-F), for the slow running doors sectional door (ST) and rolling shutter (RT-L) even 70 %. These savings can be achieved through the reduction of ventilation heat loss. Please note: the slower the opening and closing speed, the higher the percentage improvement due to the limited volume of space of the lock zone.

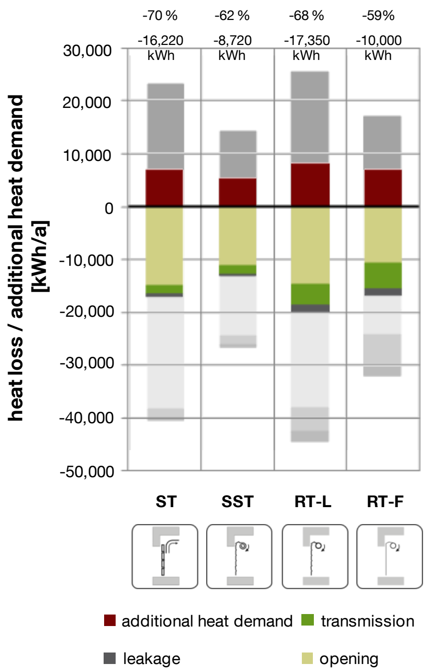


Figure 74: Reduction of additional heat demand through using a lock, scenario forklift traffic, *manufacturing building model*.

It should be noted that the lock zone is subjected to high temperature fluctuations, depending on the type of use and the associated stand-open periods of the doors, especially during the cold season. However, the use of a lock leads to a significant enhancement of thermal comfort in the remaining hall area due to a reduced temperature drop as well as cold draughts.
However, the main operations can be seriously affected. For example, the lock function in the scenario regular forklift traffic causes an additional waiting time of 15 s to prevent that both doors are opened simultaneously.
For a rational use, an airlock function has to be coordinated with the logistics processes. This requires an appropriate door control system, which can be optimized by sensory systems (e.g. laser scanner).

The following chapter describes the use of a lock for the scenarios *truck loading / unloading* and *regular forklift traffic* in the *warehouse building model*.

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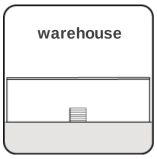
8.6.2 *Warehouse building model*



Note: since the evaluation of this scenario based on 1-shift or 2-shift operation tends to result in the same statements, only the results of the 1-shift operation are given.

Figure 75 shows the result of the simulation when using a lock for the scenario *truck loading / unloading*.
As already seen in the previous chapter, the use of a lock as a “buffer zone” has a high potential for energy savings. When using the sectional door (ST) or the high-speed spiral door (SST), the additional heat demand can be reduced by almost 90 % or more than 12,000 kWh/a, compared to the original scenario without lock. Furthermore, when using the rolling shutter or the flexible high-speed door, the additional heat demand can be reduced by up to 80 % or about 13,900 kWh/a.

Due to low internal heat loads (only artificial lighting), the use of a lock has a higher energy saving potential in this building model compared to the *manufacturing building model*.
Figure 76 shows the reduction of additional heat demand through the use of a lock for the scenario *regular forklift traffic*.
Similar to the results of the same scenario of the *manufacturing building model*, the percentage improvement is lower than for the scenario *truck loading / unloading*, as already mentioned. However, the additional heat demand can be reduced by up to 77 %.

At this point it should be noted that an airlock function has to be coordinated with the logistics processes. Moreover, this measure creates additional construction costs.

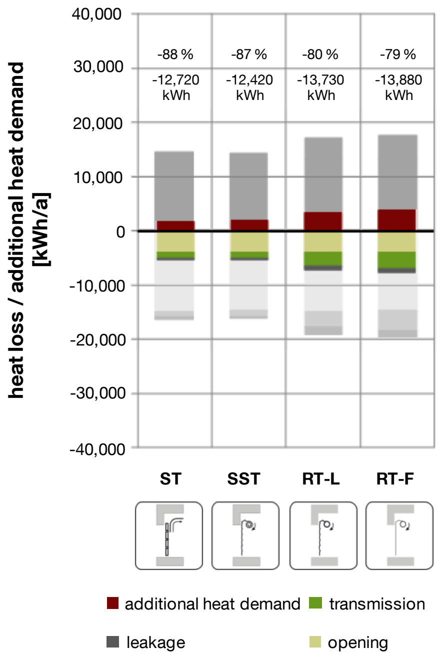


Figure 75: Reduction of additional heat demand through using a lock, scenario *truck loading / unloading*, *warehouse building model*, 1-shift operation.

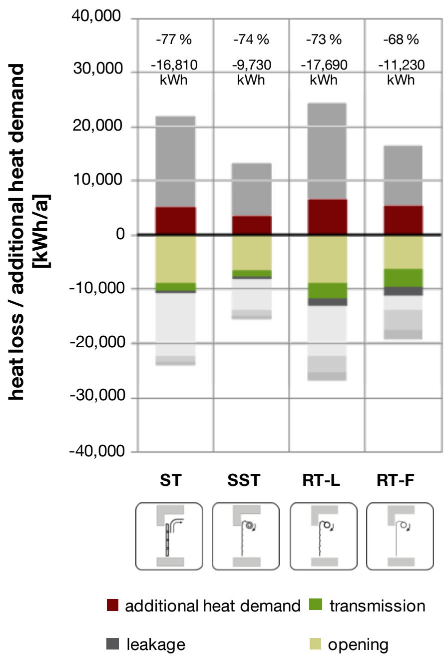
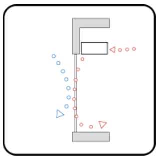


Figure 76: Reduction of additional heat demand through using a lock, scenario forklift traffic, *warehouse building model*, 1-shift operation.

8.7 Increase of thermal comfort through the use of air curtains / air wall systems



As shown in the previous chapters door openings cause an exchange of air between inside and outside which leads to heat loss and additional heat demand. "The door openings also lead to a disruption of the thermal comfort. To avoid such impairments, air curtains are installed, which generate air rollers to separate the outer and inner climate. This air roller prevents warm air from being lost to the outside (loss of energy) and cold outdoor air to flow indoors (comfort). If an air curtain system is only operated with ambient air temperature, its air jet separates the cold outside air from the warm indoor air or the warm exterior air from the cold interior air (e.g. in cold storage). The heat exchange with the exterior air is thus reduced. However, heated air curtains warm the air flow in winter, providing thermal comfort in addition to saving energy" [Ketteniß 2007, 1].

There are no standards or guidelines for the investigation of air curtain systems. However, we only refer to the manufacturers' instructions. The design of air curtain systems is mostly based on experience [Ketteniß 2007].

The task of an air wall or air curtain system is to reduce the air exchange through an open door, or even to achieve a "complete thermal shielding" of the interior space from the exterior air. According to [Cousin et al. 2008] the complete thermal shield is obtained if the air temperature in the air curtain is equal to the average air temperature of the interior space. The air curtain system behaves thermally neutrally towards the interior space. The required heat output and electrical ventilation power serve to displace or warm the exterior air. The thermal and electrical power required for the operation is a metric for the standard power requirement of the air curtain.

Air curtains can contribute to the prevision of a high comfort level, especially for tasks near the door by reducing air drafts. However, this benefit cannot be quantified in monetary terms, but only indirectly via increased comfort and lowered absenteeism of employees.

The achieved cost savings represent the reduction of ventilation heat loss. However, as mentioned above, there are no standard conditions with which an air curtain or air wall system can be accounted for.

The University for Applied Technology of Cologne [Cousin et al. 2008] follows an approach to rate the "energy efficiency" of air curtains in which the heating and fan power are set in relation with the heat loss of the open door. However, this approach is not universal, but depends on many boundary conditions such as door size, wind pressure, or temperature difference.

As shown in Chapter 8.7.1, there are different approaches and options to reduce the ingress of cold air depending on the models and manufacturers. Studies such as [Ketteniß 2007] and [Cousin et al. 2008] have shown that the "full thermal shielding" is not always achieved. The influence of wind and intermittent gusts on the shielding performance of an air curtain was not demonstrated. An additional heated air flow of the air curtain is sometimes used for additional heating of the space. The systems have distinct power consumptions depending on the temperature and flow rate of the air stream, which mainly differ between air wall and air curtains.

8.7.1 Overview of current air curtains / air wall systems

The installation of air streams for separating indoor and outdoor air can differ in design: the air jet direction is either vertical or horizontal. In this study, systems with an air outlet above the door, are called air curtains, installations where the air jet is introduced from the side (horizontal) are called air walls. An overview of suitable systems for the various door types is shown in Figure 77.

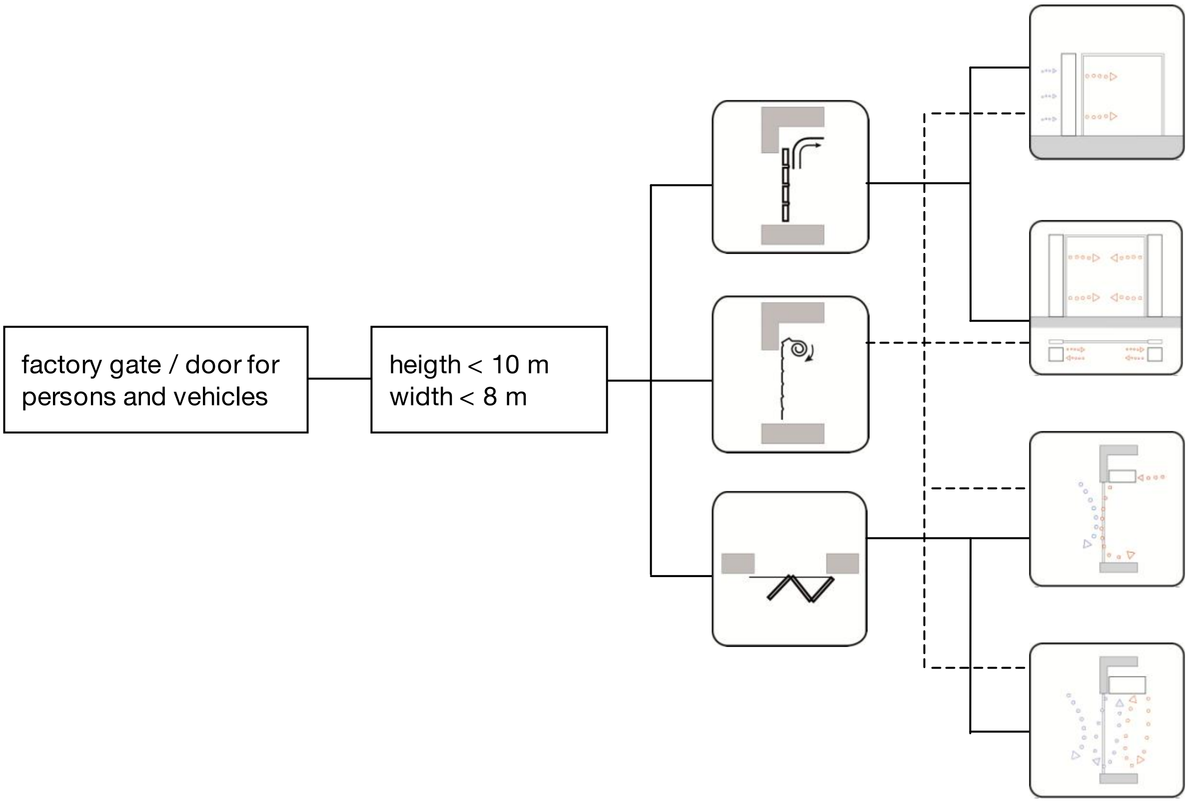


Figure 77: Overview of air curtains or air wall systems for different door types in accordance with [Frico 2013].

Due to the design of sectional doors, it makes sense to use them with air wall systems. Air curtain systems are usually used with high-speed spiral doors, roller shutters and vertical opening doors, since no additional space is required above the door for the opened door sections.

Door air curtain systems differ in the form of their air outlet. Figure 78 shows a fin outlet system and a nozzle outlet system. According to [Ketteniß 2007] systems with fin outlets are generally used with air curtains. However, these are limited in their maximum installation height. Due to the higher air discharge velocity nozzle systems can cover a higher door zone. Manufacturers of nozzle systems advertise that their devices have significantly lower energy consumption with a comparable separation effect, since the air mass flow is lower. Only horizontal nozzle systems can be installed for air walls.

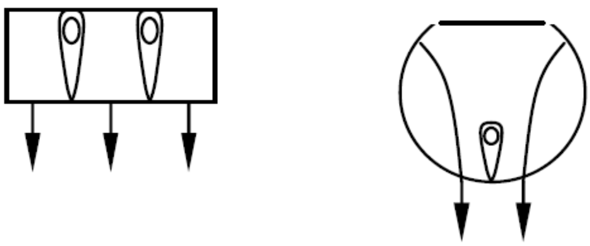


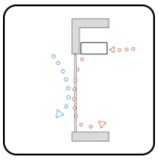
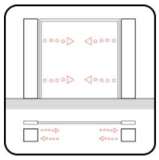
Figure 78: Comparison of conventional air outlet systems: fin (left) and nozzle (right) [Ketteniß 2007].

Different designs of air intakes are possible for vertical air curtains. In conjunction with the air outlet the following systems can be installed: air rolls with rotating direction to the room (standard installation), or a shielding air roll, in which the air wall counteracts the incoming air flow. Run as a double shielding air roll two blower units produce two counter-rotating air rolls which are heated to different temperatures. The outer unheated air roll ensures an stable shielding in the door zone, energy losses can be reduced thereby. The inner heated air roll warms the air, so that the ingressing air is not felt as a draft in the entrance area [Recknagel 2007, 1461]. In addition sub-floor systems are possible with air intakes at the bottom. This design is not used with passenger traffic.

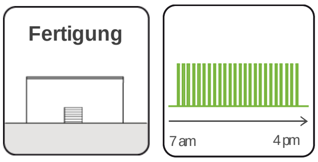
In the horizontal air jet direction, a single-sided system can be installed. In order to ensure a higher shielding performance, the air wall can be generated from both sides when using a tangential system. Here, the opposing nozzles are set at an angle to each other so that both air streams do not frontal blow each other but tangentially past one another. The distinction between horizontal and vertical air throw direction is summarized in Table 17.

In Chapter 8.7.2 the energy saving of an air wall with horizontal nozzle outlet is examined in a sample calculation.

Table 17: Comparison of vertical air curtain and horizontal air wall according to [Recknagel 2007, 1461].

	vertical air jet direction (air curtain)	**horizontal air jet direction (air wall)**
		
design options	— standard installation — installation of shielding air rolls — double shielding air rolls — sub-floor systems	— one-sided system — tangential system
boundary conditions	— thermal pressure difference is partly offset — shielding performance increases with double air rolls	— thermal pressure difference remains fully effective — shielding performance increases with tangential system
criteria for product selection	door type, door size, thermal buoyancy, wind pressure and mechanical pressure	

8.7.2 Sample calculation for energy saving through the use of an air wall system



In the following a use case is investigated, in which an air wall system is used to reduce the high ventilation heat losses for the scenario *regular forklift traffic* in the *manufacturing building model*, see chapter 7.4.3. In order to offer the highest possible savings, the slow running sectional door type is assumed. In this scenario, the stay-open time of the door is about 3.5 hours per day. The annual ventilation heat loss amounts to 38,080 kWh/a, see Figure 41.

Transmission and leakage losses of the door will not be considered for this comparison, since the air wall system is not run in continuous operation (24 hours). To simplify the calculation, the operating time of the air wall system is put on a level with the stay-open period of the door of 3.5 hours per day. However, the air wall is only operated in the heating season from November to April (129 days). This results in an operating time of the air wall of about 450 hours a year. The ventilation heat loss for the period from November to April are calculated to 25,300 kWh/a for the chosen door type according to Chapter 7.4.3.

According to the manufacturer a volume flow of 13,000 m³/h is required to shield the 16 m² opening with an horizontal air wall at a wind load of up to 1.5 m/s. The resulting fan power is specified as 7.5 kW. Based on the annual operating time the electrical energy required to accelerate the air flow results to 3,375 kWh.

In industrial halls air wall systems are often used without air heating [Recknagel 2007], so the above selected air wall is calculated without air heater for a simple economic analysis. Taking into account a heat price of 4 ct/kWh (see Chapter 7.3) avoiding a ventilation heat loss of 25,330 kWh would save heating costs of about € 1,000 per year. With the premise of a “completely thermal shielding” an air wall could avoid these heating costs. With the simplification that this complete shielding can also be achieved without heating the air wall, the heat loss must only be compared to the energy costs required to accelerate the airflow through a fan. With electricity rate of 4ct/kWh according to [BDEW 2012, 13] the calculated electrical consumption of 3,375 kWh results in operating costs of € 442 per year. Under these assumptions € 570 could be saved in energy costs.

The calculation is summarized in Table 18. The selected air wall system (including fan, heater, air duct, nozzles and installation) is estimated by the manufacturer with a purchase price of € 13,700. Since the chosen system is assessed as largely maintenance-free, the payback period in this scenario is calculated as 24 years.

Table 18: Calculation of profitability of an air wall system.

scenario regular forklift traffic	(Chapter 7.4.3)	
ventilation heat loss November-April	25,330	$kWh_{thermal}$
energy costs	1,013	€/a
air wall system		
operating time	450	h
fan power	7.50	kW
electrical energy consumption	3,375	$kWh_{electric}$
energy costs	439	€/a
annual savings	574	€/a

8.8 Summary

This chapter deals with different methods to increase energy efficiency and thermal comfort using various scenarios from Chapter 7. The following results can be pointed out:

- The additional heat demand caused by long opening periods can be reduced by up to 30% by frequent openings and closings. Due to the high number of cycles, such measures can be reasonably implemented with high-speed doors only.
- The ventilation heat loss and respectively the resulting additional heat demand can be highly reduced, assuming that a truck loading and unloading operation can be performed in the building (in this case: *warehouse building model*). Operating with several loadings and unloadings per day, depending on the door type, the savings can reach up to 72 and 89 %, although during the cold season the running-in truck may represent an additional cooling source.
- An object-size adapted door opening can be implemented using sensory systems (e.g. laser scanner). For the examined scenario *regular forklift traffic,* the opening height can be reduced to 2.5 m. Significant energy savings of up to 63% are possible with the reduction of the opening area and air exchange.
- With the use of an airlock, the ventilation heat loss and the resulting heating demand can be decreased significantly. Depending on the door type and the building model, savings of the heating demand by up to 90 % are achievable. In addition, the thermal comfort in the building can be increased. In practice this means that an airlock function has to be coordinated with logistical processes. Moreover, this measure creates additional construction costs.
- A general statement about the energy efficiency of air curtains cannot be made since the efficiency largely depends on the quality of the air shield between inside and outside. A possible efficiency enhancement for individual applications must be determined separately.
- Air curtains or air wall systems allow a significant increase of comfort; a monetary assessment is not possible.
- An air curtain or air wall system offers the possibility of retrofitting an already installed door system in case of a change of use (e.g. frequent opening or long stay-open times). Replacing a slow running door by a high-speed door involves a higher investment of € 8,000 – 16,000.

9. Conclusion

The issue of energy efficiency becomes increasingly important in the sectors of industry and commerce, trade and services. In addition to the continuous development and optimization of industrial processes, industrial and commercial buildings should also be considered. In the past, research and development activities were focused on energy efficient and sustainable residential and administrative buildings. The energy demand could be reduced to a minimum ("net zero energy buildings"). The industry sectors as well as commerce, trade and services have largely been ignored so far.
In this case, the total heating energy consumption of industrial buildings amounts to about 61 billion kWh/a – which is equivalent to about 30 % of the annual end energy consumption for heating of non-residential buildings. The saving potential in energy refurbishment of industrial buildings is estimated to be around 35 billion kWh/a [Oschatz et al. 2011, 42, 51]. The main amendments to the German "Energieeinsparverordnung" [EnEV 2009] for the construction of new buildings are air-tight building envelopes and high thermal insulation standards to reduce heat loss.

Industrial doors are a common part of industrial buildings. These prevent air flow through openings, which are necessary for the supply and removal of goods. Considering the common door systems on the market, it can be noted that there are large differences in construction materials and insulation, opening and closing speeds as well as control systems. This research project deals with different door systems and their energetic, building climatologic and economic impact on a building. To this end, several different types of buildings have been developed which are representative for a large number of industrial buildings in Germany, see Chapter 5.

To calculate the air flow through a single-sided open door a new ventilation model has been implemented in the simulation tool. This ventilation model takes into account both the thermally induced and the wind-induced air exchange. In order to verify the simulations, temperature measurements were made in the tool hall of the Department of Building Climatology and Building Services, see Chapter 4. It can be noted that the simulation provided good results in comparison to the temperature measurements. Both the temperature drop at the beginning of the opening cycle as well as the temperature rise by warm walls and ceilings after closing the door was calculated correctly in the simulation.

The door-specific properties such as heat transition coefficient, air permeability or different opening periods are examined in Chapter 6 in order to determine their influence on the energy balance of a building. It was found that the ventilation heat loss exceeds the heat losses by transmission and leakages, when the door is opened three minutes per hour during the operation time of the building. In the case of two opposite simultaneously opened doors, the additional heat demand increases by about 10 % compared to successively opened doors.
Furthermore, a flow network was implemented in the building simulation for a calculation of air flows inside the building. Therefore, initial assessments can be made on the temperature distribution in the building models. It was found that the interior temperature rapidly decreases when the door is opened during the first few minutes, depending on the outdoor climate and the type of building. This means that door openings can be optimized with respect to both comfort (drop in temperature, drafts) and energy savings by a suitable sensor system to keep the door openings as short as possible.
It has also been shown that the electrical energy required for door operations (consisting of drive, control and sensor technology), have been minor as compared to the total heat loss of the door.

In Chapter 7, several practice-oriented scenarios have been developed (e.g. *truck loading / unloading* or *regular forklift traffic*) to determine individual door opening characteristics. Finally, several door types (sectional door, flexible high-speed door, rolling shutter, high-speed spiral door) have been compared with an "ideal door". This has allowed us to recommend appropriate door types in terms of energy and economic efficiency for different applications.
At low opening cycles, it was found that a high insulation standard and air tightness of the door is required. The energy consumption of the building can be reduced, especially if there are many doors in the building façade. At frequent opening cycles, opening and closing speed of a door is primarily relevant. Insulation and air tightness

have a minor influence compared to the high ventilation heat loss.
Furthermore, the ventilation heat loss by an open door is higher than the heat losses of transmission and leakage by a closed door, regardless of the door type in almost all scenarios. Depending on the individual scenario and building model, noticeable drops of temperature near the door opening can occur of up to 30 % or about 720 h/a in the time of use.

Finally, different measures to increase energy efficiency and thermal comfort have been examined in Chapter 8. It has been shown that the door-related additional heat demand can be reduced by up to 30 % by the use of high-speed doors to avoid longer stay-open periods. An object-size adapted door opening using modern sensor technology, leads to a significant reduction of the air exchange between the inside and outside. The door-related additional heat demand can be reduced by up to 63 %. By using an airlock, the ventilation heat loss and the resulting heating demand can be decreased significantly. Depending on the door type and the building model, savings of the heating demand by up to 90 % are achievable. In addition, the thermal comfort in the building can be increased. For practical purposes, an air-lock function has to be coordinated with logistical processes. Moreover, this measure creates additional construction costs.
Air curtains or air wall systems allow an increase of thermal comfort. A general statement about the energy savings potential of air curtains cannot be made because the efficiency depends on the quality of the air shield between the inside and outside. A possible increase in efficiency is to be determined separately for individual applications.

According to the knowledge acquired in the course of this research, avoidance or minimization of ventilation heat loss caused by open doors represent the largest potential for energy savings of industrial door systems in buildings. These can be achieved with a slight effort by means of sensory systems.
It should be noted that due to the design of high insulated and tight building envelopes the proportion of door-related heat loss will tend to increase in the future.

In terms of energy efficient and sustainable construction, it is essential to include doors in the planning process. Likewise, a suitable combination of door type, drive, control and sensor has to be made depending on the use of application.
Therefore, the study provides energetic and economic guidance to choose an appropriate door system for various applications.

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13. Appendix

13.1 Questionaire “door systems in industrial buildings”

Fragebogen - Torsysteme im Industriebau

Stand: 12.05.2012

Der Lehrstuhl für Bauklimatik und Haustechnik an der Technischen Universität München (TUM) erarbeitet in Zusammenarbeit mit dem Bundesverband Antriebs- und Steuerungstechnik. Tore (BAS.T) die Studie "Torsysteme im Industriebau". In diesem Projekt wird der Einfluss von Industrietoren auf den Energiebedarf von Industriehallen untersucht.

Die vorliegende Übersicht dient u.a. einer Gegenüberstellung unterschiedlicher Torsysteme mit deren spezifischen Eigenschaften (z.B. Torgrößen und Dämmwerte, Luftdichtheit, typische Einsatzbereiche) sowie deren Vor- und Nachteilen.
Wir bitten Sie, in dieser Excel-Tabelle aus Ihrer Sicht repräsentative und sich in ihren Eigenschaften unterscheidende Produkte für Tortyp, Antriebstechnik sowie sensorische Ansteuerungen in den dafür vorgesehenen Arbeitsmappen "Torsysteme", "sensorische Systeme" sowie "Öffnungszeiten" einzutragen.
Für jede Produktkategorie ist jeweils ein Beispiel in der Tabelle aufgelistet.

Die von Ihnen gemachten Angaben werden vertraulich behandelt und dienen als Grundlage für Simulations- und Wirtschaftlichkeitsrechnungen, die durch die TUM durchgeführt werden.

Erfassungsblatt - Torsysteme			
	Beispiel	**Torsystem 1**	**Torsystem 2**
Tor			
Hersteller	Muster GmbH		
Bezeichnung, Typ	Tor 1b		
Klasse	Sektionaltor		
Material/Aufbau	doppelwandiges Stahltor mit PU-Hartschaum		
Standardgröße [m²]	☑ 25	☐ 25	☐ 25
ggf. abweichende Größe			
Maximalgröße (Breite*Höhe) [m*m]	8*7		
Verglasung möglich	☑	☐	☐
verglaste Fläche [m²]	0,0		
Lüftungsöffnung möglich	☐	☐	☐
Schlupftür möglich	☑	☐	☐
U-Wert (gesamt bei o.g. Größe) [W/m²K]	**1,0**		
Torblatt / Lamelle [W/m² K]	0,5		
Rahmen [W/m² K]	1,5		
Verglasung [W/m²K]	-		
Tordicke [mm]	42		
Windlastklasse	3		
Luftdichtigkeitsklasse	2		
Typische Einsatzgebiete	Industrietor, wenige Toröffnungen		
Listenpreis [€][1]	2500		
Vorteile	robust, langlebig, guter Dämmstandard		
Nachteile	vergleichsweise schwer		
Kommentar/Bemerkung			
Quelle			
Antrieb			
Hersteller	Muster GmbH		
Bezeichnung, Typ	Antrieb 4x		
Antriebsart	☐ Welle	☐ Welle	☐ Welle
	☑ Kette	☐ Kette	☐ Kette
	☐ Pneumatik	☐ Pneumatik	☐ Pneumatik
	☐	☐	☐
Einsatzgrenze (z.B. max Torgewicht)	max Torhöhe 7m		
Geschwindigkeit (öffnen) [m/s]	0,18 m/s (max.)		
Geschwindigkeit (schließen) [m/s]	0,18 m/s (max.)		
Leistung Betrieb (bei o.g. Größe)[W]	250		
Leistung Standby [W]	1		
Wartungsintervall	☐ Zeitdauer [Monat] ☑ Öffnungszyklen [-]	☐ Zeitdauer [Monat] ☐ Betriebszyklen [-]	☐ Zeitdauer [Monat] ☐ Betriebszyklen [-]
Antrieb	7500 Zyklen		
Listenpreis [€][1]	2000		
Vorteile	geräuscharm		

Erfassungsblatt - Sensorische Systeme

	Beispiel	Steuerungssystem 1	Steuerungssystem 2
Sensorik			
Hersteller	Muster GmbH		
Bezeichnung	SensorA5		
Typ	☐ Handsteuerung	☐ Handsteuerung	☐ Handsteuerung
	☐ Funksteuerung	☐ Funksteuerung	☑ Funksteuerung
	☐ Radar	☐ Radar	☐ Radar
	☑ Lichtschranke	☐ Lichtschranke	☐ Lichtschranke
	☐ Induktion	☐ Induktion	☐ Induktion
	☐	☐	☐
Aufhaltezeit zwischen vollständigem Durchschreiten und Schließsignal [s]	5		
Typische Einsatzgebiete	Werkstatttore, Industriebetriebe		
Höhenvariables Öffnen möglich	☑	☐	☐
Leistung Betrieb [W]	50		
Leistung Standby [W]	50		
Listenpreis [€]	2500		
kombinierbar mit[1]	☐ Funksteuerung	☐ Funksteuerung	☐ Funksteuerung
	☐ Radar	☐ Radar	☐ Radar
	☐ Lichtschranke	☐ Lichtschranke	☐ Lichtschranke
	☐ Induktion	☐ Induktion	☐ Induktion
	☑ Timer	☐ Timer	☐ Timer
	☐	☐	☐
Kommentar/Bemerkung			

Erfassungsblatt - Öffnungszeiten

	Beispiel	Nutzungsart 1	Nutzungsart 2
Nutzungsbezogene Toröffnungszeiten			
Nutzung des Gebäudes	Werkstatt		
durchschnittliche Öffnungszyklen [1/h]	2		
maximale Öffnungszyklen (bei Stoßzeiten) [1/h]	-		
Zeitraum der Stoßzeit	-		

Zweckbezogene Öffnung	durchschnittliche Aufhaltezeit [s]
LKW be- oder entladen	1200
Staplerverkehr	45
Personenverkehr	45
KFZ-Verkehr	45
...	
...	

13.2 Pressure coefficients

13.2.1 Manufacturing and *warehouse building model*s

angle of incidence / orientation of the facade	**0°**	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**
north	0.5	0.25	-0.5	-0.8	-0.7	-0.8	-0.5	0.25
east	0.5	0.25	-0.5	-0.8	-0.7	-0.8	-0.5	0.25
south	0.5	0.25	-0.5	-0.8	-0.7	-0.8	-0.5	0.25
west	0.5	0.25	-0.5	-0.8	-0.7	-0.8	-0.5	0.25
ceiling	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1

13.2.2 *Workshop building model*

angle of incidence / orientation of the facade	**0°**	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**
north	0.5	0.25	-0.5	-0.8	-0.7	-0.8	-0.5	0.25
east	0.7	0.35	-0.5	-0.4	-0.2	-0.4	-0.5	0.35
south	0.5	0.25	-0.5	-0.8	-0.7	-0.8	-0.5	0.25
west	0.7	0.35	-0.5	-0.4	-0.2	-0.4	-0.5	0.35
ceiling	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1

The pressure coefficients used are taken from the database of [IDA ICE 2012] and [Liddament 1986].