Intelligent Swing Doors

Reducing Air Infiltration Using Smarter Sensors.

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Abstract

When an automatic swing door is used in an entrance, the energy consumption increases. This is because the door cannot detect when the user has passed and therefore, for safety reasons, stands in the open position for too long. To make automatic swing doors more sustainable one needs smarter sensors that can cover a larger area and communicate with the door. In this thesis 11 different concepts of how to use more intelligent sensors to control the door to reduce the infiltration are presented. Both the times the door is opening, standing in the open position and closing are considered. To limit the air leakage even more reduction of the open angle is also analyzed. The aim is to make the door move like a manual door, which has the smallest air leakage.

To see how swing doors are configured, a survey has been performed. The results show that the average cycle is over 16 seconds long. Further, to get a greater understanding of the air leakage a field test is made where the temperature is measured for different scenarios. The result shows a temperature drop larger than 5 degrees for a typical door cycle. By start closing the door sooner the energy losses could be reduced with over 60%. The result is an improved indoor climate as well as a smaller environmental impact.

Acknowledgements

The master thesis was conducted at Assa Abloy Entrance Systems in Landskrona, Sweden. The thesis started in January 2019 and lasted until June 2019. I want to thank my supervisor Anton Cervin and my mentor Roger Dreyer for all the guidance and help during the thesis. I would also like to thank Jeppa Grosshög for all the help with the Swing door software and Dennis Jönsson for all the assistance when installing the new software on the test door. I want to thank Momo Ma for the help with some discussions and concept gathering. Lastly, I want to send out a special thanks for all the employers at Assa Abloy Entrance Systems who has been helping me with information gathering by participating in my field studies and surveys.

Contents

1

Introduction

The high emission of carbon dioxide has fueled the greenhouse effect and caused global warming. This has made the environmental questions and especially the reduction of emissions highly prioritized. In the EU, buildings are responsible for approximately 36% of carbon dioxide emissions [European Commission, 2019] . The high emissions are due to the massive energy consumption in the buildings.

In Figure 1.1 the energy consumption in commercial buildings is shown. As can be seen, the most significant part comes from space heating with approximately 32% of the total energy consumption.

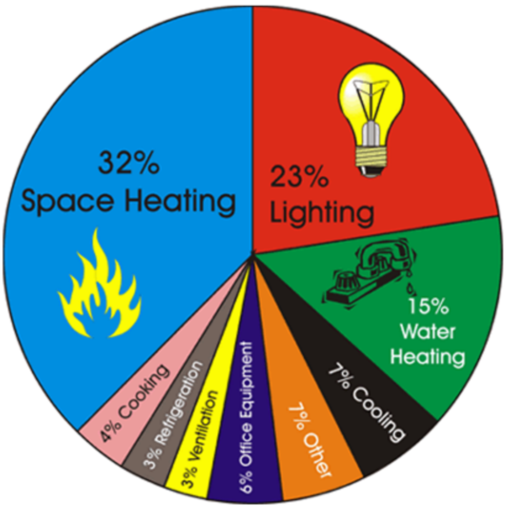


Figure 1.1: The energy use in commercial buildings. The energy used for space heating, cooling and ventilation is almost twice as large as any of the other categories [Energy Kid's Place, n.d.]

To reduce the high carbon dioxide emission EU published the Energy Performance of Buildings Directive, which forces the member countries to renovate existing buildings to become more energy efficient. The directive also requires all new buildings to be nearly zero-energy buildings meaning the energy performance must be high [European Commission, 2019].

One of the most significant contributors to the need for heating is the entrances to the buildings. Entrances for commercial buildings are often large and is frequently used. This makes it possible for the cold air from the outdoors to flow inside. Infiltration of cold air through entrances stand for the most significant heat loss.

One type of entrance system that is developed at Assa Abloy Entrance Systems AB are automatic swing doors, shown in Figure 2.2. The swing doors are nowadays accompanied by sensors scanning a small area along the door shaft to prevent it from hitting pedestrians. The small sensor area results in that the door cannot register if a pedestrian has walked through or not. Consequently, for safety reasons, the door needs to stand in the open position for a long time, 10–20 seconds, before it starts to close. In a commercial building with many people coming and going this will cause an extensive infiltration of outside air. During winter cold air will flow freely into the building while the ventilation is working trying to keep a good inside temperature. Further, during summer, the problem will be the opposite. The energy consumption throughout the year will become enormous. The extensive energy use will cost a great deal of money, and the impact on the environment will be substantial.

One thing that can be done to minimize energy consumption is to make the entrance systems more effective and intelligent. This can be done with smarter sensors that have a broader view of the entrance. During the last years, Assa Abloy Entrance Systems has been working together with CEDES to create a new sensor that can scan the entire entrance area. The new sensor is not yet fully developed, but the idea is to start a pre-study of how to use this sensor to shorten the time the doors stand open.

Purpose

In this thesis, the new sensors will be analyzed and used to optimize the opening and closing of an automatic swing door. First, the times for holding the door open will be optimized, and then some analysis of the opening angles will be made. The main goal is to compare different strategies of how to use the sensor to reduce infiltration. Strategies for minimizing air infiltration today, in 2–3 years from now and the future are presented. The concepts with low air infiltration but still a good user experience and accuracy will be chosen. Some concepts will then be tested on a real swing door to see the effect on the indoor temperature. The result will then be presented for Assa Abloy. The questions to be answered in this thesis are:

- How do the entrance doors work today? How large is the energy loss for a swing door?

Figure 1.2: The Swing door swings open when pedestrians want to pass.

- Which sensors are used? What information can we extract from the sensor?
- What are the driving forces for the air infiltration through swing doors? How can we limit them?
- Which strategies are there to control the door to minimize air leakage? How much energy can be saved? How much money can be saved?
- How do we want to control the door in the future? What is the optimal opening and closing of an automatic swing door?
- What are the regulations and laws for opening and closing times and angles for automatic swing doors?

Previous Work

As an effect of the Energy Performance of Building Direction the demand for sustainable buildings has increased resulting in that many studies and investigations of the environmental impacts due to buildings have been made. Here will some of them be presented.

The Swedish Energy Agency network BELOK did a pre-study to analyze the market for energy efficient entrance systems. In the study, they concluded that there is a large market with many types of doors, but there is a lack of information about the energy efficiency for different types of entrance systems. In the pre-study, BELOK also pointed out that the lack of design and shaping of the entrance systems results in the waste of energy, not the technology [BELOK, 2012].

In 2018 the Swedish research institute had the E2B2 thesis, incorporation with Assa Abloy Entrance Systems AB among others, whose goal was to develop a method to quantify different entrance solutions impact on the energy consumption of a building. In the study many tests were made with the focus on sliding and revolving doors, swing doors were not analyzed. In Figure 1.3 the both entrance types are shown. The result of the tests showed that the revolving door is the most energy efficient entrance solution. In one year a revolving door could save between 5000 and 26000 kWh energy, which corresponds to 60%–90% reduction of energy loss, compared to a sliding door [Huijuan Chen, 2008].

The cause of the high energy losses in buildings is the air infiltration when the entrance doors are open. The most extensive research about air leakage was produced by Yuill et al. The goal was to create a simple method to estimate infiltration rates into buildings from an opening of an automatic door. The study consisted of a laboratory study and a field study. In the laboratory study sliding and swinging doors were simulated to calculate the airflow through the doors. In the field study the relationship between how many pedestrians that passed by and how long the door stood open was investigated. The conclusion made from the survey was that air infiltration was much higher for swinging doors compared to sliding doors [Yuill et al., 2000].

The air infiltration method developed by Yuill et al. has been analyzed and used in many reports. In 2011 a master thesis was made to examine different methods to calculate air infiltration. In the study, five different methods were analyzed and used to estimate air infiltration, where one of them was from the Yuill et al. research. The findings in the report were that the performance of advanced air infiltration models was not better than the simple models. This was due to that air infiltration depends on many factors that vary with time and space [Berge, 2011].

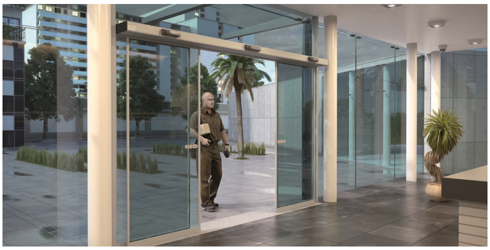
Two years later another master thesis was conducted looking at air infiltration through swing, sliding and revolving doors. A model was created to study the energy performance of building entrances. The model showed that the revolving doors were the most energy efficient with at least five times less air infiltration than any other entrance system. The entrance door with the most significant energy consumption was the swing door [Karlsson, 2013].

As mentioned before, many reports and analyses have been made. However, most of them come to the same conclusions: air infiltration depends on many factors that change over time and space which makes it hard to calculate, air infiltration through entrance doors are very high but could be improved by using other types of door systems, the best door are the revolving doors, and the worst is the swing doors.

At Assa Abloy Entrance Systems calculations and analysis of how to minimize the air infiltration for the different entrance doors have been made. Last year a group of student analyzed the energy savings when the swing doors hold the doors open for 1 second less than usual in healthcare, transportation, and retail. Their analyses showed that by just shortening the time for the door standing in the open position from 8 seconds to 7 seconds the energy saved could be estimated to between 3000 SEK to 4400 SEK [Al-Adhami et al., 2017].

Last year a master thesis was done at Assa Abloy which investigated other ways to minimize air infiltration when using swing doors from a user experience perspective. The master thesis examined many options of how to decrease the infiltration without affecting the user experience and came up with that opening time, and opening angles could be reduced. A field study was made to investigate the optimal opening angle. The study showed that if less than three persons wanted to pass the door, the optimal opening angle was 70°. When there were more than two persons, the opening angle should be increased to at least 90°. However, to implement the findings better and more improved sensors need to be used to ensure safety [Jingying Ma, 2018].

In this thesis, previous work will be used to go forward and investigate how the swing door could be improved and updated to minimize air infiltration. The software will be enhanced and newer sensors will be investigated.



(a) The Sliding door slides to the side when people want to pass.

(b) The Revolving door has rotating pockets that let people through.

Figure 1.3: Two other types of automatic entrances that are developed at Assa Abloy Entrance Systems [ASSA ABLOY Entrance Systems AB, n.d.]

1.1 Outline

The thesis will start with a chapter with background information about the swing door, air infiltration, and the sensor systems. Further in the chapter, some regulations and laws are introduced. Further in Chapter 3 different scenarios and concept which solves the air infiltration problem is presented and then evaluated. In Chapter 4 a field test is going to be performed where some of the scenarios will be implemented. In the following chapter the answers and results from a survey about how the swing doors are configured today are presented. Chapter 6 is a Discussion chapter with some overall debate about the opening cycle of the door, air infiltration and laws are performed. In the last chapter a summary of findings together with further developments is presented.

2

Background

In this chapter a brief introduction of the door type used in this report is first made. Then there comes a section showing the air infiltration model and equation. After that a segment about the sensors on the door and how they are used to detect pedestrians. At last, some laws, regulation, and guidelines for automatic swing doors are presented.

2.1 Automatic Swing Doors

The swing doors are the most commonly used door type and are a type of hinged door with hinges attached to one of its vertical sides. An automatic swing door has a door operator attached to it. The operator has an engine which makes the door open and close for pedestrians. In Figure 2.1 a single-leaf automatic swing door is shown together with the operator. As can be seen rightmost in the figure the placement of the operator can be both on the wall but also on the door shaft.

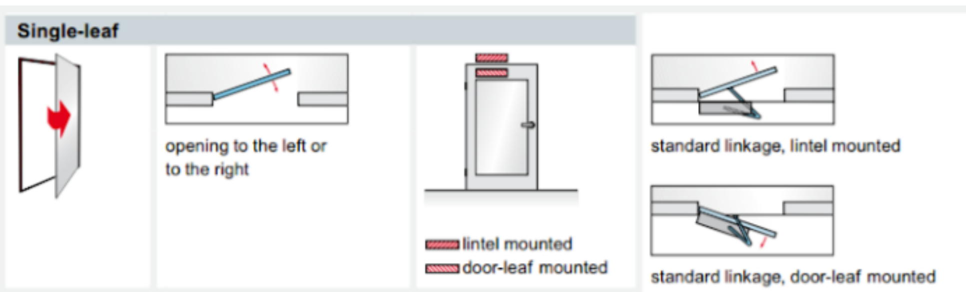


Figure 2.1: The figure illustrates an automatic single leaf swing door. In the leftmost figure, the door and opening direction are shown. In the two rightmost figures, the mounting and the linkage positions are shown [ASSA ABLOY Entrance Systems AB, n.d.]

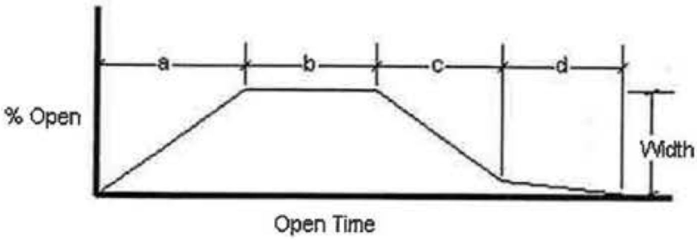


Figure 2.2: The percent of the door open versus the open time is shown for a swing door [ASSA ABLOY Entrance Systems AB, n.d.]

When a pedestrian presses the activation button or if there are activation sensors, the sensor senses that a pedestrian wants to pass the door, the operator will open up the door, hold the door open and then close the door. In Figure 2.2 below this process called the opening cycle of the door are shown. *Section a* is called the **opening time**, *Section b* the **hold open time** and *Section c* is the **closing time**. These sections of a door opening process are going to be used throughout the report. In Figure 2.2 there also is a *Section d*. *Section d* is called the latch check and is activated when the operator is closing the door, and the door angle is small, i.e., the door is close to the door frame. The latch check slows down the door, so it does not hit the door stop violently.

The opening and closing times for the door varies depending on location, which kind of people that will pass the door but also how good the safety sensor is. For doors placed in buildings with many people that could get severely hurt both the opening, closing times and the hold open times are set to be very long, even if a safety sensor is used. For buildings with healthy people the door opening cycle is still set to be very long to make sure that everyone passes through. The fastest the automatic swing doors that are sold by Assa Abloy can open the door on 2 seconds and close it on 4 seconds. The times for opening, closing and holding open are all set and decided by the user together with the service engineer installing the door and could be set to times between 2–12 seconds for opening, 4–12 seconds for closing and 1.5– 30 seconds hold open time. The door angle for fully open is also configured when installing the door. The open angle could be chosen to be between 80–180 degrees depending on operator and location.

2.2 Usage Of Automatic Doors In Entrances

How often an automatic entrance door opens and closes depends on the commercial building and the day. In Figure 2.3 the door usage over a day is shown for different commercial buildings. A trend could be viewed for different kinds of commercial buildings. For example offices, warehouses, hotels, and apartments have the same peak and off-peak hours. In Figure 2.4 this is shown much clearer. As can be seen the peak hours for retail and health care is almost five times larger than for offices and schools.

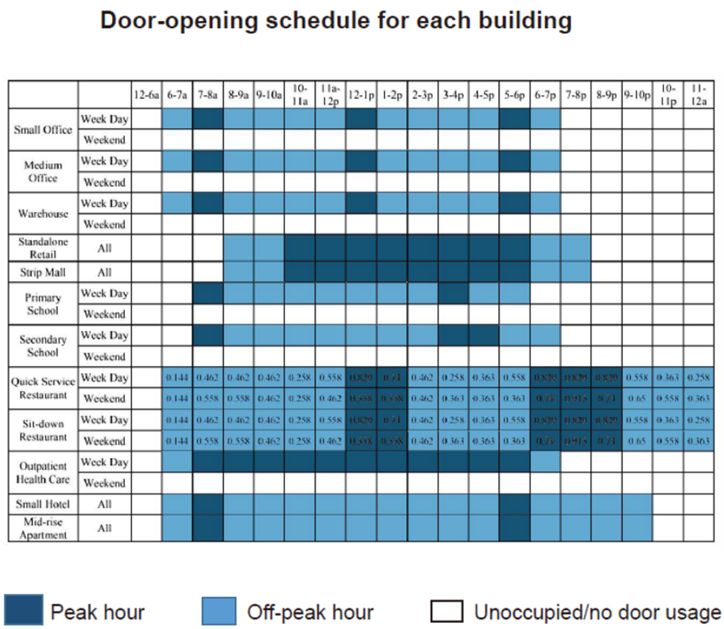


Figure 2.3: A schedule of door usage is shown. On the x axis we have the time of day and on the y-axis there is a list with commercial buildings which is split up on week days or weekend.

Door usage has a direct effect on infiltration and energy loss. During peak hours many people will pass the door and increase the air leakage. Optimization of the door opening cycle will therefore vary with the type of building and maybe also the hour of the day. The door usage will be considered and discussed later in the report.

2.3 Energy Loss In Buildings

In Figure 2.1 the energy use in a commercial building was shown. The largest energy consumption was for space heating. In Figure 2.5 the sources for energy loss in commercial buildings are shown as a pie chart. The largest piece is air infiltration through doors. Therefore the large need for space heating is mainly due to infiltration of cold air from the outside flowing into the building which stresses the importance that the door does not stand in the open position unnecessarily long.

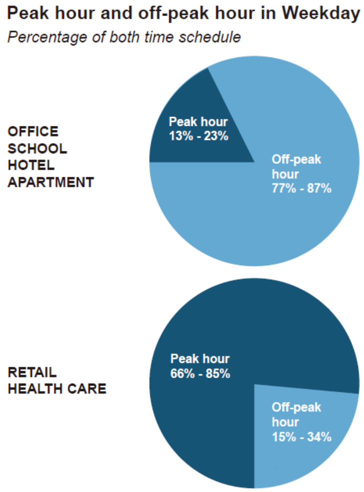


Figure 2.4: The percentage of peak and off-peak hours for different commercial buildings [Jingying Ma, 2018] .

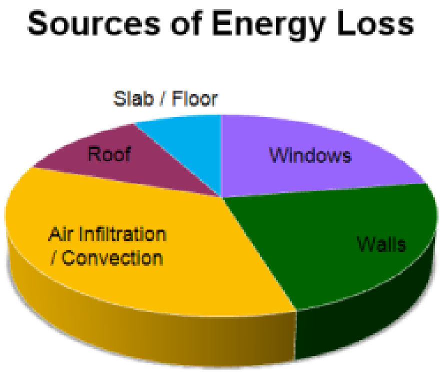


Figure 2.5: The figure shows the sources of energy loss in commercial buildings [American ICF Builders, INC, n.d.] .

Air can leak through an entrance door in 3 different ways. The most substantial infiltration comes through the open state of the door. The second largest is through small air gaps, for example between the door frame and the door. At last the air can leak through the material, air permeability. In Figure 2.6 the energy loss for a door is shown as a triangle with the most energy consuming part in the bottom. As can be seen in the figure, the top of the triangle, the electricity used to open and close the door are also an energy loss.

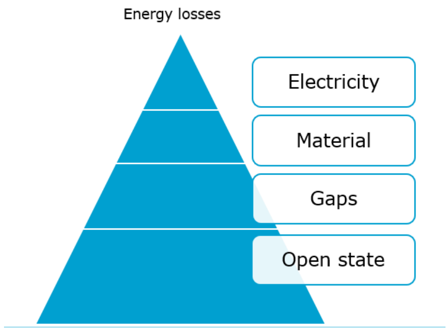


Figure 2.6: The energy losses from an automatic door. The largest energy loss is due to the open state of the door [ASSA ABLOY Entrance Systems AB, n.d.]

2.4 Air Infiltration

Previously the energy losses in buildings where presented and as could be seen the air infiltration through the open state of the door contributed to the largest energy loss in the buildings. This section will give an introduction to air infiltration through entrance systems. Equations and models for calculating energy losses due to infiltration will be presented.

Introduction

Air infiltration or air leakage is when air from outside unintentionally flows into the building. This can happen in three different ways. The first way is the diffuse flow. Diffuse flow occurs when the building foundation material is ineffective in controlling flow. The envelope material can have high permeability, the ability of a material to allow liquid and gases to pass through it, or cracks and holes that will let the outdoor air in. In Figure 2.6 this leakage is demonstrated as the blocks "gaps" and "material". The second way outdoor air can flow into a building is through an open window or door. This air leakage is called orifice flow. In Figure 2.7 the orifice infiltration from an open door is shown. The worst type of leakage is called channel flow. Channel flow is when the entry and exit point of the air is distant from each other. This result in that the air has time to cool down and condensate into liquid water that will cause mold and damage to the walls [Energy Education, n.d.] Moving forward in this thesis the focus will be on the orifice flow through entrance doors since this is the largest but also the one that Assa Abloy Entrance Systems could minimize.

For modern houses, the infiltration is considered a small part of the total energy loss. However, for commercial buildings such as office buildings the door usage is much higher and therefore air infiltration has a more significant impact on the total energy consumption. This impact can be modeled where the most vital components

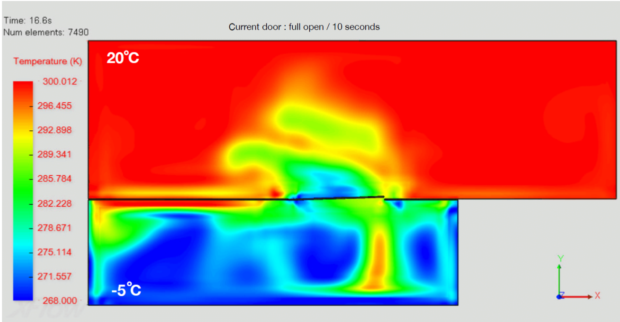


Figure 2.7: The temperature drop due to air infiltration when a swing door is fully open for 10 seconds [Jingying Ma, 2018] .

affecting the rate of air infiltration is listed below.

- Direction and strength of the wind.
- Ventilation strategy – mechanical or passive.
- Internal to external temperature differences.
- The frequency of use.
- The pressure differences between the top and bottom of the building (the stack effect).
- The orientation of the building.
- The maintenance of the building.

In the next section, a model using these parameters is presented. The only setting not used is the maintenance of the building, since this parameter is hard to calculate.

Model

The energy impact of air infiltration can be calculated through the volumetric flow rate Q_{inf} [W], given in equation (2.1) [Karlsson, 2013].

$$Q_{inf} = \rho_a C_D A (\Delta P)^n C_p (T_{in} - T_{out}), \tag{2.1}$$

where

ρ_a	= density of the air $[\frac{kg}{m^3}]$,
C_D	= discharge coefficient $[\frac{kg}{m^3}]$,
A= $areaofthedoorway$[m^2], =	
ΔP	= pressure difference between inside and outside $[Pa]$,
n	= flow exponent,
C_p	= the specific heat capacity of air $[\frac{J}{kg \cdot °C}]$,
T_{in}	= indoor air temperature$[°C]$,
T_{out}	= outdoor air temperature $[°C]$.

In the equation above the flow rate Q_{inf} depends on a variety of parameters where some of them are constant.

The coefficients that need to be calculated is the discharge coefficient C_D and the pressure difference between the inside and outside, ΔP. The discharge coefficient and the pressure difference is somewhat more challenging to interpret and calculate. In the following subsections, a presentation of the discharge coefficient and its calculations are first shown followed by a presentation of the pressure difference and the equations for that.

Discharge Coefficient

The discharge coefficient describes the ratio of mass flow through the door. The area of the doorway changes with the door angle resulting in that the mass flow through the door also changes with the door angle. In Figure 2.2 the opening time, hold open time and the closing time where defined. Using the notions from the figure the average discharge coefficient can be calculated as the sum of the discharge coefficient from each of the sections divided by the total opening time, Equation (2.2).

$$C_D = \frac{(C_{Da} \cdot a + C_{Db} \cdot b + C_{Dc} \cdot c + C_{Dd} \cdot d}{a+b+c+d}, \tag{2.2}$$

where the C_{Dx} is the discharge coefficient for section x. The expression for the discharge coefficient for section x is shown below, Equation (2.3).

$$C_{Dx}(\theta) = 0.01344 \cdot \theta - 7.0635 \cdot 10^{-5} \cdot \theta^2, \tag{2.3}$$

where θ is the door angle. To get the average C_D Equation (2.3) where integrated over all the angles in each section [Yuill et al., 2000].

Pressure Differences

The pressure gradient over the building envelope results in a force driving the movement of air. When a door opens the pressure difference pushes air from the inside to the outside and air from the outside to the inside resulting in that the pressure difference has the greatest impact on the infiltration. Therefore, it is important to calculate the pressure difference to be able to calculate the infiltration. The pressure

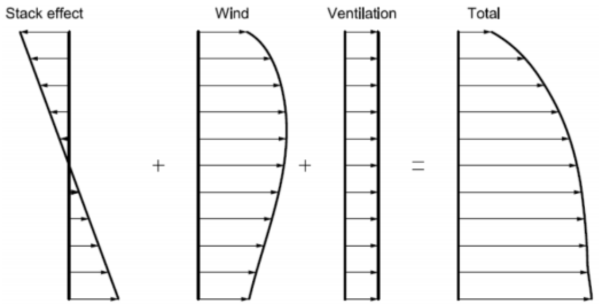


Figure 2.8: The figure shows the three main components of the pressure differences; stack, wind and mechanically induced pressure together with the total pressure difference [Karlsson, 2013] .

difference is composed of three components: the stack effect, wind pressure, and mechanically induced pressure. The total pressure difference can be calculated as a sum of these three components.

$$\Delta P_{tot} = \Delta P_s + \Delta P_w + \Delta P_v \tag{2.4}$$

where:

ΔP_{tot} = the total pressure difference [Pa],
ΔP_s = the pressure difference from the stack effect [Pa],
ΔP_w = the pressure difference from the wind pressure [Pa],
ΔP_v = the pressure difference from the mechanically induced pressure [Pa].

In Figure 2.8 the different components together with the total pressure difference are shown. Going further in this report the pressure is defined positive when the pressure is higher on the outside than the inside. Thus, a positive pressure difference answer to the air flowing into the building [Berge, 2011].

The Stack Effect. The stack effect, shown to the leftmost in Figure 2.8, is created by the temperature differences across the building envelope. When cold air from the outside flow into a building with warm air a density difference between the different airs is introduced creating air buoyancy. The warm air inside rises and creates positive pressure at the top of the building, which pushes air out of the building. At the bottom of the building, there is negative pressure, due to the risen warm air, drawing cold air in through both open doors and windows. The air pressure increases with increasing height and air density differences between the outdoor and indoor. The stack effect can be calculated as in Equation (2.5).

$$P_s(z) = P_{ref} + z \cdot \rho \cdot g \tag{2.5}$$

where:

$P_s(z)$ = the stack pressure at elevation point z [Pa],
P_{ref} = the pressure at a reference point [Pa],
z = the elevation from reference point [m],
ρ = the air density [kg/m^3],
g = the gravitational constant [m/s^2].

As can be seen, the stack pressure varies throughout the building. Since the air flow into and out from a building must be equal, there is a point where the inside pressure is equal to the outside. In figure Figure 2.8 the reference point $z_{ref} = 0$ is in the middle and z increases when going downwards in the picture. This positioning result in that the stack pressure is positive beneath the reference point and negative above.

To calculate the total pressure the difference in inside and outside pressure is needed. In the Equation (2.6) below the final pressure difference due to stack effect ΔP_s is shown.

$$\Delta P_s = P_{out}(z) - P_{in}(z) = z \cdot (\rho_{in} - \rho_{out}) \cdot g = z \cdot 3456 \cdot (\frac{1}{T_{out}} - \frac{1}{T_{in}}) \tag{2.6}$$

In the equation above the assumption that air acts as a perfect gas have been made. In the last step in the equation the relationship between density and temperature has been utilized [Berge, 2011].

The Wind Pressure. When wind hits the building the kinetic energy in the wind is transformed into pressure. The intensity of the wind pressure depends on the air density, wind speed and the pressure constant C_p. The pressure constant is a representation the wind pressure distribution over the building and thus varies depending on where and with which angle the wind hits the building. The formula for the difference in wind pressure ΔP_w is shown in Equation (2.7).

$$\Delta P_w = C_p \cdot \rho \cdot v^2/2 \tag{2.7}$$

where:

C_p is the wind pressure coefficient,
ρ is the density of the air [kg/m^3],
v is the wind velocity [m/s].

The wind pressure coefficient of C_p is generally calculated and obtained through experimental testing. A positive value of the coefficient means that the wind wants to push air into the building [Karlsson, 2013].

The Mechanically Induced Pressure. The last component inducing a pressure difference is the mechanically induced pressure. This is usually due to the ventilation system. Depending on the ventilation system a negative, neutral or positive pressure can be induced. Once again, a positive pressure difference results in airflow into the building and a negative one a suction of air out of the building.

The total pressure difference is then calculated as the sum of the three pressures described above. The total pressure difference together with the discharge coefficient calculated in the previous section can be inserted into Equation (2.1) to get the flow rate through the door.

2.5 Indoor Climate Problems Due To Air Infiltration

When cold air from the outdoor leaks into a building it could cause some problems. One of the most obvious problems is the temperature drop due to energy loss. The cold from the outdoor chills the indoor climate. There is no law for how the temperature indoor should be set, but there are some guidelines and demands depending on the purpose of the building. The VVS Technical society has set up some guidelines and recommendation of indoor temperature in both households and commercial buildings, called R1. The lowest operative temperature they recommend is +18°C in dwellings and workplaces and +20°C for hospitals, pre-schools, and elderly intuition. Figure 2.9 is taken from one of their presentations and shows the working efficiency versus the indoor temperature. As could be seen the optimal indoor temperature is $22°C$ where the working efficiency is almost 100%.

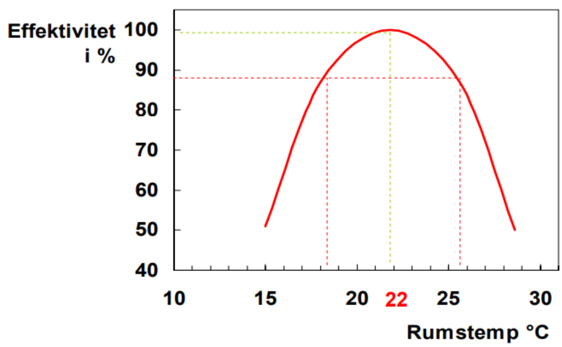


Figure 2.9: The room temperature versus the efficiency in percent is shown [Bülow-Hübe, n.d.] .

The target value for indoor temperature for buildings with much of still work, for example, classrooms, offices, and dwellings, the temperature should lay around $20°C$–$26°C$. For buildings with much of movement, the temperature could be lower, around $16°C$–$25°C$. When the temperature goes below or above these temperatures the efficiency and comfort will decrease. With the reduced comfort and focus the risk of injuries will increase [Bülow-Hübe, n.d.] .

There are also other problems due to air infiltration. The outside air can contain dust, bad odors, and pollution. Outdoor insects, like flies, bugs, and mosquitoes, can also flow into buildings as the door open. If the building is close to a busy road, the noise from the outside will come in. The wind draft that happens every time the door opens also affects the indoor climate. Short term the above problems will cause headache, lower efficiency, employer discomfort and irritation. Overall the infiltration can cause diseases, more sick employers and the indoor stuff and surrounding will also get affected negatively by the infiltration.

Other alternatives to minimize air leakage

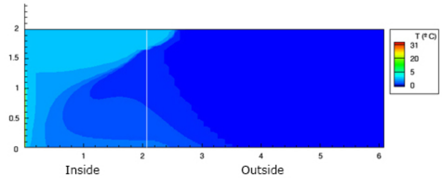
In this thesis, the focus lays on to shorten the hold open time and maybe also the open angle for the door to minimize the air leakage, but there are other ways to minimize air leakage without affecting the opening times or angles for the door.

Air curtains. When entering some commercials buildings, one can feel a fan blowing onto the hair. This is the effect of the air curtain. An air curtain blows air over the doorway to create an air barrier. The air barrier separates the indoor and outdoor environment without preventing or limiting people to enter and exit the door. In Figure 2.10 an air curtain and its benefits are shown. As can be seen,

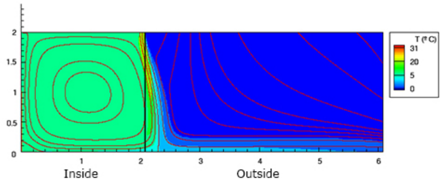
Figure 2.10: The air curtain and its advantages when placed above an entrance are shown [airtécnics, n.d.] .

the air curtain prevents outdoor air from flowing into the building. The air curtain reduces heating and cooling costs by up to 80%. In Figure 2.11 the benefits are clearly shown as the inside temperature when there is no air curtain versus when an air curtain is used.

The disadvantages of air curtains are that they are noisy and consumes much energy [airtécnics, n.d.]



(a) An open entrance door at x=2 is shown. As can be seen, outdoor air flows freely into the building.



(b) The benefits of the air curtain is shown. The door is placed at x=2. As can be seen, the indoor air is still warm even if the door standing open.

Figure 2.11: The figures shows the difference between not having an air curtain, to the left, and with an air curtain, to the right[airtécnics, n.d.] .

Vestibules. Some buildings with large entrances could sometimes have an enclosed vestibule in the entrance that separates the cooled/heated space from the outdoor air. The vestibule prevents the outdoor air from flowing indoors by placing self-closing doors far from each other. The doors open at different times, making the outdoor air stay in the vestibule.

2.6 Sensors

Let us move forward and look at the sensors used currently on the door and the sensors that will be used in this thesis.

Automatic swing doors always need to be used together with a safety sensor. The task of the safety sensor is to detect a pedestrian in the safety zone. The safety zones are the area in front of the door and behind it and are used to ensure that the door does not hit anyone when opening or closing. In Figure 2.12 the safety zones are shown. where sensor signals that the door movement in the areas should be:

Area 1 (safety) = when closed the door should not open if anything is detected here.
Area 2 (reverse) = when opening or closing the door should move in the opposite direction when something is detected in the doorway.
Area 3 (stop) = when open the door should not close if anything is detected here.

The automatic door could also be occupied with an activation sensor. The activation sensor can detect pedestrians who want to pass through the door. If an activation sensor is not mounted on the door or if it does not recognize the pedestrian, the door could also be open by pressing the activation button, or door opener button, placed near the entrance. When the activation button is pressed, or the activation sensor has detected a pedestrian an impulse is sent to the control unit of the door making the door open.

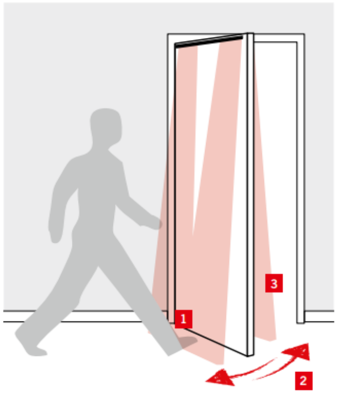


Figure 2.12: The safety zones of the door. The safety zones ensure the safety of the pedestrians [ASSA ABLOY Entrance Systems AB, n.d.]

In this thesis, an activation sensor and a safety sensor will be used. However, as could be seen in Figure 2.12 the safety area is small and cannot be used to detect if a pedestrian has passed through the door. A new safety sensor is under development with the ability to scan a wider safety area. This sensor is utilized. However, let us first present and give more details about the old safety sensor and then the new safety sensor to get a greater understanding.

Old Safety Sensor. The safety sensors used on the current doors can be seen in Figure 2.13 and has the safety area as shown in Figure 2.12. The safety sensors use optical triangulation to detect pedestrians in the safety zone. Therefore, it is always mounted near the top of the swinging door frame, as can be seen in the figures. The optical triangulation sensors send out an 880 nm LED light to the floor. The light bounces against the floor and is then reflected to the sensor. The sensor has two photodiodes, one adjacent to the LED light and one further away. The floor will reflect the light straight to the sensor, with almost a 90° angle to the floor. If a pedestrian is in the area, the light will get reflected with a different angle and be received by the photodiode that is further away from the light source. If a pedestrian is detected an impulse is sent to the control unit. In Figure 2.14 the theory behind the optical triangulation sensor is shown. A pedestrian is detected through an angle difference. In the figure, point A can be viewed as the floor and point B the pedestrian. If the distance between the points is far enough from each other, the sensor will signal that someone is there.

New Safety Sensor. The new Safety sensor that is used in this thesis is called TOFswing and can be seen to the left in Figure 2.15. The sensor is a camera sensor under development and yet not on the market. The sensor is developed together with CEDES in Switzerland. As can be seen, in Figure 2.15a the sensor is divided into

Figure 2.13: The old safety sensor is the long black sensor attached to the top of the door leaf. The grey box mounted on the wall is the operator. The little black sensor attached to the left of the operator is the activation sensor.

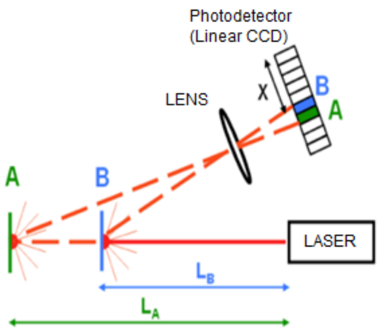
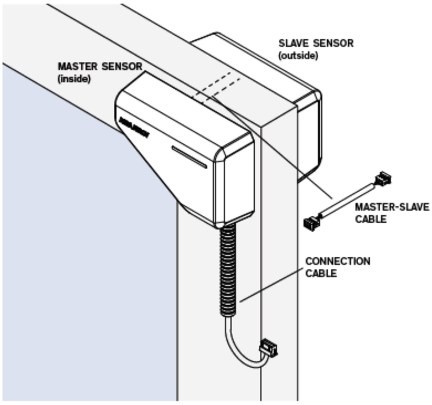
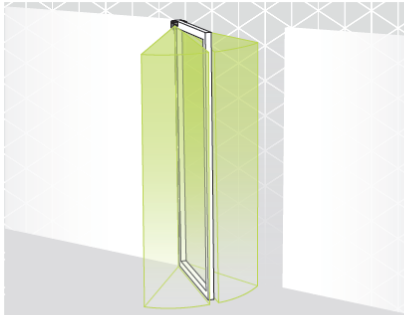


Figure 2.14: The figure shows the theory behind the optical triangulation. When there is a pedestrian in the doorway the reflection angle is changed. The triangulation method is used in the old safety sensor[Julight, n.d.] .



(a) The new sensor is shown. As can be seen, the sensor is divided up to two parts placed on each side of the door.



(b) A figure showing the safety area of the new sensor. The new sensor can detect anything in the doorway not only things close to the door shaft like the old sensor [ASSA ABLOY Entrance Systems AB, n.d.] .

Figure 2.15: The figures show the TOFswing sensor that is used in this thesis.

two sensors, one placed on the outside of the door, the slave sensor, and one on the inside, the master sensors. The new safety sensor has a larger safety range. The range is shown to the right, Figure 2.15b. The sensor area covers the whole door opening which is a great improvement. Another improvement is that the sensor also scans the area close to the hinges which hold the door from closing when anything, like for example fingers, is close to the hinges.

The sensor uses an IR laser together with the Time of flight (TOF) principle to measure the distance between the sensor and object. In Figure 2.16 the TOF principle is shown. The distance to the object is calculated as the time difference between the emission IR light and its return to the sensor. The IR laser from the sensor creates a grid with pixels in the safety zone. When the distance to four or more pixels is reduced, the sensor will assume that someone is in the safety area and signal this to the door. By using an IR laser, the disturbances from the environment are reduced.

The sensor has two outputs. One for the slave sensor and one for the master sensor. When an object is detected on either side of the doors safety zone the signal changes from "clear" to "object detected" for that output.

The Sensor Market. Today the market for safety sensors is extensive with a large variety of sensors. Most of these sensors are based on either optical triangulation or time of flight. No sensors that are on the market have a full view of the entire doorway, but many sensor companies are working to create sensors with a broader perspective. Note that the TOFswing is not on the market yet. The reason why there are no sensors that have a full view of the doorway is because of the difficulties of

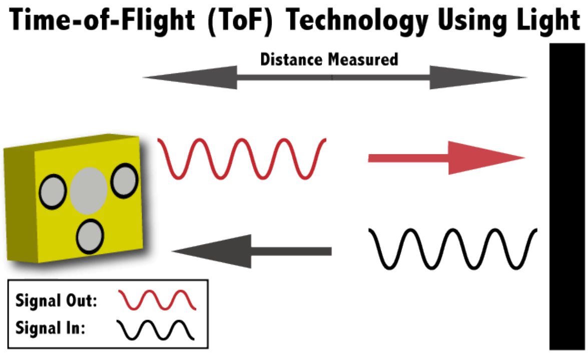


Figure 2.16: The theory behind the time of flight sensor is shown. The distance to the object is measured as the time difference between the emission light and its returning. The Time of flight is used in the new safety sensor[Generation Robots, n.d.] .

detection when the object is a long distance away, both in x and y-direction, from the sensor.

2.7 Simulation Model

In the next section, some scenarios where the opening cycle of the door is changed are presented. To be able to determine how good the different concepts are more accurate calculations of the air infiltration are made. To do this, a model is used that simulates a door opening and closing. The simulation model was developed during my summer job at the company.

The model used in this simulation is a mass-spring system with two masses and one spring. In Figure 2.17 the scheme of the model is shown.

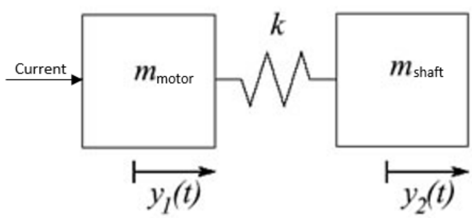


Figure 2.17: A model of a mass spring systems which is used to simulate the behavior of a swing door system. The input to the system is the current and the output is speed and position.

In the figure, one mass represents the motor, and one represents the door shaft. When a current is sent into the system the engine will move forward pushing the shaft also to move forward. The spring between the shaft and the motor will control how much the masses can move in comparison to each other. The current will create a torque on the engine and the door shaft. The torques can be calculated as the position difference between the masses times the elasticity spring constant. The equations for the torques are shown in (2.9),

$$\tau_{motor}(t) = \tau_{current}(t) + (y_1(t) - y_2(t)) \cdot k, \tag{2.8}$$

$$\tau_{shaft}(t) = (y_2(t) - y_1(t)) \cdot k, \tag{2.9}$$

where $\tau_{current}$ is the torque on the motor from the current sent into the system, t is the sample time in seconds, and k is the elasticity spring constant of the system. Additionally, the torques from the gearbox and the spring in the operator are taken into account. The velocity of the door, v_{door} can then be calculated as

$$v_{door}(t) = v_{door}(t-1) + \frac{\tau_{motor} \cdot t}{GR \cdot GR \cdot I_{motor}}, \tag{2.10}$$

where GR is the gear ratio and I_{motor} is the inertia of the motor. The position of the door, x_{door}, could approximately be calculated as the velocity multiplied with the sample time $x_{door} = v_{door}(t) \cdot t$. To get the position of the door the geometry of the arm system, how the door angle varies with the angle of the arm system, is calculated using simple geometry.

The simulation model has been integrated into the software testing of the door and the constants have been adapted to the current door. The user could send open and close commands to the model and the output will be the velocity and position of the door. The model will here be used to extract the angle of the door to be able to estimate the air infiltration. By using the simulation model, it is easier to control the door movement and to test more concept.

2.8 Laws And Regulations

In this chapter, the relevant laws and regulations for automatic swing doors will be presented to get a better understanding of what is possible to be done to minimize the air infiltration.

EU Regulations

In 2010 the EU stated the Energy Performance of Building Directive which states that the large energy consumption in buildings must be reduced. The improvement of the energy performance of buildings will save both money and energy. The directive applies to all buildings in countries within the EU. The regulation has resulted in that the energy consumption for new buildings is only half as much as for old buildings, i.e., that are over 40 years old. In 2016 the Energy Performance of Building Directive got updated to promote and accelerate building renovations. At the same time, the EU started to track the energy performance of buildings in Europe. Last year the EU once again amended the Directive aiming at accelerating the renovation of existing building even further. The vision off the Directive is that the building stock by 2050 should be decarbonized. Other requirements are that all new buildings must be nearly zero-energy buildings by 31 December 2020 [European Commission, 2019].

In April 2013 the new EU regulation for automatic doors, EN 16005:2012, came into force. The new regulation covers the safety of pedestrians and applies to all member countries. In the regulations, protection and avoidance of protection points for swing doors are stated. The main point is to regulate the force generated by the door not to cause any great harm if a collision with a pedestrian happens. If the automatic door is in Low Energy Mode, the kinetic energy and force are limited, and no sensors are needed. If a faster opening and closing is desired the door must be equipped with sensors that will ensure the safety for pedestrians both in the opening and closing direction. In areas with elderly, disabled or young people additional protective devices and monitors shall be installed to avoid any contact between the door and the user [Swedish Standards Institute, 2012].

Other Standards

ANSI A.156.10. Another standard for power operated pedestrian doors is ANSI A.156.10 which was issued by the American National Standards. In the standards sensor requirements as well as the minimum time for the opening, closing and hold open are specified. In the sensor section, the activation zones, as well as the safety zones for the swing doors, are specified. The standard also demands that the automatic door never should be in contact with a pedestrian. Further on the minimum opening time, from close to 80 degrees, is 1.5 seconds. After the sensor has lost detection of the pedestrian, i.e., the pedestrian has gone through the door, the door should hold open for at least 1.5 seconds before starting to close. The minimum closing time to latch check T is also regulated depending on width D and weight W of the door as $T = D\sqrt{W}/188$ [Builders Hardware Manufacturers Association, Inc., 2015].

ASHRAE 90.1 - Energy Standards for Buildings. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) develops standards with a focus on buildings systems, energy efficiency, and sustainability. In the Energy Standards for Buildings (ASHRAE 90.1) the air leakage for doors and fenestration is specified. For example, the maximum air leakage from doors and fenestration should not exceed 1.0 cfm/ft^2 tested at pressure 1.57 psf. Further on all doors and fenestration should be labeled and date certificated with the air leakage. At last inspections and verification should be carried out. In 90.1 requirements for when a building should have a vestibule and how it should be designed is also stated [American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2016].

ADA Accessibility Guidelines. The ADA Accessibility Guidelines contains technical requirements for accessibility. In the guidelines, Paragraph 4.13.5, the minimum clear doorway width is 815 mm for all types of door, measured when the door is opened at 90 degrees. In Paragraph 4.13.10 the closing speed is regulated to a minimum of 3 seconds when the door goes from 70 degrees to 75 mm from the latch. The closing speed regulations give the user more time to get through the doorway [Board, n.d.]

Swedish Construction Laws. In Sweden, the National Board of Housing, Building, and Planning (Boverket) have set up some construction laws. In Section 9 about energy management, it is stated that buildings should be designed in such a way that the energy consumption is limited. Further, the air leakage from a building should not exceed 0.6 l/sm^2 when the pressure is $+1$ Pa [Boverket, 2008].

3

Scenario Analysis

3.1 Assumptions

To be able to finish the master thesis in time some assumptions were made:

- The analysis is only going to be made on a single leaf swing door.
- The door is placed in Sweden, and the outdoor temperature is around 8° C which is the average outdoor temperature in Lund according to yr.no.
- Indoor temperature is set to 20°C.
- The only infiltration is through the door opening, air leakage through materials and gaps is assumed to be zero.
- The primary focus is on the safety sensor.
- The only advantage the intelligent door can result in is energy saving. No analysis of the other good reasons like minimize air pollution or better indoor environment will be done.
- No vestibule or air curtain in the entrance.
- The latch check, Section d, is assumed to be zero.
- Electrical energy needed for reheating is considered to be the same amount as thermal energy losses

3.2 Scenarios

At the beginning of this thesis many different scenarios were considered. The scenarios with good user experience, accuracy, and large energy savings were kept and will be presented below. The entire list and first evaluation of the scenarios can be found in Appendix A. The enumerations used for the scenarios in the appendix will be written in parenthesis.

The TOFswing sensor is not yet launched but many sensor companies are working towards creating more advanced sensors therefore the scenarios are going to be divided into three parts. In the first part scenarios that can be applied to the TOFswing sensor today are presented. In the second part scenarios that can be implemented in a couple of years from now when the sensors have become more advanced are analyzed. In the last part, future scenarios are presented.

Implementable Today

In this section, the typical door behavior are first presented followed by some scenarios applicable with the old safety sensor and then some scenarios using the new TOFswing sensor. In Scenario 1, it is assumed that the door opens by manually pressing an activation button, but the rest of the scenarios assume that activation sensors are used to open the door.

Scenario 0 - The door today. This scenario is a representation off how the door cycle is today. When the user presses the activation button or walks into the activation area an opening impulse is sent to the control unit off the door. The door opens and when in the open position the door holds open as long as the hold open time is set to. When the hold open time has passed the door starts closing.

Scenario 1 (A). In scenario one, the only sensor that is needed is the old safety sensor. The activation button is developed to be split up into two parts, one with a short hold open time and one with a longer hold open time. An illustration of the activation button can be seen in Figure 3.1. If a pedestrian is in need for a longer time to pass the doorway, they should press on the top part, but if the pedestrian can pass the door quickly, they should press the bottom part of the activation button which will set a short hold open time.

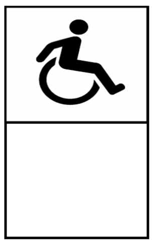


Figure 3.1: The activation button described in Scenario A. Depending on which part you press the hold open time will be long or short.

Scenario 2 (E). As seen in Figure 2.4 the door usage varies with the hour of the day and type of commercial building. This could be used to save energy. When the clock is off-peak, there should be a larger focus on energy savings since there are not as many people passing through. An idea could be to cut the hold open time to half when it is an off-peak hour, and when it is peak hour the hold open time is as normal. Since there still is a safety sensor on the door, it will prevent the door to close/open on a pedestrian.

Scenario 3 (F). In this scenario, the new TOFSwing sensor will be used. The door will open normally, and the default hold open time is set to the usual 15 seconds. When the TOFSwing sensors senses that someone is in the area the hold open time is changed to 1.5 seconds. The new hold open time will start when the TOFSwing sensor signals that the area is clear. This scenario follows all the regulations that we have today.

Scenario 4 (G). The door opens normally. As soon as the door is fully opened and the TOFswing sensor cannot detect anything in the area, it is assumed that the pedestrian has passed the door and an impulse is directly sent to close the door. A graph for this scenario is shown in Figure A.3. The difference from Scenario 3 is that this scenario does not have any hold open time, which is against today's regulations. But what is the point of holding the door fully open for 1.5 seconds when no one is in the doorway and no one wants to pass?

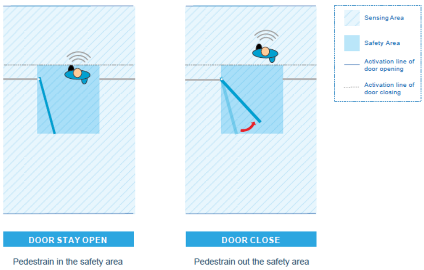


Figure 3.2: As soon as the pedestrian leaves the safety area the door should close [Jingying Ma, 2018].

Scenario 5 (L). In this scenario, the door will first open to 70 degrees. The narrower width of the doorway will in the majority of times work well but can cause some problems for some pedestrians. This is handled using the TOFSwing. If the TOFSwing sensor signals "object detected" for longer than 2 seconds, then either someone is having trouble passing the door or that many people want to pass through. In both cases, the door will open to 90 degrees. If no one is having trouble through the door, the door will start closing as soon as the sensor area is empty. The hold open time for this scenario is set to zero, i.e., the door will only stay open if someone is in the sensor area. This scenario can be seen in Figure 3.3.

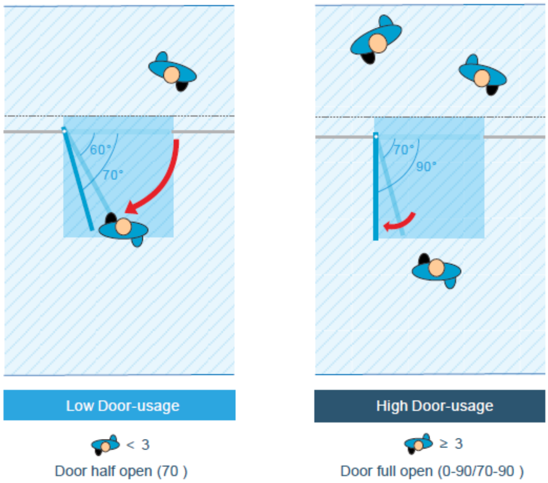


Figure 3.3: The door changes the opening angle depending on how many pedestrians that are in the doorway [Jingying Ma, 2018].

Implementable in 2–3 years

In a couple of years, the market will probably have more advanced sensors which could be used to control the door even further. Things that can be improved in the current TOFswing sensor is to have a wider safety area and add more outputs to be able to make the door smarter. One output that will be good to have is the number of people that are in the doorway and where in the doorway they are. Since the TOFswing sensor uses the time of flight method with pixels to detect pedestrians, these improvements should be easy to implement. Simple algorithms can then be implemented to calculate where and how many pedestrians there is in the doorway. Another adjustment can be to split the safety zone into two parts. The area nearest the door shaft should be called safety zone, but the area outside could be renamed to the detection zone, see Figure A.5. By separating the zones, one could use the safety zone to ensure safety and the detection zone to minimize the air infiltration.

Scenario 6 (N). With a sensor that can sense how many pedestrians that are in the doorway the door angle can be modified. As described in the previous work, Chapter 1, the optimal door angle for two people, found in last year's master thesis, was 70° and for more than two is the normal fully open state, 90°. Using this information, the opening could be optimized. The scenario is shown in Figure 3.3. When the sensor detects that one or two persons wants to pass through the door, the door only opens to 70° but if a third pedestrian is detected the door opens to 90° . The difference between this scenario and Scenario 5 is that the opening angle is directly set to the right angle, considering the density. For example, if 3 or more pedestrians are

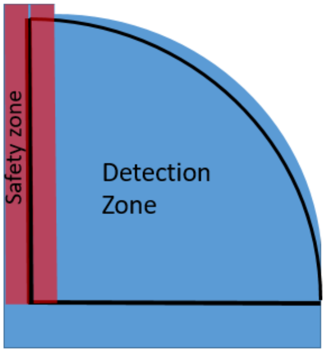


Figure 3.4: The safety area is shown in red. The blue area is the detection zone.

coming towards the door, this scenario will open the door maximally, but Scenario 5 will first open to 70 degrees and then, after 2 seconds, continue opening.

Scenario 7 (P). With a larger sensor area it will be easier to keep track of the users. This could be used to switch the door cycle from opening to closing as soon as the users has passed the door. In this scenario, the door will get an opening impulse and open normally but as soon as the sensor senses that the pedestrian has entered and exited the safety area the door will abrupt the opening and start a closing. This scenario will prevent the door from continue opening when the pedestrian has already passed.

Scenario 8 (Q). The detection zone can be split up into two zones. The different zones can later be used to easier and more accurately detect where the pedestrian is. In Figure 3.5 the zones are shown. When a pedestrian is coming from the pull side and is in Zone 1, the door could start to close. This scenario can feel scary for some users but by using two zones it could be made accurate and comfortable for pedestrians since one could detect when the door is coming closer to the pedestrian, Zone 2 is activated, and therefore stop earlier than when the user is in the safety zone.

Scenario 9 (R). With wider sensor areas the accuracy will decrease. Today is it hard for one sensor to cover both the doorway and the shaft. One way to solve this is to use more than one sensor. In Figure 3.6 this scenario is shown. The red area is the safety zone from an old safety sensor along the shaft, and the blue area is the detection area from two sensors placed in the top corner of the door. By using separate sensors to watch over different parts of the doorway the placement of the sensors could be changed for optimal scanning of each area.

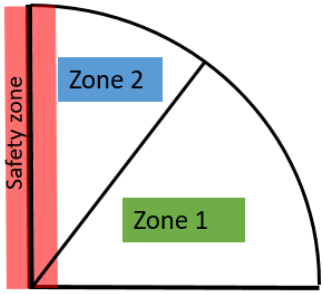


Figure 3.5: The sensor area is shown. The safety zone is the red area near the door leaf. The rest of the detection area is split into two zones, Zone 1 and Zone 2.

Figure 3.6: Two sensors are scanning the whole doorway. One sensor creates the safety zone, the red area near the door leaf. The other sensor is used to optimize the opening by over viewing the doorway, blue area [BEA, n.d.] .

Implementable In More Than 3 Years From Now

With smarter sensors, the communication between sensor and door system will be developed further. Today the sensor only sends "object detected" or "clear" impulses, but with a further developed CAN bus communication setup between sensor and door operator more information could be extracted, and the air infiltration could be minimized even further.

Scenario 10 (T). The increased sensor area can also be used to detect the density and direction of the pedestrians but also rule out wrong signals from stones, insects, smaller animals, etc. Further by calculating the direction of the pedestrians the door could only open when pedestrians are walking with a certain angel towards the door, this is shown in Figure 3.7. The angle of the door in the open state is once again set by the number of pedestrians in the doorway.

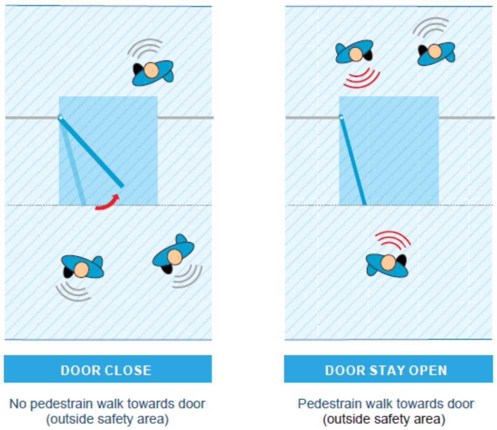


Figure 3.7: Scenario 10 is shown. As can be seen, when no pedestrians are walking towards the door the door starts to close. But if a pedestrian is walking towards the door the door stands open or opens [Jingying Ma, 2018].

Scenario 11 (U). In the previous scenarios, the sensor is assumed to be quite accurate, but with a wider sensor area, the accuracy is decreased. One way to increase accuracy is to divide the sensor area into more zones, maybe three or four zones. It is probably easier for the sensor to detect in which zone the pedestrian is rather than exactly where it is. The accuracy and safety could hence be increased.

Scenario Optimal Future In an optimal opening, the air infiltration needs to be minimized and negligible. To do that the door opening needs to prevent air from flowing freely and directly into a building. One such example is to use some passage like a revolving door or to create some pocket where the pedestrian could enter and then the pocket rotates. This is illustrated in Figure 3.8 where the grey area shows the rotating pocket and the black lines are walls. The pocket leaves little space and time for the air to flow in.

One often says that the optimal opening is the manual opening because when manually opening a door the user does not open wider than needed to pass and the door start closing when the user lets go of the handle to walk through the door. The manual opening can be described almost like a mixture of Scenario 6 and 8 where the door angle is reduced and the door starts closing sooner. This is probably one of the best ways to control a swing door.

To reduce the air infiltration even further one can view the airflow patterns and use this to create an optimal vestibule where the doors are placed to avoid leakage. On the front page and in the air infiltration section a caption of the air infiltration

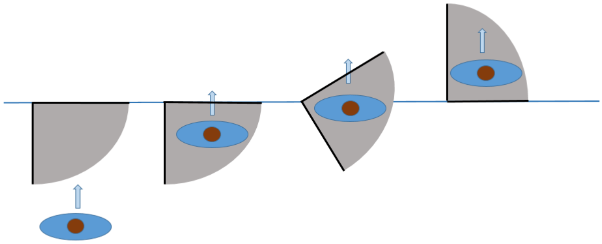


Figure 3.8: A rotating pocket is shown. When a user comes inside the pocket, it rotates. In both the start and end position the air leakage is negligible.

through swing doors is shown, Figure 2.7. Using this information one could create a vestibule like Figure 3.9. A combination off a proper vestibule, intelligent sensors and swing doors that do not stay in the open position unnecessarily long will make the airflow from the outdoor to the indoor at a minimum. Vestibules are often used in entrances, but the placement of the doors are many times too close resulting in that both doors will stay open at the same time and let air flow freely.

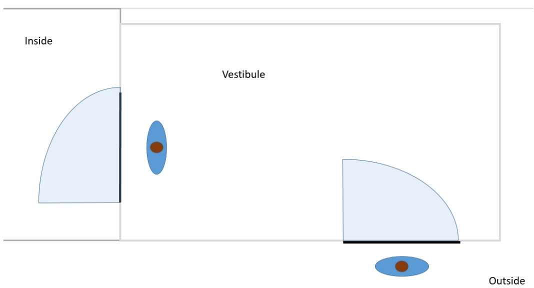


Figure 3.9: By knowing about the air flow patterns one could create a vestibule with doors placed in such a way that the air flow is decreased

One could also increase the opening and closing speed of the door and even start to close sooner.

The above scenarios will all minimize the air leakage and therefore save energy. However, how comfortable and safe will it be for the users? This will be discussed in Section 6.

3.3 Evaluation Of Scenarios

In this evaluation, the scenarios are going to be analyzed further. The cost of buying, creating and selling the concepts will now be considered. The average air infiltration is going to be calculated and later used to be compared with the cost to implement the situation. In the next subsections, the air infiltration calculations are explained.

Air infiltration

The simulation model, described in Section 2.7, is used to extract the door angles when the scenarios are implemented. The door angles are then used to calculate the discharge coefficient C_D with Equation (2.2) and Equation (2.3). The air leakage is calculated using Equation (2.1) where the above calculated discharge coefficient is used. In Table 3.1 the coefficients used in Equation (2.1) that are assumed constant and their values are shown.

The result is the volumetric flow rate, Q_{inf}, for each scenario. The air leakage and costs for different hold open times (HOT) is shown in Table 3.2. In the cost for a day the door is assumed to be opened and closed 100 times every hour for 10 hours. In the calculations for the yearly cost, it is assumed that the door is used 365 days a year.

That a door is used 1000 times a day is maybe quite much for some buildings but for many office buildings or schools the average door use per day is around this value.

Table 3.1: The constant coefficients and their values used in Equation (2.1).

Coefficient	value
ρ_a	1.204 kg/m^3
ΔP	1 Pa
A	1 m^2
n	0.65
C_p	1000 $J/(kg \cdot ^\circ C)$
T_{in}	$20^\circ C$
T_{out}	$8^\circ C$

Note once again that the driving force of air infiltration through swing doors is the pressure difference. If the building has only one or two floors and the inside height is 6 meters the pressure difference between outside and inside only depending on the temperature can be calculated as Equation (2.6). The pressure difference then becomes 3 Pa which result in that the Q_{inf} become twice as big, see Equation (2.1). If one takes the wind pressure also into account, the pressure difference can become even more significant. If the pressure difference is $\Delta P = 8$ Pa the cost will grow four times as big.

Table 3.2: The table shows the air leakage and cost for reheating, in SEK, for different hold open times.

HOT (s)	Air Leakage (kW)	Cost/opening (SEK)	Cost/day (SEK)	Cost/year (SEK)
15s	1.68	0.35	347	126 530
10s	1.14	0.21	213	77 868
5s	0.58	0.11	107	38 935
1.5s	0.18	0.03	35	12 653
1s	0.13	0.024	24	8 760
0s	0.09	0.019	19	6 813

Calculations for scenarios

In this section, the cost of the air leakage but also for producing the scenarios will be investigated further using the results above. The assumptions made in this section is that almost 50% of the users are disabled and therefore needs more time. For healthy pedestrians, the time to pass the door is assumed to be 1 second. The large percentage of disabled users is to get a value on how much one can minimum save.

The velocity of the door is unchanged, the opening time is set to be 3 seconds and closing time to 4 seconds, which is the standard case. The hold open time is set to 15 seconds for the typical case and the case the scenarios will be compared to scenario 0.

The thermal losses due to the volumetric flow rate through the door are assumed to be equal to the energy needed to retrieve the same indoor climate again. The energy price is believed to be 2 SEK per kilowatt hour.

(Today) Scenario 0. This scenario is the standard door opening. It has high user experience and accuracy but no consideration off the energy savings. Each time the door opens a large amount of cold air will flow in. If we assume that the hold open time is 15 seconds the cost for reheating the air from one opening is 0.35 SEK. The yearly costs will become 126530 SEK.

Going forward he savings yearly for implementing the new scenarios will be compared to this scenario.

Scenario 1 (A). This scenario is easy to understand and use. The safety of the pedestrian is not affected since a safety sensor is attached to the door. The cost to implement the first scenario is small, probably around 100–300 SEK for the company. No new or additional sensors are needed. The only cost is to design and develop the new activation button. If half the pedestrians press for a short hold open time, 1.5 seconds and the other half press for a longer hold open time, 15 seconds, the energy saved over a year is approximately $57,000$ SEK. The energy consumption for each part of the button is shown in Figure 3.10. The average energy consumption is reduced to half the size.

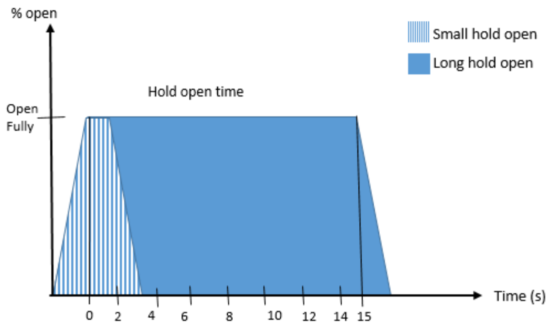


Figure 3.10: The door opening cycles for Scenario 1 is shown. The dark blue area is for the long hold open time, and the lined area is the short hold open time. The average HOT for this scenario is just above 8 seconds which result in that the one can cut the cost in almost half.

Scenario 2 (E). For buildings with many off-peak hours, this scenario will save a great amount of energy. The scenario is easy to implement by either attaching a digital clock to the control unit or a counter that signals, when it is peak hour and many people want to pass through the door. The cost is around 100–500 SEK and will only be related to easy software changes. When it is peak hour the door will be used frequently; hence the hold open time is 15 seconds. When off-peak the door holds open for 1.5 seconds. If 75% of the time is off-peak, which it is for most office buildings, the energy saved is almost $70,000$ SEK each year. Observe that the savings will vary depending on the number of off-peak hours.

Scenario 3 (F). In this scenario, the new TOFSwing sensor is going to be used. This will probably increase the cost with 400–800 SEK in comparison with the old safety sensor. But the accuracy and safety for the users will also be increased since the safety area are larger. The energy losses in this scenario are a little hard to calculate since it takes different times for the users to reach the sensor area. If one assumes that it takes 3.5 seconds for the disabled, making the hold open time 5 seconds, and almost 0 seconds for the healthy users, hold open time 1.5 seconds then the average cost for the air leakage each day is 75 SEK and yearly $27,558$ SEK. If one compares this scenario to the cost today, hold open time is 15 seconds, the savings is almost $100,000$ SEK.

Scenario 4 (G). This scenario also has an increased cost due to the TOFSwing sensor however, using the new sensor, it will be possible to close the door sooner. The average time for a healthy person to pass the door is 1 second, hold open time is 1 second. For a sick or disabled person, the time to reach and pass a door is

5 seconds. By closing the door as soon as the pedestrian has walked through the energy consumed is 25,760 SEK. The energy saved each year is estimated to over 100,700 SEK. This can be seen in Figure 3.11. By implementing this scenario, the energy consumed is almost a 5:th of the energy consumed for when the hold open time is 15 seconds since the average hold open time is 3 seconds.

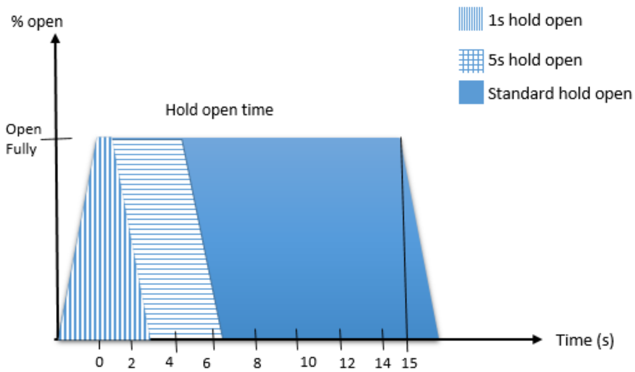


Figure 3.11: The door opening cycle for Scenario 4 is showed. The dark blue area is the standard hold open time, the area with horizontal lines are the cycle for healthy pedestrian and the vertical area is the added hold open time for disabled persons.

Scenario 5 (L). In this scenario, the standard open angle of the door will be set to 70° which will narrow the area of the door, which can decrease the user experience. However, the energy savings will increase since in some cases the door shaft will prevent wind from some directions. When doing the calculations, the area of the doorway will be reduced, but the wind direction is not taken into account and therefore not either that the shaft will prevent some air from leaking in. Once again it is assumed that half the people using the door is in need for the full door width and 5 seconds to pass. With these assumptions, this scenario will result in that the energy cost yearly will be just below 25,000 SEK each year. The energy saved is over 101,800 SEK. The cost when implementing this scenario will increase since some larger software changes need to be done, maybe around 500–1000 SEK.

Implementable in* 2–3 *years. Going further and looking at the scenarios that could be implemented 2–3 years from now more assumptions are made to be able to do the calculations. The assumptions made will be introduced in each scenario.

Scenario 6 (N). In Scenario 6 it is assumed that about 70% of the healthy users come towards the door one and one or two and two making the door only open to 70°. When three or more pedestrians are walking through the door, the opening angle is set to 90° and the time for them to pass through is approximately 5 seconds. The better sensor will increase the user experience when information about the density of pedestrians makes it easier to set the correct opening angle from the beginning. The energy consumed yearly is 30,600 SEK which is 96,000 SEK less than when the hold open time is 15 seconds. The door cycle for this concept is shown in Figure 3.12.

The energy saved by reducing the angle by 20° is over 1900 SEK each year. In the calculations, it is assumed that half the users are disabled and hence need a more wide doorway and take a long time passing through. The cost of this concept is probably more significant than for the other scenarios since a more advanced sensor, and software is needed, maybe around 800–1500 SEK.

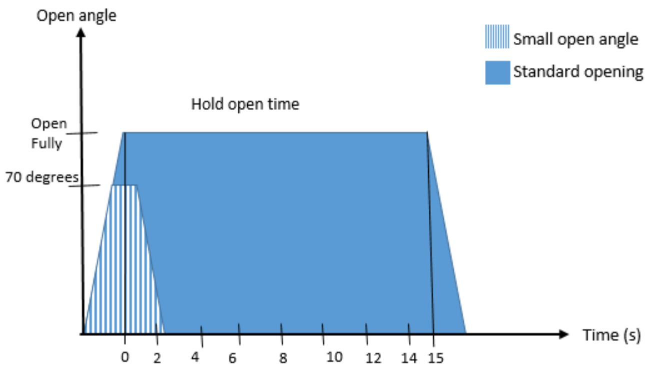


Figure 3.12: The door opening cycle for Scenario 6 is showed. The dark blue area is the standard hold open time, the area with vertical lines are the reduced door angle used when less than 3 users want to pass the door.

Scenario 7 (P). This scenario is hard to calculate since the open angle and therefore also the area of the doorway will vary depending on the users. Each time a pedestrian has passed the door the door will start closing. If it is assumed that the door when a healthy people passes has not to reach fully open, HOT is 0 seconds and for people in need of more time and space to pass the door opens to 90° and HOT is 5 seconds. The energy savings each year, in that case, will accumulate to over 102,000 SEK. Note that the saved energy will vary depending on where the activation button and sensor is placed and how fast the pedestrians walk towards the door. The cost of this scenario will be 1500–2500 SEK since larger software changes are needed.

In Figure 3.13 the opening cycles with some possible switching points between opening and closing are shown, red circles. The openings that are used in the calculations are lined, horizontal for when the hold open time is 5 seconds and vertical for no hold open time.

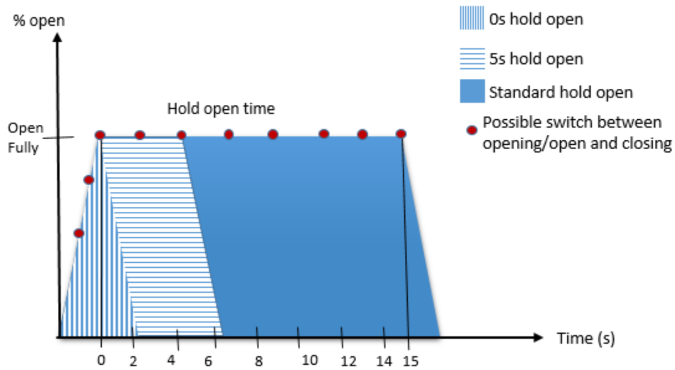


Figure 3.13: The door opening cycle for Scenario 7 is showed. The dark blue area is the standard hold open time, the area with horizontal lines are the cycle for healthy pedestrian and the vertical area is the added hold open time for disabled persons.

Scenario 8 (Q). By dividing the safety zone into two zones, the door could start to close earlier when the pedestrians are coming from the pull side. By keeping a small safety area one could ensure that the door shaft does not touch the user. In the beginning, when implementing this scenario it can feel a little scary for old and sick people to pass but the safety can still be considered good. The sensor has a larger view hence the safety area could be made wider which can increase the safety and the user experience further. The energy costs could also be reduced since the door sometimes can start to close sooner. If the pedestrians come from the pull side half the time and they enter Zone 2 when the door only has reached 70°. For the push side, the hold open time is assumed to be 0 second. For the case for sick users, the hold open time is assumed to be 5 seconds in both directions. The energy saved is over 102,400 SEK. The cost for this scenario is smaller, 1000–2500 SEK.

Scenario 9 (R). When additional sensors are added to the door, the accuracy will increase but also the cost for the customer. The cost for the company will increase and maybe become around 2000–2500 SEK. The energy saved by adding a sensor will be the same as for the typical case just that the accuracy and the safety for pedestrians are increased. If it is assumed that the additional sensor will keep track of where the pedestrian is and therefore be able to close the door after the pedestrian the energy saved will be 102,000 SEK, as in Scenario 7.

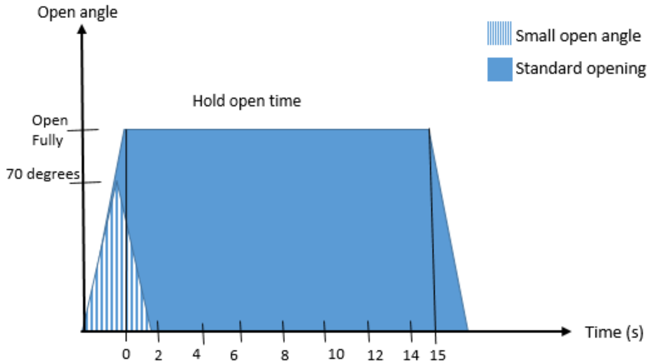


Figure 3.14: An example of the door opening cycle for Scenario 8 is showed. The dark blue area is the standard hold open time, the area with vertical lines are the cycle for healthy pedestrians.

Improvement in more than* 3 *years. In more than 3 years from now the sensors will have developed further and will be more advanced which will increase the cost of the sensors for the user but save more energy.

Scenario 10 (T). Today many door openings are unnecessary since none of the sensors sold with a swing door can detect in which direction the pedestrian is going. Therefore, when anyone passes the door, it will open even if no one wants to walk through which result in unnecessarily air infiltration. This scenario could be applied to all the other scenarios. The amount of additional openings varies depending on the building and placement of the door. If a swing door with an activation sensor is placed in a corridor with many people walking by then the amount of useless opening will increase. If it is assumed that almost 10% of openings are unnecessarily the energy consumption will decrease. For example, if the more advanced sensor is used in Scenario 6, the user could save 10% more. Yearly the advanced sensor could save over $101,000$ SEK which is $2,750$ SEK more than in Scenario 3. Observe that today there already is additional sensors that can prevent some unnecessary openings. These sensors are often sold with other door types. This concept is an argument for also using the direction sensing sensors on swing doors.

Scenario 11 (U). Scenario 11 will probably save a little more energy than Scenario 9, but the accuracy and safety of the pedestrians will be increased. The cost of implementing this scenario will be a little more than for Scenario 9 since the sensor needed needs to be more advanced.

Summary Of Scenarios

In this section, a summary of the evaluation is done. In Table 3.3, the final results of the yearly savings the customers can make together with the cost for the company to buy and develop the different concepts are shown. Be aware that the cost for implementation is a one time cost for the company, but the savings is yearly for the consumer.

Table 3.3: The table shows the cost for the company to implement the concept and savings the customer can make each year, in SEK, for each scenario.

Scenarios	Cost for Assa Abloy (SEK)	Customer saves yearly (SEK)
0	0	0
1	100-500	56 939
2	100-500	69 592
3	400-800	98 972
4	400-800	100 770
5	500-1000	101 820
6	800-1500	95 868
7	1500-2500	102 070
8	1000-2500	102 450
9	2000-2500	102 070
10	2000-3000	101 522
11	2000-3500	103 070

To reduce the energy consumption the door needs to spend less time in the open position. As can be seen in the table above and in the previous section all the scenarios that close earlier save energy and money. However, this will result in that the user experience will get decreased. Even if all the scenarios presented are assumed to be safe it could feel uncomfortable to walk through the door. To be able to pick the best scenarios a more extensive investigation of the users experience for the different concept but also which ones that actually can be implemented need to be done.

If we consider the regulations and laws stated in Section 2.8 there are some problems with some scenarios. In all the situations stated above the opening and closing times have not decreased. Therefore the opening and closing forces have not increased, and they should fulfill the EU regulations, EN 16005. The door does not have any contact with the users in any scenario, which is according to the rule.

In ANSI A.156.10 it is stated that the door should hold open for at least 1.5 seconds after the detection of pedestrians, this regulation will not be fulfilled, but that is probably not a problem, a further discussion about that can be found in Section 6. In ADA Accessibility Guidelines the criteria for accessibility is stated. The minimum cleared doorway should be at least 815 mm when the door is open to 90° degree. When the opening angle is set to 70°, the minimum cleared doorway is 658 mm, which is too small. This can create a problem, especially for wheelchairs, and is discussed later on in the report, Section 6.

4

Field Test

To show the effect of the different scenarios a field test is made. The idea of the field study is to test the scenes and hopefully be able to show the benefits of using more advanced sensors. The study is performed on an entrance swing door at Assa Abloy Entrance Systems AB in Landskrona. The door is a side entrance door used frequently in the morning hours, between 7–9 o'clock, and in the afternoon, between 15–18 o'clock. In the experiment, the temperature in the entrance is measured to show the energy losses due to air infiltration. The door opens automatically by pressing an activation button but can also be opened manually. While doing the test the users are instructed to use the activation button. The study is made at the beginning of March when the outside temperature lays around $8°C$–$9°C$.

4.1 Setup

In Figure 4.1 the setup for the field study is shown. In the picture, one can see the position of the temperature measurement unit, blue circle, which is placed 3 meter from the door and a little bit to the right to not block the exit. In the figure, it can also be seen that there is both ventilation outsource and a radiator near the test door.

In the field test, there is two different tests on three different setups. In the first test, the door will open once every minute for about 15 minutes. This test can be used to compare the different configurations directly. In the second test, the door will open only when it is used. This test will give a greater understanding of how the temperature is on a regular day.

Sensor

During the field study, the TOFSwing sensor is used. The sensor is one of the first working prototypes. The sensor has only two outputs, "clear" or "object detected", on each side of the door. When the sensor output from the outside of the door is "object detected" the door is not allowed to continue opening. If the sensor detects an object in the doorway, inside of the door, the door is not allowed to close. When the area is clear the output will be changed to "clear".

Figure 4.1: The setup for the field study is shown. The Blue circle encircles the temperature measurement position, the yellow circle is the activation button, the red circles show the ventilation, and the radiator and the green circles encircle the two sensors. The leftmost green circle is the old safety sensor, and the rightmost is the new TOFSwing.

Door Configuration

The door that is used in the field study is a swing door with a swinger 200 operator (SW200) with a push arm. The operator uses a DC motor for opening and closing. The door will be activated using an activation button. When the button is pressed an opening signal is sent to the control unit, and the door opens. When the hold open time has elapsed, the operator will close the door automatically. The software in the operator is written in C with fixed opening angles, opening speed, closing speed and hold open times. Parameters that are changed for the field study is the open angles and the hold open time. The opening and closing speed will be fixed throughout the study to 3 seconds when opening and 4 seconds when closing.

Test 1 - Hold Open Time 15 seconds

In the first test, the door configuration that the customers of Assa Abloy Entrance Systems have will be tested. The configuration was presented in Scenario 0 which had a hold open time fixed to 15 seconds. This makes the minimum opening cycle time of the door to about 21 seconds. The test was made on Monday the 4 March and Tuesday the 5 March when the outside temperature was around $9°C$, and the wind speed was $10m/s$.

Test 2 - Hold Open Time 1.5 seconds

In the second test, the hold open time of the door will be set to 1.5 seconds, which is the minimum hold open time for the doors today. This test aims to see how much energy could be saved by just updating the sensor on the door and not the software. Since the test will be made in an office with healthy employers the time to go from the activation button and through the door is smaller than the time for the door to open to fully. The second test is hence a field test of Scenario 3 presented above. The minimum opening cycle time for this case is about 9 seconds.The test was made the 5 March and the 6 March. The temperature on the 5:th March was around $9°C$ with a wind speed of 10m/s. The temperature the 6 March was colder, $8°C$, and the wind speed was 10m/s.

Test 3 - Reduced Angle And Hold Open Time 0 seconds

In the last test Scenario 5 will be implemented. The software of the door will be changed to optimize the opening and closing. The software will control the door to first open up to 70 degrees. When the door is stable in 70 degrees, a clock will count the time the pedestrian is in the sensor area. If the user is in the area for longer than 2 seconds, the door will open up completely, to 90 degrees to make it easier to pass. If the pedestrian passes the door in under 2 seconds, the door will start closing as soon as the sensor area is empty. Since the hold open time is set to zero the door will only stand in the open position as long as someone is in the doorway. The minimum opening cycle takes approximately 7 seconds. The test started on 19 March when the outside temperature was 7 degrees and the wind speed 6m/s. The next day, the 20 March, the trial continued. The outside temperature was then 8 degrees, and the wind speed was 8m/s.

4.2 Results

Test 1 - Hold Open Time 15 seconds

In Figure 4.2 the result from the first test is shown. During about 15 minutes the door is opened once every minute. As can be seen in the figure the inside temperature in the office is above $20°C$ in the beginning but decrease as the door opens. After 15 minutes the door stays closed for a long time allowing the outside air to spread in the building. The average temperature is shown as a red line in the figure and is around $17°C$.

As can be seen the result from the first test are quite significant. Every time the door opens the temperature in the room drops due to the infiltration. The temperature drop is sometimes over $10°C$. This can also be seen in the mornings and evenings when the door was used to enter and leave the office. The result from the mornings and evenings can be seen in Appendix A.

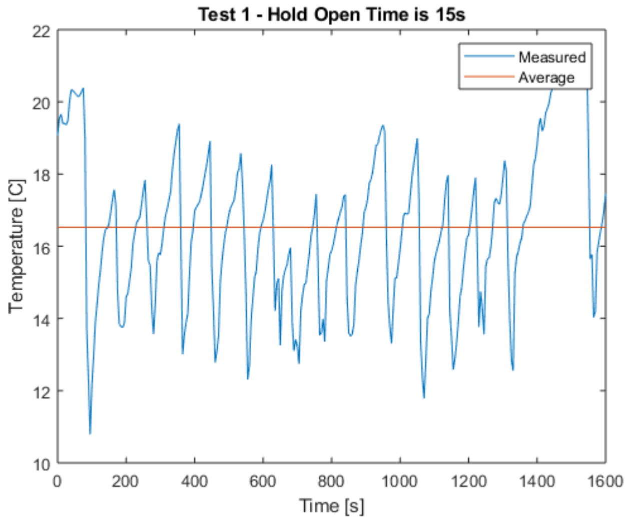


Figure 4.2: The temperature when a swing door opens once every minute and the hold open time is 15 seconds, Test 1.

Test 2 - Hold Open Time 1.5 seconds

The result from the second test is shown in Figure 4.3. Once again the door is opened once every minute for 15 minutes. Observe that the y-axis for the different tests is not the same. The red line is the average temperature during these 15 minutes.

To increase safety the TOFswing was attached to the door. The safety area had now increased to cover the whole doorway resulting in that the sensor will signal to the control unit to open as long as the sensor detects something in the area. When the area is cleared the hold open counter starts counting and holding the door open for 1.5 seconds before closing as Scenario 3.

This test satisfies all the requirements for an automatic swing door under the assumptions that the TOFswing sensor is working correctly. As can be seen in Figure 4.3 the temperature drop is not as significant as in the previous test. The largest temperature drop during the test was on less than $5°C$, almost half the decline compared to the temperature drops in Test 1. In the figure one can also see that many times the temperature is above $17°C$ even when the door opens and close. This can be compared to the first test where the average temperature during the test was lower than $17°C$ with many drops below $14°C$.

Another thing to notice is the width of the drops. In the first test the long hold open time resulted in wider temperature drops compared to the falls in Test 2. This becomes clear in the measurements taken in the mornings and evenings. In the morning measurements for the second test one can see that the temperature drops almost as low as the first test, $7°C$–$9°C$. The important difference between the tests

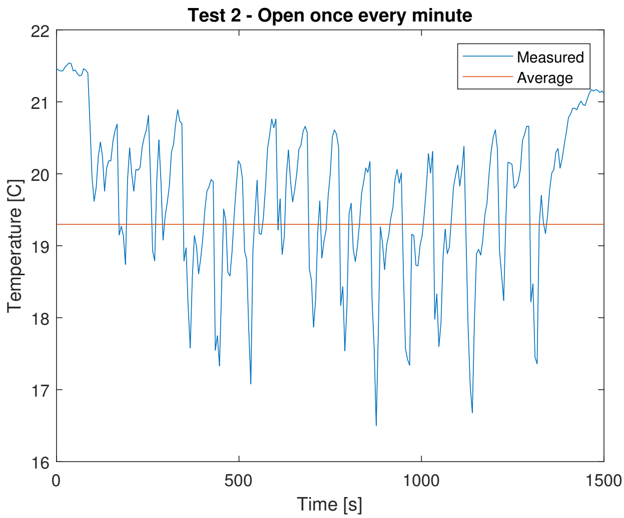


Figure 4.3: In the second test the hold open time is reduced to 1.5 seconds to imitate Scenario 3. The temperature variations when the door opens once every minute for this scenario is shown above.

is the width of the drops or the time the temperature is low. With a longer hold open time the infiltration increase which causes the increased width.

Test 3 - Reduced Angle And Hold Open Time 0 seconds

In Figure 4.4 the test results from the last test is shown. During the trial, the default door open angle is reduced to 70 degrees and the hold open time is also reduced to zero. The smaller door angle will reduce the area and direction that the wind can flow into the building. The removal of the hold open time will hopefully not affect the users that much since the door will always stay open as long as someone is in the doorway.

In Figure 4.4 the temperature measured during the test is shown. In the figure the temperature drop when the door opens goes down to $16°C$ the majority of the time. Sometimes the temperature drops down below that temperature. The average temperature during the test is approximately $19°C$. If the third test is compared with the second test one could see that the air infiltration is lower in the second test than the third. If one instead views the figure from the evening rush the temperature drop is not that large and the average temperature lays around $22°C$, almost $1°C$ lower than the normal temperature in the room. In the measurements from the evening the temperature sometimes drops only $1°C$–$2°C$ every time the door opens. By comparing the evening measurements from Test 2 and Test 3 the improvement of Test 3 can be seen more clearly.

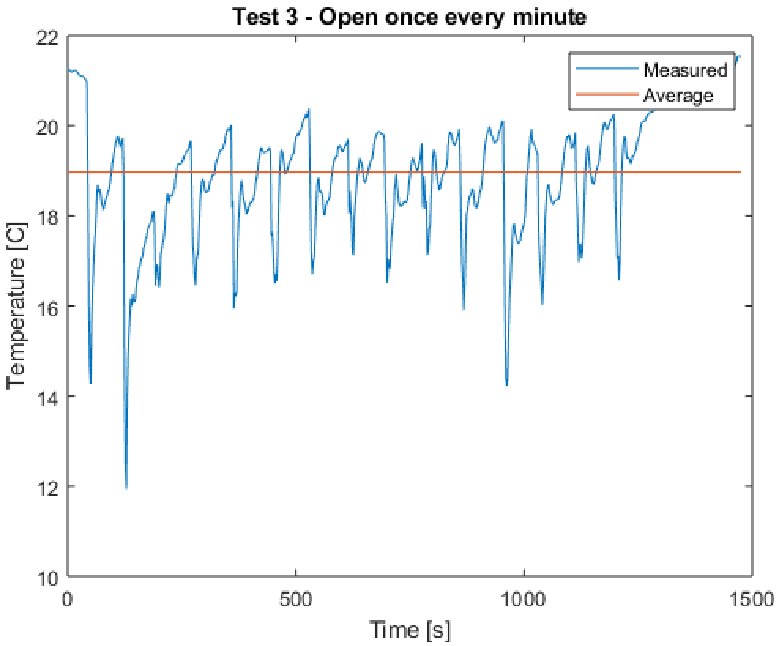


Figure 4.4: In the last test Scenario 5 was implemented which resulted in that the angle was reduced and the hold open time removed. The temperature when the door opened once every minute is shown in the figure.

Test 3 gave mixed reactions from the users. The users that used the activation button to exit the office had not noticed the decreased opening angle. When the users come in the opposite direction, from the outside, the reactions were more negative and more users noticed the change. When the users had come after each other the door had time to reach the open position and start to close before the next user had arrived at the door, which is good from an infiltration perspective but was not as comfortable for the users. It is worth to take note that the third test does not fulfill the regulations and laws we have today.

5

Survey Of How Swing Doors Are Configured

To be able to minimize the air infiltration it is essential to gain knowledge of the door setup and configurations today. To do that a survey was sent out to the service engineers and technicians on the company. Questions about how many swing doors are used in entrances, how long they stand open and how they open and close where asked. In the survey, also questions about how the door receives opening impulses and how many doors that are accompanied by safety sensors are also proposed. Lastly, the participants could give their thought of how to minimize the air infiltration. The survey was sent out to 226 people working in different countries around the world.

The participants in the survey came from all around the world, for example Australia, Canada and Denmark. The majority of the participants in the survey came from the USA, 17 participants. The next big participant count came from Sweden with 7 participants.

In Figure 5.1 the reader can see that the over 33% answered that half the swing door they encountered are entrance doors. Overall 75% of the participants answered that more than half the swing doors are entrance doors.

On the question about how the door receives opening impulses the participants had three options; activation buttons, automatic sensors or to add another option. The answered retrieved was that 30% of the doors are only accompanied with activation buttons, 50% of the doors are accompanied with activation sensors and that many times the doors are accompanied with both activation sensor and button.

In Figure 5.2, the answers about how many sensors that are accompanied by safety sensors are shown. As can be seen many doors fulfills the requirements and are accompanied by safety sensors but there is still many that does not. Almost 20% stated that less than half the swing doors have safety sensors.

Further in Figure 5.3 and Figure 5.4 one can see that the opening time and the closing time for the majority of the doors are larger than 4 seconds. This can

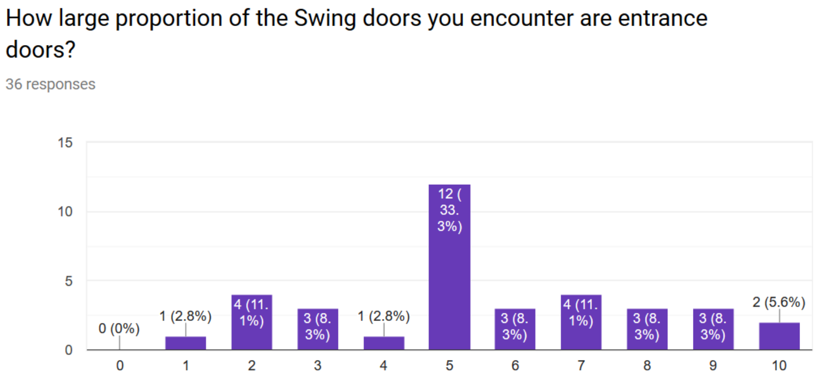


Figure 5.1: The distribution of how the participants answered the question about how many automatic swing doors that are entrance doors.

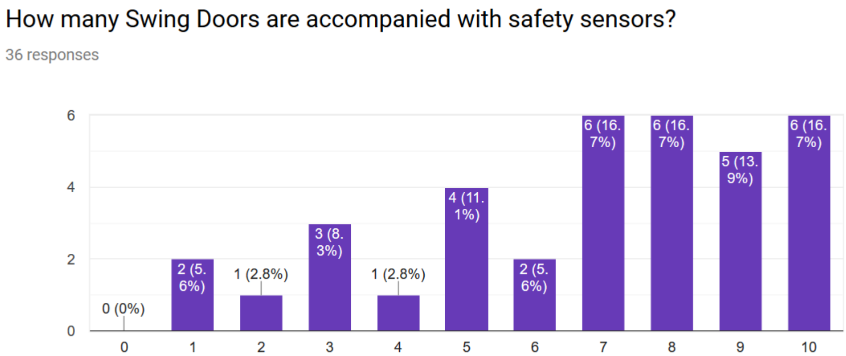


Figure 5.2: The answers on how many swing doors that have safety sensors.

especially be seen in Figure 5.3 where the majority answered that more than 80% of the doors have an opening time larger than 4 seconds.

The question about the hold opening time was divided into three questions. One part that asked for the proportion of doors that had a hold open time smaller than 8 seconds, the second part for how large portion had 8–12 seconds hold open time and the third for a hold open time larger than 12 seconds. In Figure 5.5 the answers for these three questions can be seen. The different hold open times are on the x-axis and the number of participants on the y-axis. In the figure the color of the block represents how large proportions of the swing doors that have the questioned hold open time. As can be seen the answers are quite spread out for all the hold open times. Leftmost in Figure 5.5 one can see that almost half the participants

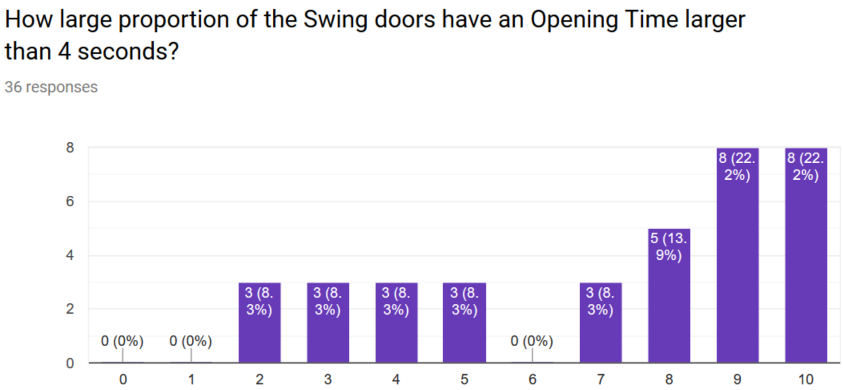


Figure 5.3: One can see that the majority of the participants answered that the hold open time was larger than 4 seconds.

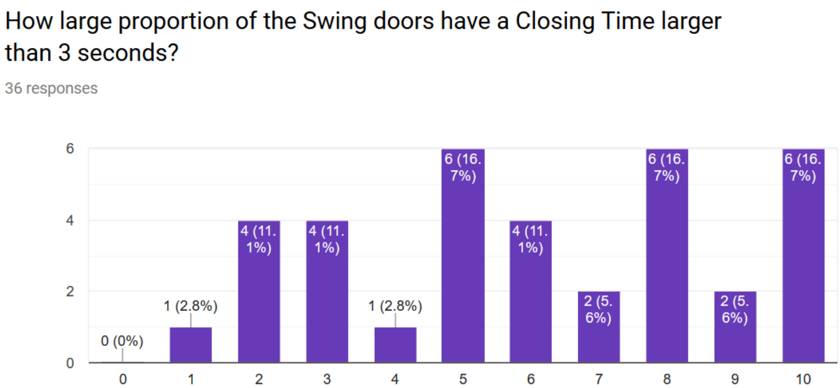


Figure 5.4: In this figure the proportion of swing door with closing time larger than 4 seconds are shown.

answered that less than 30% of the doors have a hold open time smaller than 8 seconds meaning that more than 70% of the swing doors have a hold open time larger than 8 seconds. Looking into the specific answers one could see that the large participant count from the USA answered that the hold open time for the swing doors in the majority of the cases is either smaller than 8 seconds or larger than 12 seconds. The participants from Sweden were quite different. Here the hold open time for the swing doors was either between 8–12 seconds or larger than 12 seconds. The differences between different countries will be discussed later on in the report, Chapter 6.

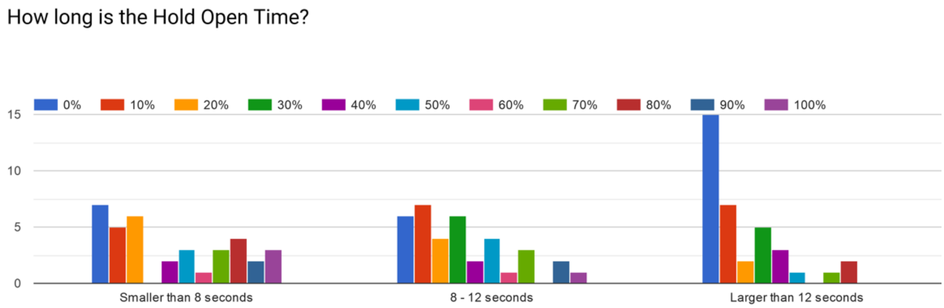


Figure 5.5: The figure shows the distribution of how the participants answered on the three questions about the hold open time.

In the last question of the survey the participants had the opportunity to give their thought off how to reduce the air infiltration. The majority who answered said that one should use air curtains or vestibules to reduce the infiltration. One service technician from Denmark also stated that there they include an air curtain when selling an entrance swing door to reduce infiltration. There were also some participants that thought that one could add more or better sensors to reduce the opening times and angles.

6

Discussion

6.1 General

Automatic swing doors are rarely used in main entrances but more often in the side and alternative entrances. The results from the survey showed that more than half the automatic swing doors are entrance doors. Through doors, but also cracks and windows, the outside air can leak into the buildings resulting in an energy loss. When investigating the energy losses in buildings one could see that the largest energy loss is due to air infiltration, see Figure 2.5, especially from the open states of doors, see Figure 2.6. The energy loss due to swing doors becomes huge since the door follows the cycle regardless of how fast or slow or how many or few pedestrians that want to pass the door. The average length of the cycle is approximately 16 seconds where the time the door stands in the open position is around 8 seconds.

From Equation (2.1) one could see that the amount off air that leaks into a building depends on the temperature difference, the pressure difference, the area of the doorway and the time the door stays open. By optimizing all these factors, the air infiltration will become negligible. However, some factors are hard or not possible to change. For example the temperature difference between the inside and outside cannot be changed without affecting the indoor climate negatively and decreasing the efficiency, see Figure 2.9. The pressure difference between the indoor and outdoor is a significant driving force of the air infiltration. As mentioned before, if the pressure difference increase from $+1$ Pa to $+3$ Pa the infiltration will become twice as big. The value can be minimized by compensating for the pressure difference with a mechanically induced pressure from the ventilation that is as large as the wind and stack pressure but in the opposite direction. To be able to do this some pressure measuring advice, like a barometer, could be mounted near the entrance doors that can control the ventilation so that the pressure difference becomes minimized. Since the pressure difference has such a significant effect on the infiltration the savings from this resolution will be noticed. The two parameters that are left is the opening time and area. In Chapter 3 many scenarios where both these parameters where changed were considered. The energy saved by implementing the different scenarios were presented in Table 3.3. As could be seen the energy savings became huge.

The significant yearly savings seemed too good to be realistic. Therefore, to gain more knowledge off the effect of a swing door opening a field test was conducted. In Test 1 the temperature variations for the natural door cycle, scenario 0, were measured. The results from Test 1 showed that the air infiltration was enormous, as seen in the calculations. Further, to see the effect of a reduced hold open time or reduced angle two more tests were conducted. The outcome showed a reduced variation of temperature and that much energy could be saved. The idea was to use the measured temperature to calculate the energy losses but there were too many factors varying which made the task too hard. One conclusion made from the field test was that there is a possibility to reduce the infiltration but to be able to do so we need new and improved sensors to be developed. Smarter sensors that can extract more information and monitor larger areas.

The sensors used today have small safety areas which result in that the door sometimes does not have time to stop completely. This was noticed in the field test and is against the ANSI A.156.10 standard, see Section 2.8. In the same standard, it is stated that the door is only allowed to start closing 1.5 seconds after that the safety sensor has lost detection. Many of the scenarios and Test 3 in the field test did not fulfill this requirement. I do not think this will be such a big problem since the regulation and laws we have today are old and was decided for the old safety sensor. With a new sensor which can ensure that the doorway is empty before closing the regulations and laws can be changed.

When the opening angle of the door is reduced it could cause some accessibility problems. In ADA Accessibility Guidelines the minimum cleared doorway is specified. Once again, this guideline could be passed with more advanced sensors. With a smart sensor that can detect the density of the user/users that wants to pass the door, the open angle could be controlled in a way to always open fully if a larger "object", for example a wheelchair or pram, is detected or when many pedestrians are coming towards the door. The sensor could also count how long the user is in the area to use it to open the door further helping the pedestrian to pass the door, as done in Test 3.

Over the past years' laws and regulations about energy use have become stricter. Today the doors should be labeled and certified with the air leakage in the closed position according to the energy standard ASHARE 90.1. This is one step in the right direction to spread the information and knowledge but also to make it easier for the customers to choose a better and in the long run cheaper alternative, both for their wallets but also for the planet. With the deadline for the Energy Performance of Building Directive coming closer the energy regulations in buildings will become even stricter. It is a matter of time before the same types of labels and certificate will also be issued to the opening cycle off a door.

The thing that can block the development of smarter doors are the users. With a decreased opening area and time, the user experience also decreases. In many cases, the optimal energy saving opening is different from the optimal user experience opening. One should not forget that many old and sick people need to use the door and feel safe and comfortable. The goal is to find the intersection between both. One such scenario is to imitate a manual opening of a door. That the door only opens if someone is in the doorway, as soon as the pedestrian has left the doorway the door should start closing. This idea was described in Scenario 7. To be able to implement a scenario like this the opening and closing trajectories off the door needs to be changed to make it possible to abrupt an opening and start closing smoothly. Optimally is to also use a vestibule where the two optimized swing doors are placed smartly. This will enclosure the little cold air from the outside that passes the first door.

6.2 Scenarios

To improve the opening cycle of the door about 20 scenarios were considered, some that could be implemented today, some in a couple of years from now and some in the future. For the scenarios that could be implemented today the best one was Scenario 3 which utilized the increased sensor area to detect when the doorway was empty and still fulfilled all laws and regulations. If one would implement Scenario 3 the energy losses could be smaller than fourth the size then for the standard case, scenario 0. For scenarios that could be implemented in a couple of years from now Scenario 7 was one of the best that gave a good user experience but still reduced the energy loss. If one would like to reduce the infiltration even more Scenario 8 could be implemented which starts to close the door sooner if the pedestrian comes from the pull side but reduced the user experience and may decrease the safety.

The safety of the pedestrians is always the focus and the main question. All scenarios presented in the previous section could be made safe for the users. For the scenarios and concepts that can impact the safety additional features could be added to the door. For example, could all the automatic doors also be accompanied by activation buttons that will override the implemented scenario and open as the door do today, with the long hold open time when the activation button is pressed. Sick, disabled or people that need a long time to pass the door are used to look for activation buttons that will open the door for them and could therefore use the button to get a longer time to pass the door.

If the safety needs to be improved further additional sensors could be monitored on the door. An example is Scenario 9 were one of the sensors is used to ensure that the door does not touch the pedestrian. As mentioned in the evaluation of the scenarios the additional sensor will increase the cost. However, in some commercial buildings cost is not a concern when it comes to safety. This can be the case in hospitals. Another way to increase the safety for all pedestrians is to add side rails to the doors which will enforce the users to walk in specific areas, sensor area or out of harm’s way.

The scenarios with increased or decreased opening and closing speeds were removed early and can be found in the Appendix. The reason was that the controller on the door could not handle larger speed in any of the directions without a noticeable overshoot. In practice this means that increased speeds will result in that the door will slam into the door stop, door frame or people which is not the desired behavior.

The focus on the opening angle was to come closer to a manual opening. When manually passing a door the user seldom pulls or pushes the door completely open. Therefore, the opening angles were reduced in some scenarios. In other scenarios the door switched to start closing as soon as the doorway was empty which imitates a manual opening but still gives a good user experience.

6.3 Field test

The results from the field test can be seen in Chapter 4. In the following section, a discussion about the different test is first made where the result is analyzed. Thereafter a summary of the observations made during the field study and some issues are presented.

In Test 1 the long hold open time resulted in that the cost for reheating landed on over $120,000$ SEK each year. A value that felt completely wrong until the test started. By looking at the result from the first test in Figure 4.2 where the door opens once every minute, i.e., 15 pedestrians walks through the door the huge cost seems more reasonable. It is worth noticing that in the calculations the temperature difference between the inside and outside always was $12°C$.

In Test 1 the door opening cycle became almost 21 seconds long resulting in that if more than 3 customers want to go through the door each minute the door will always stay open. The indoor temperature will drop even further making the indoor environment even worse. Even when the ventilation system is working on max the persons sitting on the front desk or in the entrance will get cold during winter or warm during summer. Worth noting is that the door opening and closing speed in the test was selected as the highest speed possible, which is not always the case. With a lower speed the door cycle will get even longer. From the supervision of Test 1 one conclusion that was made was that the door always stood open longer than necessary.

In Test 2 the hold open time was reduced to 1.5 seconds. The cost for reheating Test 2 was approximately $12,000$ SEK each year. By going from the 15 seconds hold open time to 1.5 seconds the cost saved is almost $100,000$ SEK each year. The cost has become almost a tenth and when questioning the users about their experience going through the door all answered that it was good. Actually no one had noticed that the hold open time of the door had decreased with 90%. This is a good outcome. The energy losses are heavily reduced but the user experience or safety have not been jeopardized.

In the field test the opening time for the door was set to 3 seconds which gave the users 4.5 seconds to walk from the activation button to the door, see Figure 4.1. Since the test was made in the office, there were no problems for the users to reach the door and the sensor area. It is worth noticing that if the activation button is further away from the hold open time may need to increase so the pedestrians have time to reach the door before it starts closing.

During Test 3 the hold open time of the door was removed completely and the opening angle was reduced to 70°, Scenario 5 was implemented. The door angle was reduced to decrease the air infiltration even further. The reduced angle will result in a smaller area the air can flow into the building but also the wind direction since the door will stand in the way for some winds. From a previously done study about user experience the optimal door angle was 70° which would decrease the air infiltration without giving a bad user experience. Theoretically, the yearly energy savings for Test 3 was calculated to over 101,000 SEK.

One problem during Test 3 was that the door during office hours was not locked. This resulted in that the door could be opened manually by just pulling the door handle. The problem that occurred in the manual opening was that the operator only allowed the door to open to the decreased open angle, namely 70°. So, when the users came from the outside and pulled the door handle the door will first help the user to open but then abruptly stop at 70°. This came as a shock for some users and created some problems in the morning measurements since some users still tried to open the door fully. This happened so many times that the operator attached to the door timed out and held the door in the open position until a reset was done. Even though this affected the results dramatically the test was not remade. This was due to that the field study had lasted for a couple of days and that the door during the period was marked to be under testing, that the users most use the activation button and that the door only opens to 70°. Therefore there was no reason to believe that the users will start using the activation button so that another test will give better results.

Summary of field test

By measuring the temperature and observing the users for different cases some conclusions could be made. First, the test was made in an office building where the door was heavily used in the mornings and evenings. The Figure 2.4, shown in the introduction, is a good schedule of the peak and off-peak hours in the office. A better case had probably been to implement a mixed version of Scenario 2 and Scenario 3 where the hold open time varies depending on the hour of the day. In the morning and evenings, when there are peak hours, most of the people pass the door and often many people come at the same time, therefore there should not be a large focus on the optimization. During the off-peak hours, when people drop in one by one, the opening will be optimized and hold open time shortened.

Another observation made was that air infiltration is the largest as the door opens. Then the temperature and pressure difference between the inside and outside is the largest. When the door is fully open the air infiltration decrease even if the inflow area is larger. This is because of that the temperature inside has dropped decreasing the temperature difference and the driving force of the infiltration. By looking at Figure 4.2 this is clearly seen. The temperature drops low almost immediately and then it starts to increase. The increase is slow due to that the door is still open allowing cold air to flow in. This is interesting since it indicates that the first seconds of the opening cycle is the most important. When the door starts to close the door shaft push cold air from the outside in resulting in a small temperature drop. This is clearly seen in the second and third test, Figure 4.3 and Figure 4.4. This indicates that the size of the door and the open angle matters since a larger door which is completely open can push a larger volume of air from the outside to the inside.

Some issues during the field study were, as mentioned above, that not all users used the activation button, even though they were told. In the first test this resulted in that the door would only hold open for 1.5–2 seconds and then starts to close. This is due to that the door is set to manual mode when someone pushes the door open. The manual mode resulted in that the measured temperatures for the first test were better than they should have been. Another problem with the manual mode was that when the user opens the door manually the door will only open to the open angle it has learned, which in Test 3 was 70°. This resulted in that the results for the third test were much worse than they should have been. Especially during the morning measurements when users were too lazy to go all the way to the card reader and instead pulled the door handle. To get better results in the field study the door always needs to be locked to prevent the users from doing a manual opening or the software needs to be changed to allow a manual opening to 90°.

Another issue that was noticed was that the reaction time for the sensors was some time too long. This could especially be seen for the old safety sensor which has a narrower safety area. The time the door had from that something entered the safety area and the door should stop to that it stopped was sometimes shorter than the reaction time for the sensor resulting in that the door leaf sometimes touched the pedestrian. This is especially noticed when the door speed is high. The new TOFswing sensor did not have a significant problem with this issue thanks to the broader safety area which will sometimes allow the sensor a longer time to act before the door leaf hits the pedestrian. But when the user is close to the door blade the TOFswing is also having the problem to prevent the door from a collision with the user.

6.4 Survey

The survey was sent out to 226 employers around the world with knowledge of swing door configurations and installation. The answering percentage was about

16%, 36 answers. From the answers one could see that many automatic swing doors are placed in entrances, over 75% of the participants answered that over 50% of the swing doors they encounter are entrance doors. This indicates that the problem addressed in this thesis is common in many buildings. This becomes even more clear when the Swedish service technicians answer that over 70% of the swing door they encounter has a hold open time larger than 8 seconds. Some of those clearly state that the majority of the doors they encounter has a hold open time larger than 12 seconds. The average hold open time for automatic swing doors around the world is, according to the survey, between 8–12 seconds.

One interesting thing is that the service technicians working in the USA sometimes have a completely different setup with much smaller hold open times. The reason for the small hold open time can be due to that in the USA one often has two kind of safety sensors. One regular safety sensor on the door but also one Overhead Presence Detect (OPD) sensor which monitors a larger area. The safety areas look similar to Figure 3.6. The OPD sensor is used to increase safety and will keep the door open as long as someone is in the safety zone. Hence there is no need to set a long hold open time since the OPD sensor will ensure that the door is in the open position if someone is in the doorway. The increased use of safety sensors is also seen in the survey question about the usage of safety sensors where most of the answers from especially the USA said that over 70% of the swing doors have safety sensors. In Sweden there was not a large proportion of swing doors with safety sensors.

One thing that almost all the service technicians had in common was that the opening time was larger than 4 seconds. Over half the technicians answered that over 90% of the swing doors has an opening time larger than 4 seconds. For the closing time the majority also stated that the closing time was above 4 seconds but how large proportions of the doors which had these configurations were more spread. By combining the information, one could estimate the average opening cycle of an automatic swing door to be over 16 seconds.

The last question in the survey gave the technicians a chance to give their opinions and thoughts. Even if the question was not required to be answered almost 80% of the participants took the time to answer. Many of the answers were to install air curtains or to build vestibules. There were also some participants who thought we should get better sensors to be able to close sooner but also to minimize the number of false openings from bypassing people. An interesting answer was from the Danish technicians who answered that they are aware of the enormous infiltration through the swing doors and tries to help the customers by offering complete entrance systems with air curtains to decrease the infiltration.

One issue with the survey was that the answers about the hold open times were skewed. Many participants filled in proportions that did not add up. For example, could an answer be 0%, 10% and 30%. One could assume that the answer is not serious but since those participants answered the optional question seriously it is hard to draw any conclusion. By looking into the specific answers, one could however sometimes gain a better understanding. If we go back to the example above one could assume that the majority of the doors have a hold open time around or above 12 seconds. However, this will not be shown in the total results.

6.5 Recommendations

From the above results and analysis one can conclude that there are many doors used in entrances and that they stay in the open position longer than necessary. In the field test one could see that it is possible to close sooner without anyone getting hurt if a smarter sensor was used. Therefore, the first step to save energy should be to implement Scenario 3 which full fills the laws today. When one starts to show the improved indoor climate and reduced energy loss it will be easier to change regulations and start closing even earlier, implement Scenario 4. The aim and goal should be to control the door to move as a manual door, Scenario 7. This goal will be hard to reach and will depend on that smarter sensors are on the market but with a clearly defined goal it will be easier to work towards it.

7 Conclusion

7.1 Summary Of Findings

Today the entrance swing doors follow a predefined opening cycle with opening, hold open and closing times decided by the user. The door follows the cycle no matter if the pedestrian has already passed or are stuck in the doorway. The only time the door recess from the cycle is when the safety sensor detects something in the safety area and send a stop signal to the door. All automatic swing doors are not accompanied by safety sensors but it is becoming more common. The information that can be extracted from the safety sensor is limited to "object detected" or "clear". This has lead to that there are no strategies at all to optimize the openings. This result in that the infiltration through the door becomes enormous, especially when it is really cold/warm outside. The temperature difference will create a pressure difference which will induce a larger infiltration. In the thesis the energy cost for one door cycle when the hold open time is 15 seconds is 0.35 SEK. The cost seems quite low but if one assumes that the door is used quite heavily the yearly cost will become over $126,000$ SEK. If one instead had a hold open time on 5 seconds the cost per opening is a third, 0.11 SEK. For a heavily used door one could yearly save almost $90,000$ SEK.

To reduce the infiltration even further one would like the door cycle of an automatic door to look more like the opening cycle for a manual door. When manually opening a door the user seldom opens the door fully and the door starts to close as soon as the user has passed. Further one could look into installing vestibules and air curtains to reduce the infiltration even further. The tricky part with reducing the hold open time and opening angle of the door is the many regulations and laws that specify minimum cleared areas and hold opening times. For accessibility the door angle is not allowed to be reduced and for safety the hold open time off the door must set to at least 1.5 seconds after that the safety sensor has detected the pedestrian. However, with better sensors that can ensure safety and easy passage the regulations can be changed.

7.2 Further Development

Some further developments that can be made are to do a study of the user experience of the different scenarios to see how comfortable the users are when passing the door. The study can also give a greater understanding of what more can be optimized and in which way.

Some of the scenarios above could not be implemented today because of the construction of the opening and closing trajectories. By remodeling those the energy loss can be decreased sooner. For example Scenario 7 could be implemented which can abrupt an opening and start closing if the pedestrian has gone through the door.

The calculations on the air infiltration were simplified due to that many parameters varied with time and space. The calculations could be refined by taking more measurements or set up a wind chamber. But since all reports, including this one, have come to the same conclusion, that much energy is lost when the swing doors open the focus should lay on minimizing the opening and hold open time as much as possible but still have a good user experience. When the opening has optimized a vestibule or/and air curtain could be used to decrease the air flow further.

Bibliography

Al-Adhami, A., W. Dahlgren, R. Marklund, L. Olsson, and E. Persson (2017). "Cost savings in automatic swing doors". *Course at Lund University*.

airtécnics (n.d.). *What is an air curtain?* Accessed: 2019-01-16. URL: https://www.access-board.gov/guidelines-and-standards/buildings-and-sites/about-the-ada-standards/background/adaag#4.14.

American ICF Builders, INC (n.d.). *Energy performance r-values*. Accessed: 2019-01-12. URL: http://www.aicfbuilders.com/Homeowner/Energy_Performance.htm.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (2016). "Energy standard for buildings except low-rise residential buildings".

ASSA ABLOY Entrance Systems AB (n.d.). *Information gathered from the company.* Accessed: 2019-02-16. URL: http://www.http://assaabloyentrance.se/.

BEA (n.d.). *Pedestrian sensing solutions*. Accessed: 2019-02-02. URL: https://www.bea-sensors.com/en/segment/pedestrian-sensing-solutions/swing-doors.

BELOK (2012). "Energieffektiva entréer(förstudie)".

Berge, A. (2011). "Analysis of methods to calculate air infiltration for use in energy calculations". *Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design, Chalmers University*.

Board, U. S. A. (n.d.). *Ada accessibility guidelines*. Accessed: 2019-01-28. URL: https://www.airtecnics.com/technology/what-is-an-air-curtain.

Boverket (2008). "Regelsamling för byggande, bbr 17, avsnitt 9, energihushållning (building regulations, bbr 17, section 9, energy management)".

Builders Hardware Manufacturers Association, Inc. (2015). "Standard for power operated pedestrian doors".

Bülow-Hübe, H. (n.d.). *L11: indoor climate targets for energy-efficient buildings*. Accessed: 2019-01-16. URL: http://www.ebd.lth.se/fileadmin/energi_byggnadsdesign/images/Utbildning/AEBF01/AEBF01_F11_function_requirements.pdf.

Energy Education (n.d.). *Air infiltration and exfiltration*. Accessed: 2019-01-08. URL: https://energyeducation.ca/encyclopedia/Air_infiltration_and_exfiltration.

Energy Kid's Place (n.d.). *Energy use in commercial buildings*. Accessed: 2019-01-15. URL: http://www.scuolacascia.it/attivita/clil2/webquest/resources/energy%5C%20kids%5C%20page/www.eia.doe.gov/kids/energyfacts/uses/commercial.html.

European Commission (2019). *Energy performance of buildings*. Accessed: 2019-01-08. URL: https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings.

Generation Robots (n.d.). *Teraranger one b frame: the terabee distance sensor that loves to be forgotten*. Accessed: 2019-01-22. URL: https://www.generationrobots.com/en/402461-teraranger-one-b-frame.html.

Huijuan Chen, S. S. (2008). "Energy performance of door solutions". *The swedish energy agency project number: 40845-1*.

Jingying Ma Qiu, X. (2018). "Intelligent swing door system design aiming to minimize air infiltration through door opening in buildings". *Master of Science Thesisin the Master's Programme Industrial Design, Lund University*.

Julight (n.d.). *Electro-optical sensing*. Accessed: 2019-01-20. URL: http://www.julight.it/electro-optical-sensing//.

Karlsson, N. (2013). "Air infiltration through building entrances". *Master of Science Thesis in the Master's Programme Structural Engineering and Building Technology, Chalmers University*.

Swedish Standards Institute (2012). "Svensk standard SS-EN 16005:2012".

Yuill, G. K., R. Upham, and C. Hui (2000). "Air leakage through automatic doors". *ASHARE 4381*.

A

Appendix

A.1 Scenarios

Let us look at some scenarios where the sensor can be used to shorten the hold open time. The idea is to brainstorm and present many scenarios in the beginning and then try to sort out which ones are worth looking further into. In the first part scenarios that can be applied to the TOFswing sensor today are presented. In the second part scenarios that can be implemented a couple of year from now when the sensors have become more advanced are analyzed. In the last part future scenarios are presented.

Today

In this section, scenarios using the old safety sensor are first analyzed, and then some scenarios using the new TOFswing sensor are presented. In the first two scenarios, it is assumed that the door opens by manually pressing an activation button, but the rest of the scenarios assume that activation sensors are used to open the door.

Scenario A. In scenario one, the only sensor that is needed is the old safety sensor. The activation button is developed to be split up into two parts, one with a short hold open time and one with a longer hold open time. An illustration of the activation button can be seen in Figure A.1. If a pedestrian is in need for a longer time to pass the doorway, they should press on the top part, but if the pedestrian can pass the door quickly, they should press the bottom part of the activation button which will set a short hold open time.

Scenario B. Once again, the door opens when the user presses the activation button. Depending on how long the press is the hold open time for the door is short (quick press) or long if the press lasted for more than 3 seconds.

Scenario C. In this scenario the activation sensors are used together with the old safety sensor. When a pedestrian is coming towards the door and walks into the activation area, the activation sensors will register this and open the door. When the pedestrian has walked through the door and is on the other side, going into the

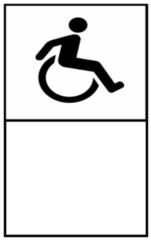


Figure A.1: The activation button described in Scenario A. Depending on which part you press the hold open time will be long or short.

other activation sensor's area, this sensor will detect that the pedestrian has passed through, and signal to close the door. This is depicted in Figure A.2.

Scenario D. In Scenario D, the old safety sensor is used together with an advanced activation sensor. More advanced sensors can detect the direction and how fast the pedestrians are going towards the door. The speed of the pedestrian can then be taken into account to regulate the hold open time for the door. For example, if the pedestrian is walking fast, there is no need for a hold open but if the pedestrian is walking slow a hold open time should be set.

Scenario E. As seen in Figure 2.4 the door usage varies with the hour of the day and type of commercial building. This could be used to save energy. When the clock is off-peak, there should be a larger focus on energy savings since there are not as many people passing through. An idea could be to cut the hold open time to half when it is an off-peak hour, and when it is peak hour the hold open time is as normal. Since there still is a safety sensor on the door, it will prevent the door to close/open on a pedestrian.

Scenario F. In this scenario, the new TOFSwing sensor will be used. The door will open normally, and the default hold open time is set to the usual 15 seconds. When the TOFSwing sensors senses that someone is in the area the hold open time is changed to 1.5 seconds. The new hold open time will start when the TOFSwing sensor signals that the area is clear. This scenario follows all the regulations that we have today.

Scenario G. The door opens normally. As soon as the door is fully opened and the TOFswing sensor cannot detect anything in the area, it is assumed that the pedestrian has passed the door and an impulse is directly sent to close the door. A graph for this scenario is shown in Figure A.3. The difference from Scenario 3 is that this scenario does not have any hold open time, which is against today's regulations. But what is the point of holding the door fully open for 1.5 seconds when no one is in the doorway and no one wants to pass?

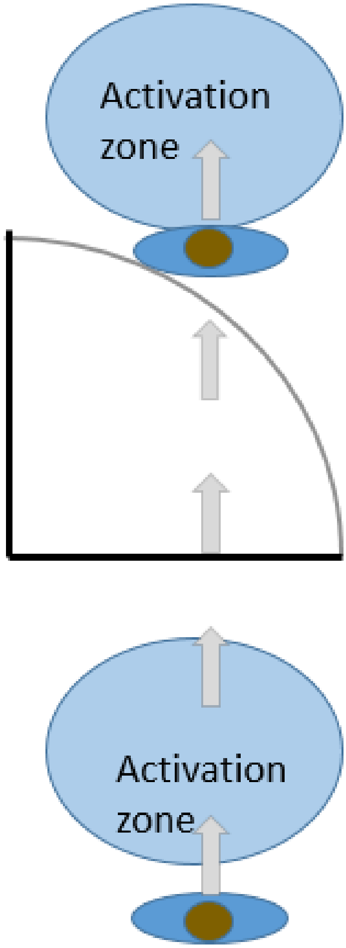


Figure A.2: The activation areas for Scenario C are shown together with the pedestrian walking through the door.

Scenario H. The door opens slowly and then when the sensor signals that the area is clear the control unit switch to closing. The door does not have to be completely open before the closing starts. This scenario will shorten the hold open time but also the opening angle if the pedestrian is walking fast.

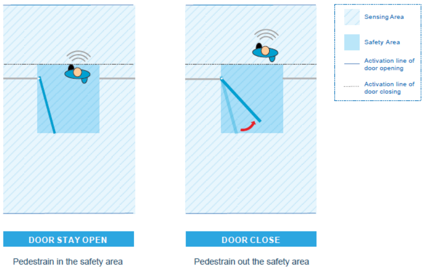


Figure A.3: As soon as the pedestrian leaves the safety area the door should close [Jingying Ma, 2018].

Scenario I. This scenario is an extended version of Scenario H. In Scenario H the door always opens slowly and then closes when the area is clear. In this scenario, the density of pedestrians walking through the door will be considered. Since nor the new safety sensor not the detection sensors can detect how many pedestrians that are in the doorway the combined information from all of them will be taken into account. When both activation and safety sensor are activated, the door should open with normal speed, to be able to pass more people through. However, if only one sensor is detecting a pedestrian, the door should open slowly, as in Scenario H.

Scenario J. In this scenario, the speed of the door will be controlled to minimize air leakage. When the activation sensor detects a pedestrian, the door waits for a moment and then opens up faster than normally. When the doorway is empty, the door closes quickly. The speed in both the opening and closing direction is increased and the hold open time is reduced.

Scenario K. In Scenario K, the door will open to 70 degrees allowing pedestrians to pass through. When a pedestrian walks by the TOFSwing sensor will sense that someone is in the doorway. As soon as the pedestrian enter the sensor area, the doors will continue a slow opening from 70 degrees to 90 degrees. When the sensor signal clear the door will start closing normally. This scenario will decrease the air infiltration when no one is in the doorway but still give a good user experience since the user feels that the door is almost completely open.

Scenario L. In this scenario, the door will first open to 70 degrees. The narrower width of the doorway will in the majority of times work well but can cause some problems for some pedestrians. This is handled using the TOFSwing. If the TOFSwing sensor signals "object detected" for longer than 2 seconds, then either someone is having trouble passing the door or that many people want to pass through. In both cases, the door will open to 90 degrees. If no one is having trouble through the door, the door will start closing as soon as the sensor area is empty. The hold open time for this scenario is set to zero, i.e., the door will only stay open if someone is in the sensor area. This scenario can be seen in Figure A.4.

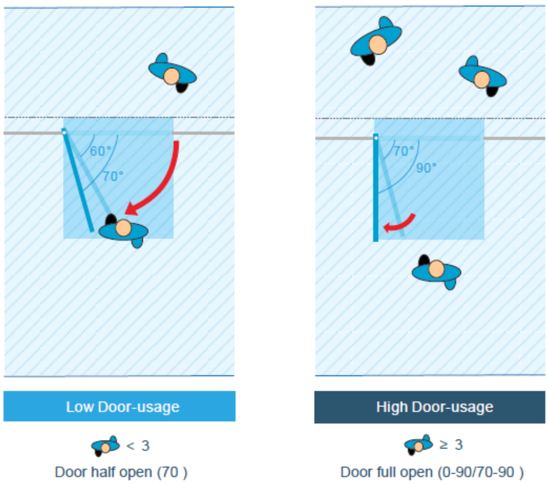


Figure A.4: The door changes the opening angle depending on how many pedestrians that are in the doorway [Jingying Ma, 2018].

Implementable in 2–3 years

In a couple of years, the market will probably have more advanced sensors which could be used to control the door even further. Things that can be improved in the current TOFswing sensor is to have a wider safety area and add more outputs to be able to make the door smarter. One output that will be good to have is the number of people that are in the doorway and where in the doorway they are. Since the TOFswing sensor uses the time of flight method with pixels to detect pedestrians, these improvements should be easy to implement. Simple algorithms can then be implemented to calculate where and how many pedestrians there is in the doorway. Another adjustment can be to split the safety zone into two parts. The area nearest the door shaft should be called safety zone, but the area outside could be renamed to the detection zone, see Figure A.5. By separating the zones, one could use the safety zone to ensure safety and the detection zone to minimize the air infiltration.

Scenario M. In this scenario, the sensor is going to work together with the activation sensor to shorten the time. The door opens normally but if the pedestrian comes to the pull side of the door the sensor sends out a close command to the door as soon as the pedestrian is inside the detection area making the door close as the pedestrian is walking through, i.e., the door follows the pedestrian as it walks through. Once again, depending on how fast the pedestrian is the door could start closing before

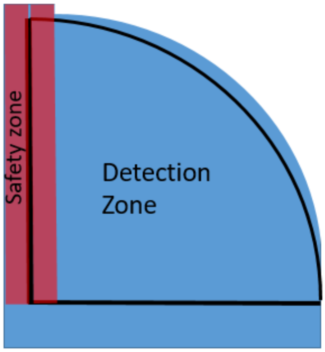


Figure A.5: The safety area is shown in red. The blue area is the detection zone.

even going to fully open. If the door shaft is to close to the pedestrian, the safety area will signal this to the operator.

Scenario N. With a sensor that can sense how many pedestrians that are in the doorway the door angle can be modified. As described in the previous work, Chapter 1, the optimal door angle for two people, found in last year's master thesis, was 70° and for more than two is the normal fully open state, 90°. Using this information, the opening could be optimized. The scenario is shown in Figure 3.3. When the sensor detects that one or two persons wants to pass through the door, the door only opens to 70° but if a third pedestrian is detected the door opens to 90° . The difference between this scenario and Scenario 5 is that the opening angle is directly set to the right angle, considering the density. For example, if 3 or more pedestrians are coming towards the door, this scenario will open the door maximally, but Scenario 5 will first open to 70 degrees and then, after 2 seconds, continue opening.

Scenario O. One way to increase the user experience and decrease wear on the door system is to increase the area on the sensor even further. With a larger area, the sensor will be able to detect if more pedestrians want to walk through the door and can then stay in the open position instead of closing and then opening. An image of this is shown in Figure A.6 where the dark blue area is the newly extended area.

Scenario P. With a larger sensor area it will be easier to keep track of the users. This could be used to switch the door cycle from opening to closing as soon as the users has passed the door. In this scenario, the door will get an opening impulse and open normally but as soon as the sensor senses that the pedestrian has entered and exited the safety area the door will abrupt the opening and start a closing. This scenario will prevent the door from continue opening when the pedestrian has already passed.

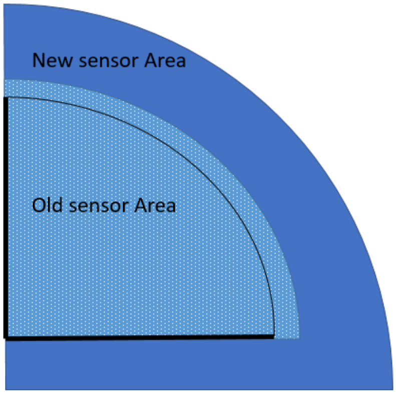


Figure A.6: The old sensor area is shown in light blue and the new sensor area is shown in dark blue.

Scenario Q. The detection zone can be split up into two zones. The different zones can later be used to easier and more accurately detect where the pedestrian is. In Figure A.7 the zones are shown. When a pedestrian is coming from the pull side and is in Zone 1, the door could start to close. This scenario can feel scary for some users but by using two zones it could be made accurate and comfortable for pedestrians since one could detect when the door is coming closer to the pedestrian, Zone 2 is activated, and therefore stop earlier than when the user is in the safety zone.

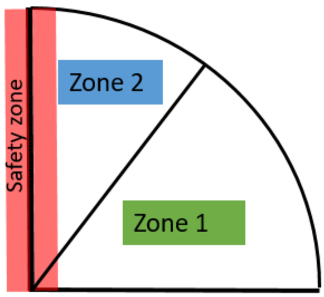


Figure A.7: The sensor area is shown. The safety zone is the red area near the door leaf. The rest of the detection area is split into two zones, Zone 1 and Zone 2.

Scenario R. With wider sensor areas the accuracy will decrease. Today is it hard for one sensor to cover both the doorway and the shaft. One way to solve this is to use more than one sensor. In Figure A.8 this scenario is shown. The red area is the safety zone from an old safety sensor along the shaft, and the blue area is the detection area from two sensors placed in the top corner of the door. By using separate sensors to watch over different parts of the doorway the placement of the sensors could be changed for optimal scanning of each area.

Figure A.8: Two sensors are scanning the whole doorway. One sensor creates the safety zone, the red area near the door leaf. The other sensor is used to optimize the opening by over viewing the doorway, blue area [BEA, n.d.] .

Implementable In More Than 3 Years From Now

With smarter sensors, the communication between sensor and door system will be developed further. Today the sensor only sends "object detected" or "clear" impulses, but with a further developed CAN bus communication setup between sensor and door operator more information could be extracted, and the air infiltration could be minimized even further.

Scenario S. The sensor area has increased making it possible for the sensor to calculate how fast the pedestrian is walking and where the pedestrian is in the area. From this information, the sensor could use bus commands to make the door follow and close directly behind the pedestrian.

Scenario T. The increased sensor area can also be used to detect the density and direction of the pedestrians but also rule out wrong signals from stones, insects, smaller animals, etc. Further by calculating the direction of the pedestrians the door could only open when pedestrians are walking with a certain angel towards the door, this is shown in Figure A.9. The angle of the door in the open state is once again set by the number of pedestrians in the doorway.

Scenario U. In the previous scenarios, the sensor is assumed to be quite accurate, but with a wider sensor area, the accuracy is decreased. One way to increase accu-

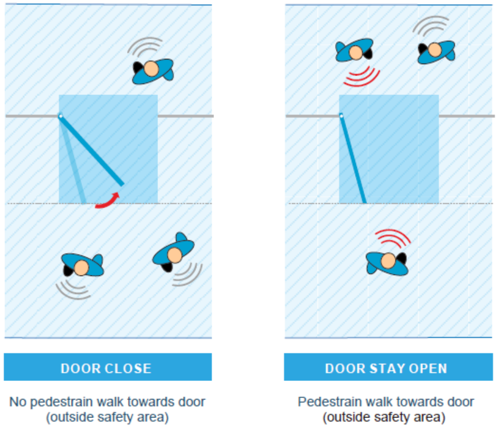


Figure A.9: Scenario 10 is shown. As can be seen, when no pedestrians are walking towards the door the door starts to close. But if a pedestrian is walking towards the door the door stands open or opens [Jingying Ma, 2018].

racy is to divide the sensor area into more zones, maybe three or four zones. It is probably easier for the sensor to detect in which zone the pedestrian is rather than exactly where it is. The accuracy and safety could hence be increased.

Scenario Optimal Future. In an optimal opening, the air infiltration needs to be minimized and negligible. To do that the door opening needs to prevent air from flowing freely and directly into a building. One such example is to use some passage like a revolving door or to create some pocket where the pedestrian could enter and then the pocket rotates. This is illustrated in Figure A.10 where the grey area shows the pocket and the black lines are walls. In this scenario, the pocket will prevent the air from flowing into the building.

Another example is to view the airflow patterns and use this to create an optimal vestibule where the doors are placed to avoid leakage. On the front page and in the air infiltration section a caption of the air infiltration through swing doors is shown, Figure 2.7. Using this information one could create a vestibule like Figure A.11. The airflow from the outdoor to the indoor will hence become small. Vestibules are often used in entrances, but the placement of the doors are in many times too close resulting in that both doors will stay open at the same time which will barely decrease the infiltration.

One could also increase the opening and closing speed of the door and even start to close sooner as described in previous scenarios. By not opening longer and more than needed the time and area that will let air inside is minimized.

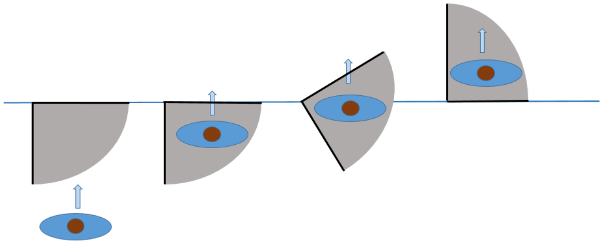


Figure A.10: A rotating pocket is shown. When a user comes inside the pocket, it rotates. In both the start and end position the air leakage is negligible.

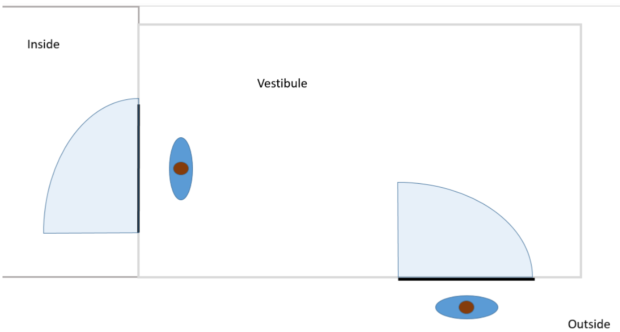


Figure A.11: By knowing how the air flow patterns one could create a vestibule with doors placed in such a way that the air flow is decreased

A.2 First Evaluation

To be able to evaluate the different scenarios a point system is used. The idea is to evaluate each scenario and give points in three different categories.

Accuracy. The first important category is accuracy. There should be no chance of a door hitting a pedestrian. The safety of pedestrians is always considered as a priority. The accuracy is graded on a 0–10 scale where 0 is unsafe, and 10 is accurate.

Energy savings. The second category is energy saving. The energy savings for each scenario is calculated as the amount of air infiltration. To make it easy to evaluate the energy savings is graded on a 0–10 scale where 0 is no energy savings and 10 is maximum optimization.

User Experience. The last category is the user experience of the door. If it easy to go through the door or if the user will feel that the door is uncomfortable since the shaft is to close, to fast, etc. The user experience is also graded with a 0–10 scale. The best user experience is represented with a 10 and the worst experience with a 0.

Points For Each Scenario

In Table A.1 the points for scenairos implementable today is shown. The points for scenarios implementable in 2–3 years are shown in Table A.2. In Table A.3 are the points for scenarios implementable in more than 3 years from now.

A.3 Data From Test 1

The results from Test 1 can be found below. In Figure A.12 the results form when the door is opened once every minute in is shown. The data from the evening are shown in Figure A.14 and the morning in Figure A.13.

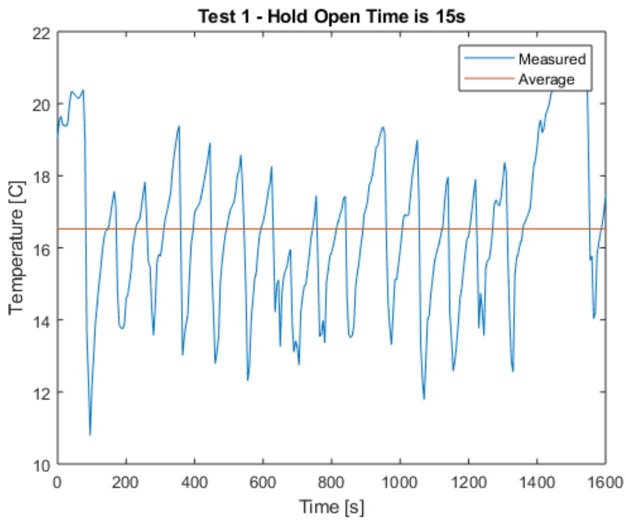


Figure A.12: The data from Test 1 i shown. The door is open once every minute.

A.4 Data From Test 2

The results from Test 2 can be found below. In Figure A.15 the results form when the door is opened once every minute in is shown. The data from the evening are shown in Figure A.17 and the morning in Figure A.16.

Table A.1: The table points for each category for each scenario Today.

Scenarios	Accuracy	Energy Savings	User Experience	Motivation
A	9	4	8	Could be hard to understand the new activation button.
B	9	4	6	A sign needs to be added to inform the user of the situation.
C	1	7	2	Accuracy is bad, especially if persons are coming from both sides of the door.
D	4	6	6	The advances activation sensors are not accurate. Problems if many people want to go through the door.
E	8	3/7	6	Energy savings depends on the building type.
F	9	7	10	The user experience is good since the user has already passed the door when it starts closing.
G	8	8	9	Much energy could be saved and but can be a little risky with no hold open time.
H	9	8	4	Can be a long wait for wheelchairs and prams.
I	9	7	6	Can still be a long wait for wheelchairs and prams.
J	4	6	2	Can result in that the door slams into the door stop or worse, a pedestrian.
K	9	7	8	The reduced open angle can make it uncomfortable to enter the door.
L	9	8	7	Can be a long wait for wheelchairs and prams.

Table A.2: The table points for each category for each scenario for 2-3 years from now.

Scenarios	Accuracy	Energy Savings	User Experience	Motivation
M	2	8	5	There is a large risk that the door hits the pedestrian from behind.
N	7	8	7	Can sometimes feel narrow to pass through the door.
O	8	6	8	With an increased area the accuracy is probably also increased.
P	9	9	7	Can create a problem if many pedestrians wants to go through the door.
Q	8	8	8	The divided zones result in that the door could close earlier but still be safe for pedestrians.
R	9	8	8	By separating the sensor the accuracy is increased.

Table A.3: The table points for each category for each scenario in $>$ 3 years from now.

Scenarios	Accuracy	Energy Savings	User Experience	Motivation
S	9	10	8	Can feel scary to have a door that closes directly behind you.
T	9	10	9	Users must walk straight towards the door.
U	10	9	9	More accurate.

A.5 Data From Test 3

The results from Test 3 can be found below. In Figure A.18 the results form when the door is opened once every minute in is shown. The data from the evening are

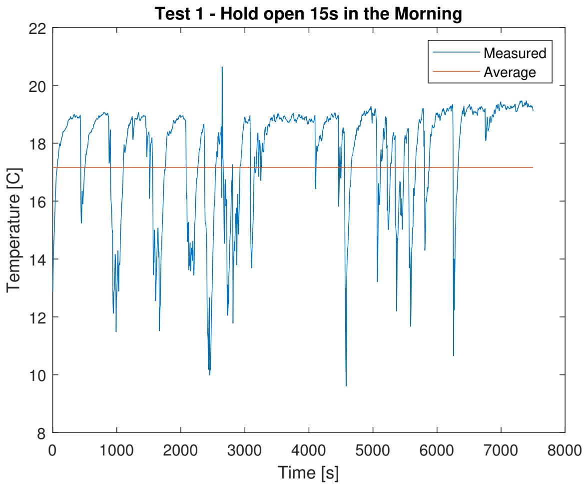


Figure A.13: The data from Test 1. The test result from the morning rush.

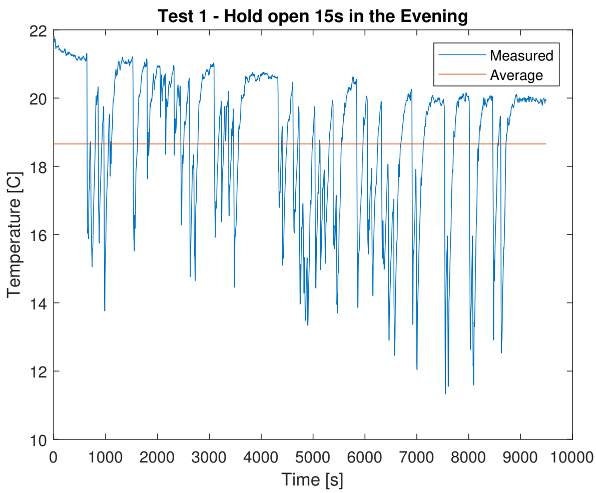


Figure A.14: The data from Test 1. The test result from the evening rush.

shown in Figure A.20 and the morning in Figure A.19.

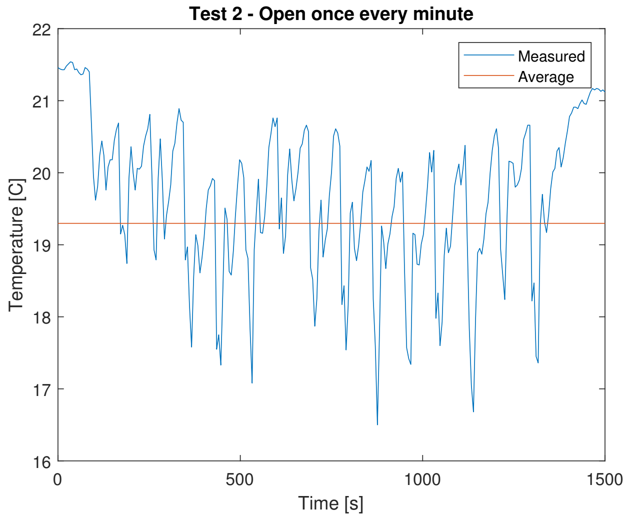


Figure A.15: The data from Test 2 i shown. The door is open once every minute.

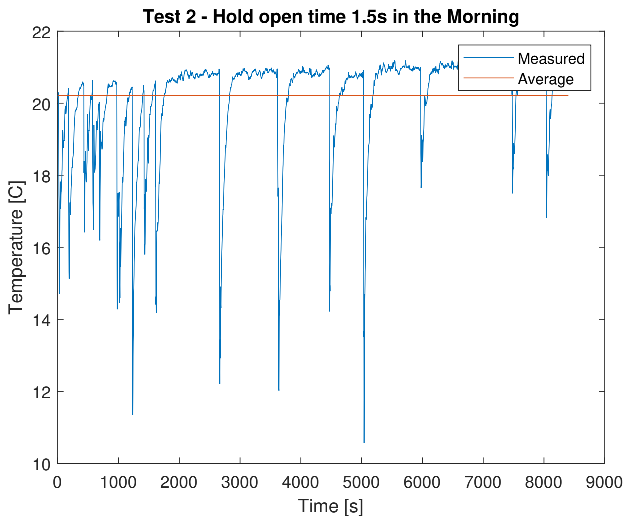


Figure A.16: The data from Test 2. The test result from the morning rush.

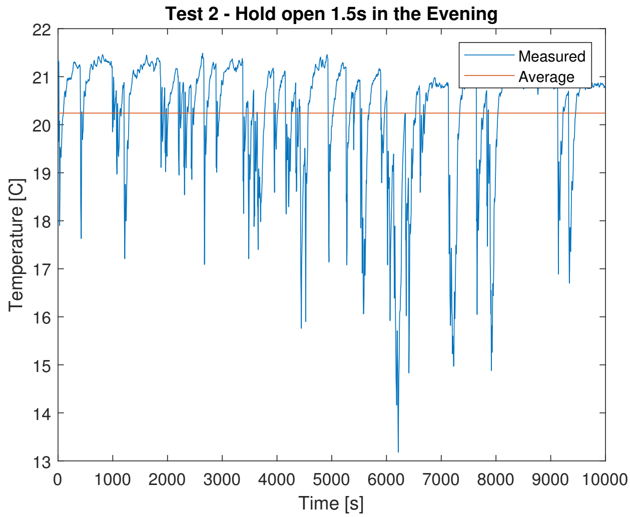


Figure A.17: The data from Test 2. The test result from the evening rush.

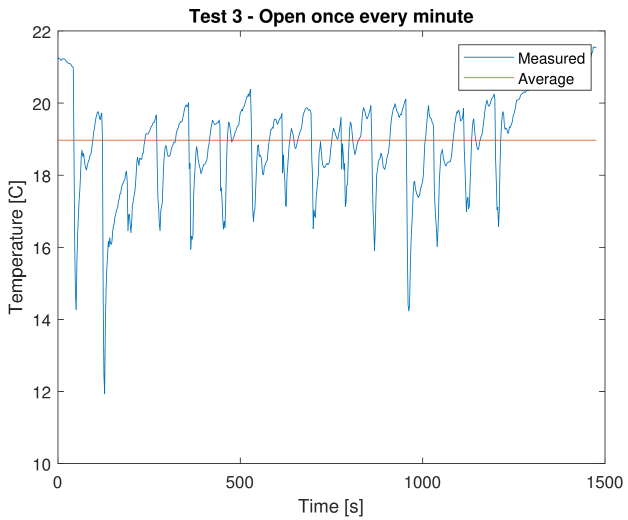


Figure A.18: The data from Test 3 i shown. The door is open once every minute.

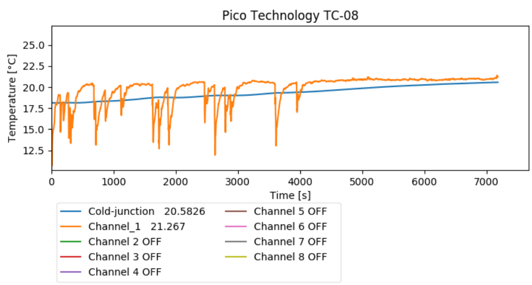


Figure A.19: The data from Test 3. The test result from the morning rush. Observe that the graph is different and that the blue line is the cold-junction and not the average temperature

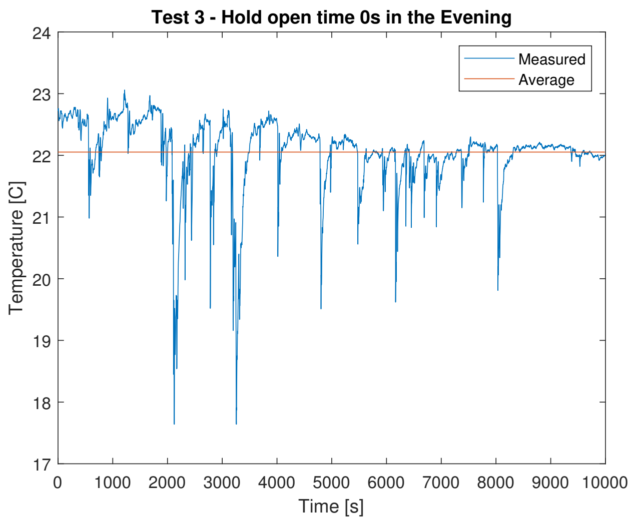


Figure A.20: The data from Test 3. The test result from the evening rush.

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Title and subtitle

Intelligent Swing Doors
Reducing Air Infiltration Using Smarter Sensors.

Abstract

When an automatic swing door is used in an entrance, the energy consumption increases. This is because the door cannot detect when the user has passed and therefore, for safety reasons, stands in the open position for too long. To make automatic swing doors more sustainable one needs smarter sensors that can cover a larger area and communicate with the door. In this thesis 11 different concepts of how to use more intelligent sensors to control the door to reduce the infiltration are presented. Both the times the door is opening, standing in the open position and closing are considered. To limit the air leakage even more reduction of the open angle is also analyzed. The aim is to make the door move like a manual door, which has the smallest air leakage.

To see how swing doors are configured, a survey has been performed. The results show that the average cycle is over 16 seconds long. Further, to get a greater understanding of the air leakage a field test is made where the temperature is measured for different scenarios. The result shows a temperature drop larger than 5 degrees for a typical door cycle. By start closing the door sooner the energy losses could be reduced with over 60%. The result is an improved indoor climate as well as a smaller environmental impact.

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