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Energy performance of door solutions

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Entrelösningars energiprestanda

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E2B2

Förord

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Entrelösningars energiprestanda är ett av projekten som har genomförts i programmet med hjälp av statligt stöd från Energimyndigheten. Det har letts av *RISE* och har genomförts i samverkan med *Frico AB, Assa Abloy Entrance Systems AB, Viametrics AB, ÅF-Infrastructure AB, Västra Götalandsregionen, Equa Simulation AB, Ansys Sweden AB och Härryda Kommun*.

I projektet har ny kunskap tagits fram om olika entréutformningars energiprestanda. I dagsläget finns en kunskapsbrist om hur energiförlusterna genom entréer påverkar byggnadens totala energianvändning. För att åstadkomma en bättre noggrannhet i beräknad energiprestanda krävs det bättre modeller och antaganden kring den ofrivilliga infiltrationen genom entréer. I projektet har forskarna främst studerat det ofrivilliga luftutbyte som sker när en dörr öppnas eller stängs.

Stockholm, 1 januari 2018

Anne Grete Hestnes,

Ordförande i E2B2

Professor vid Tekniskt-Naturvetenskapliga Universitet i Trondheim, Norge

Rapporten redovisar projektets resultat och slutsatser. Publicering innebär inte att E2B2 har tagit ställning till innehållet.

Sammanfattning

Syftet med projektet var att utveckla kunskap om olika entrélösningars energiprestanda. De dörrtyper som vi har fokuserat på är automatiska skjutdörrar och roterande karuselldörrar. Förlusten genom en dörr påverkas av dess U-värde, infiltrationen genom otätheter vid stängt läge samt ofrivilligt luftutbyte när dörren är öppen och används. Det är den sistnämnda aspekten, det ofrivilliga luftutbyte vid användning, som främst behandlas i denna rapport och som också är den mest signifikanta delen när det kommer till energiförluster genom entredörrar.

För att samhället ska lyckas nå uppsatta miljömål måste energianvändningen i byggnader minska. I dagsläget råder en kunskapslucka om hur energiförlusterna genom entréer påverkar byggnadens totala energianvändning. Problemställningen avseende entréerna negligeras i beräkningar av lågenergibyggnader trots att de i vissa fall kan ha en stor inverkan på energianvändningen. Samtidigt är det ofrivilliga luftutbytet via dörrar en parameter som har en stor osäkerhet och är mycket svår att uppskatta vid dessa beräkningar. För att åstadkomma en bättre noggrannhet i beräknad energiprestanda krävs det bättre modeller och antagande kring den ofrivilliga ventilationen via entréer.

I projektet har vi i vårt labb mätt luftutbytet genom en karuselldörr och undersökt effekten av temperaturdifferens och dörrens rotationshastighet, för en karuselldörr i reducerad skala 1:2. Både temperaturmätning och spårgasmätning genomfördes, och tempereraturmätningen gav ett stabilare resultat. Det uppmätta luftutbytet påverkades mer av dörrens rotationshastighet än av temperaturdifferensen, inom de mätområden som testades.

Vidare har vi också analyserat och applicerat befintliga beräkningsmodeller för entredörrar. Beräkningar för att uppskatta en dörrs energiförluster genomfördes för en kontorsbyggnad i Göteborg utifrån ett antal olika beräkningsmodeller för skjutdörrar och en karuselldörr. Beräkningsresultaten för det här specifika fallet visar att en karuselldörr kan motverka upp till 60-90% av förlusterna jämfört med en skjutdörr, beroende på vilket antagande som görs för luftflödesprofilen genom skjutdörren, dvs. om luftflödet antas vara dubbelriktat eller enkelriktat. Bättre kunskap behövs för att förstå hur luftflödesprofilerna faktiskt ser ut i verkliga fall när skjutdörren är installerad i en byggnad. Vidare behöver mer studier genomföras på karuselldörrar för att säkerställa resultaten från den här studien, exempelvis utökade labmätningar och även fältstudier. Dessutom behöver andra parametrar, såsom vind (styrka, riktning och infallsvinkel) och dörrens användningsfrekvens, studeras vidare för att öka förståelsen för hur de påverkar luftutbytet. Nästa steg i att ta fram en tillförlitlig modell för karuselldörrar är att repetera mätningar som gjordes i det här projektet på en fullskalig karuselldörr och med ett större antal mätpunkter.

Nyckelord: energiprestanda, roterande karuselldörrar, skjutdörrar, luftutbyte, mätning, beräkning

Summary

The project aim was to develop knowledge about the energy performance of different door solutions. The door types that we have focused on are automatic sliding doors and revolving doors. Losses through a door depend on its U-value, infiltration leakage through the seal when closed and unintended air exchange when the door is open and in use. It is the last factor, the unintended air exchange when in use, which is mostly addressed in this report and it is also the most significant part when it comes to energy losses through entrance doors.

To achieve environmental targets, energy use in buildings must be reduced. There is a gap regarding knowledge about the energy losses through the entrances and how it affects the total energy use of the building. The problems regarding entrances are neglected in calculations of low energy buildings, even though they in many cases may have a large impact on the energy use. Meanwhile, the unintended air exchange through the doors is a parameter that has a large uncertainty and that is difficult to predict in energy calculations. To achieve a better accuracy in calculated energy performance, better methods and estimations regarding the unintentional air exchange through the entrances is needed.

In the project we measured air exchange rates through a revolving door and investigated the effect of temperature difference and door rotation speed in our laboratory, based on a reduced scale revolving door with the scaling 1:2. Both temperature measurements and tracer gas measurements were performed, and the temperature measurements gave more stable results. The measured air exchange rate was affected more by the door rotation speed than the temperature difference, within the measuring ranges that was tested.

Further, we have also analyzed and applied existing calculation models for entrance doors. Calculations for estimating the energy losses for a door was made for a simple case study of an office building in Gothenburg, based on a number of different calculation models for sliding doors and revolving doors. The calculation results for this specific study show that the revolving door can prevent up to 60-90% of the losses compared to a sliding door depending on which air flow scenario, i.e., single sided- or cross ventilation, is considered for the sliding door. Better knowledge is needed to understand the actual air flow profile of real cases when the sliding door is installed in a building. Furthermore, additional studies are needed for the revolving door to ensure the results from this study by e.g., extended laboratory measurements and also field tests. Also, how other parameters such as wind (magnitude, direction and incidence angle) and door usage affecting air exchange through a revolving door is needed to be investigated further. Next step to develop a reliable model for revolving doors is to repeat the measurements performed in this project on a full scale revolving door and with a larger test range.

Keywords: energy performance, revolving door, sliding door, infiltration, measurement, calculation

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1 Introduction and background

When constructing and renovating buildings there is a need for tools that can help with the decision of which entrance solution that is most appropriate for the building and the particular usage of the door. Such tools are not in place today, neither is the theoretical knowledge available for developing these tools. There are a few studies available in the literature that has developed analytic models for the most simple door alternatives. However, there is a lack of studies that has repeated or tested the reliability of these models.

The purpose of this project was to develop a method of measuring and calculating energy losses due to air exchange through exterior doors while they are in use, by means of laboratory measurements and theoretical calculations. The main focus has been on automatic sliding and revolving doors. Automatic sliding doors are known to be a major source of air leakage. Revolving doors are designed to reduce the losses, but there is lacking knowledge about how much more efficient they are compared to sliding doors. And both these door types are normally installed where large numbers of people use the door. Air-exchange through a sliding door can be simplified to the case of flow through a large opening and it can be predicted by a number of empirical models developed by previous studies. Although different models could give different results, it would be interesting to compare the results and explore pros and cons for each model and make further suggestions. Revolving door has been reported to be the most efficient entrance solution. Few studies have been found from published literature databases and most of them focused on doors that were manufactured in the 60s. It would be useful and meaningful to perform more studies to update the information for modern doors.

Improvements on building envelop and efficient heating, ventilation and air-conditioning (HVAC) systems result in more energy efficient buildings. The building envelops are becoming more air tight and well insulated. The HVAC systems have more efficient components and better control. We can calculate the energy losses through the building envelope, and also calculate and monitor the energy use in the building. However, methods for calculating and measuring the actual losses through the exterior doors are not sufficiently developed. Meanwhile, losses through doors are becoming a more important part of a building's overall energy need, as the energy efficiency of other components are improved. Thus, they should not be neglected.

The energy performance of an exterior door should include the U-value and infiltration through the seals when de door is closed. For automatic doors the electricity use should also be included in the performance evaluation. However, in most cases the largest impact on the energy performance is due to the air exchange while the door is in use. This is also the area where least knowledge is available. Therefore, air exchange though the door when in use is the major focus of this report. The externally driving force for the air exchange is determined by the temperature differences, stack effect and wind. Other factors that influence the air exchange are the type of door, position, size, if it is manual or automatic, time and frequency of operation, door speed and the room configuration where it is installed.

2 Methodology

This chapter gives an overview and description of the methodology chosen and used within the project. The methodology is divided between three main methods; literature study, measurements and empirical predictions. The project was conducted by RISE Research Institutes of Sweden in collaboration with Frico AB, Assa Abloy Entrance Systems AB, Viametrics AB, ÅF-Infrastructure AB, Västra Götalandsregionen, Equa Simulation AB, Ansys Sweden AB and Härryda Kommun. This report has been reviewed by Svein Ruud, energy expert at RISE.

An extensive literature study was performed in the beginning of the project, focusing on energy performance of different door solutions, including the importance of different parameters, empirical correlations, and methods used for developing empirical models. The literature study provided an in-depth insight on possible methods for measuring and calculating energy performance of entrance doors. This gave important input to the methodology design and to understand what the challenges are of accurately predicting energy losses through exterior doors.

Design of entrances varies a lot between buildings. However, in general, for entrances with a high number of people passing by, automatic and/or revolving doors are most often installed. Also, when designing a building, a common and highly important question is whether to choose a sliding door or a revolving door. There are no good methods available or rule of thumb to evaluate how this choice will affect the energy losses of the building due to the air exchange when the doors are in use. Since this is an obvious and pressing question to the industry we chose to focus on these two solutions as our main focus for the study.

With regards to automatic sliding doors there were several models available in the literature that predicts the air exchange through an open door. For revolving doors, on the other hand, only a few studies have been found in the literature, and the one made by Schutrum et al. (1961) is the most widely cited. Schutrum et al. (1961) provides a series of design curves that can be used for calculating air-exchange through revolving doors, by conducting laboratory measurements for a revolving door manufactured in 60s. Du et al. (2014) published their experimental results on a reduced-scaled revolving door (1:10) and presented a scaling method. This is the latest study found from database, however Du's study gives unrealistically different predictions comparing to Schutrum's work. Therefore, we decided to conduct our own lab measurements on a revolving door to understand which of these models that is most accurate.

In parallel with the literature study, we started preparing for measurements. According to the project proposal there was an initial plan of conducting field measurements. During the preparation phase for these measurements we visited a number of buildings with one or several combinations of entrance doors in Härryda kommun. Based on these visits we started to evaluate how to use existing theoretical models in order to set up a measuring plan that would contribute most to the knowledge in the field. This analysis gave us a deeper insight to the limitation of available models and knowledge. It became evident that the theoretical models were not yet applicable for evaluating actual air exchange rates accurately enough in real case scenarios.

Therefore, we came to the conclusion that there were basically two separate paths that we could choose between within the project. First path being, that we could still perform field measurements. However, it would have provided only a minor contribution to the general knowledge on the energy performance of door solutions. With this path we would still have followed the initial project plan. The second path was to set up the methodology in a way that would provide lasting knowledge that can be used for future development. This meant a redesign of the project methodology from performing field measurements to conducting lab measurements instead. Since this was the path that we foresaw would give the most value both for industry and researchers, this was the path that we chose. Even though, this meant stepping away from the initial proposed methodology. In summary, no field measurements were performed within the study. The reason for this was that the more thorough analysis of available knowledge revealed a lack of methods for performing such measurements with acceptable accuracy. Therefore, lab tests were introduced instead.

The laboratory measurements were one of the major activities within the project. The reason for performing lab measurements was to provide a better understanding of how the air exchange through a door is affected by different parameters. This information is useful for creating better analytical models. The advantage of laboratory measurement is that it provides stable and well-controlled test conditions, which is important for studying the effects of different parameters and model development. The laboratory tests therefore provides important information to progress on the TRL level, i.e., from lab measurements to more real-world measurements as well as full-scale field measurements in the future.

A reduced scaled revolving door model (1:2) was provided by the project partner Assa Abloy. Laboratory measurements were carried out to identify the influence of important parameters and to measure the air exchange rate through the door. In the performed laboratory measurements, both a heat balance method (based on temperature measurement) and a tracer gas method were used to determine air exchange through the reduced revolving door model at different test conditions. A scaling method was used to scale up the results from the reduced scaled model to a full size door.

A calculation method has also been developed in the project. Energy performance of a revolving door and a sliding door for an office building were estimated by using empirical correlations developed by previous studies, in combination with additional necessary input data/information to those models. Results from different calculation models for sliding doors were also compared with each other. The input data to the empirical models includes climate data, door usage profile for office buildings, and size of the door. This resulted in an Excel-based calculation of a case study of an office building in Gothenburg which can be developed and used for other cases as well in the future. This was a new way of combining and using existing models and knowledge, which makes the theoretical models more available and useful for the industry. The final calculation gives energy performance in kWh for a year and the saving potential of the revolving door compared to sliding doors.

3 Results

3.1 Measurement results from the reduced-scale revolving door model

Air exchange through a revolving door includes two parts: (1) the air leakage through the gaps and seals between the wings and the door housing due to pressure differential, caused by stack and wind effects; and (2) the air displacement due to door rotation (Du et al., 2014).

3.1.1 Air exchange/leakage through the door seals (door closed)

Results from tracer gas measurements showed that the air leakage through the door seal was very small, which was about 1.5 L/s at the temperature difference of 21.6 °C. Test at another temperature difference of 10 °C was also made which gave very similar results. The test cell was taped carefully, and leakage due to un-tightness of the test cell was very small and neglected.

3.1.2 Total air exchange through the revolving door

Various testes were made to determine the air exchange rate through the reduced scale door model under a number of conditions, including different temperature differences, i.e., 10 and 22°C, and different door rotation speeds in terms of rotation per minute (rpm), i.e., 1.6 and 4.6 rpm.

Table 1 shows the results from the temperature measurements, and the air exchange rate through the revolving door was determined from the heat balance equation applied to the air inside the test cell. Air temperature both inside and outside and the electrical power into the heater installed in the test cell were monitored. A small mixing fan (2W) was used during the test. A constant temperature difference between indoor and the lab environment was maintained after reaching steady state. Transmission losses through the test cell envelope was subtracted from the total heat provided to the room. Since the air exchange through the door seal was very small, less than 2 L/s, the total air exchange was used and presented in this report.

In our measurements, transmission loss is much larger than that caused by air exchange through the door, accounting for about 70% of the total heat losses. The overall heat transfer coefficient for the test cell was estimated to be 4.4 W/(m^2 K). In case 1, the transmission loss is 95 W and the air exchange loss is 46 W at the temperature difference of 21.6 °C.

Table 1. Impact of different temperature differences and door rotation speeds on air exchange rate through the revolving door model (from temperature measurements).

Case	**Door rotation speed (rpm)**	**ΔT (°C)**	**Electrical power (W)**	**Estimated air exchange rate through the revolving door (l/s)**
1	0	21.6	134	1.5
2	0	10.3	69	1.8
3	1.6	21.1	1078	39
4	4.6	21.1	2146	81
5	4.6	10.3	886	68

Impacts of the door rotation speed (case 3 and 4 in Table 1) and the temperature difference (case 4 and 5) on the air-exchange rate through the door is shown in Figure 1 and Figure 2, respectively. The door rotation speed showed more significant impact than the temperature difference on the air-exchange rate through the door. As the door rotation speed was increased from 1.6 to 4.6 rpm, the air exchange rate was increased from 40 to 80 L/s; while when the temperature difference was increased from 10 to 20 °C, the air exchange rate was increased from 70 to 80 L/s. It should be noted that the door rotation speed of 1.6 rpm is very low, which is not a representative speed when people pass the door. A higher door speed, e.g., 4-6 rpm, would be more justifiable to study the door rotation speed effect.

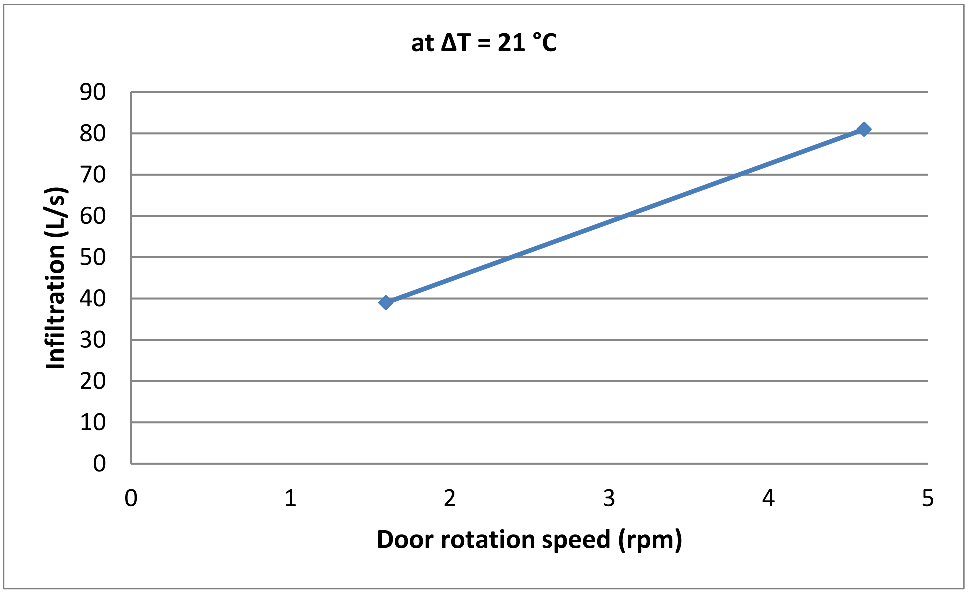

Figure 1. Air exchange rates measured at different door rotation speeds.

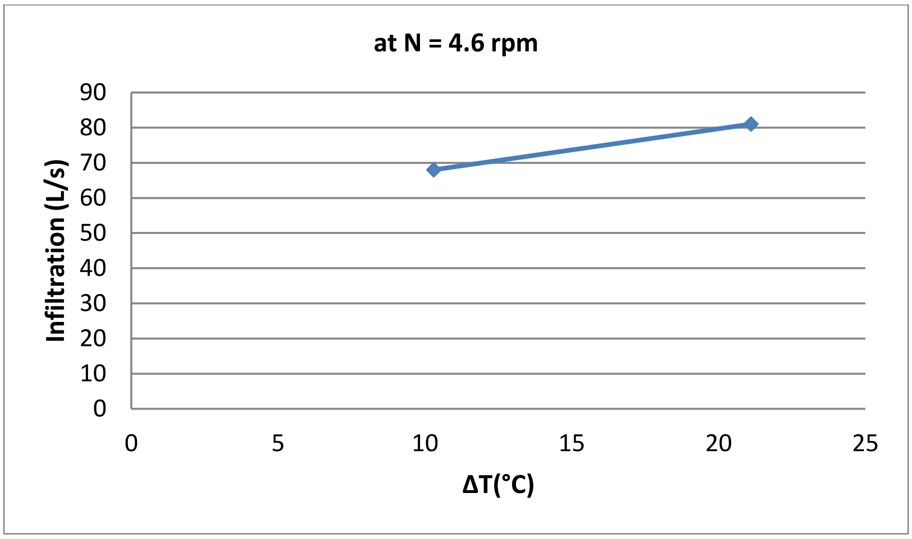

Figure 2. Air exchange rates measured at different temperature differences.

Results presented above is mainly from the temperature measurements, we have also obtained some data from tracer gas measurements. However, these two methods do not seem to give similar results. We believed that the temperature method can give more stable and reliable results than the tracer gas method, because the temperature method can be performed for long time, e.g., up to 10 hours or even longer, while the tracer gas measurement can only be performed for a very short time due to the fast decay of the tracer gas concentration and small margin of CO2 difference between the test room and the lab environment. More results from the trace gas measurement can be found in the thesis work by Gavilan (2017).

3.2 Scaling up the results to a prototype full-size door

In this project, we also tried to scale up the results for a full-size door, and the method we used is the one presented by Du et al. (2014). In Du's study, a very small revolving door (with a scaling factor of 1:10) was used, and the ratio of the door rotation speed between the small door model and full-size door is 100. This means that to achieve the same door rotation speed, the small door model has to rotate 100 times faster than the full-size door. However, how the door movement affect the results is not clear and it has not been addressed in Du's study. And also, Du et al. (2014) considered that the revolving door behaves like a fan and used the fan law to define the airflow factor, which makes the scaling method less appropriate. Since we have not found any other methods for scaling up the results, we applied Du et al. (2014) method in our project though we are aware of the weakness of their method. Results are shown in Table 2. For a full-size door with a low rotation speed (i.e., 1.2 rpm), the air exchange rate at ΔT of 10 and 21°C is 132 and 162 L/s, respectively.

Table 2. Scaling up the results from the reduced scale revolving door model to a full-size door.

	Reduced-scale door model (1:2)		**Prototype full-size door**	
ΔT (°C)	rpm	air exchange rate (L/s)	rpm	air exchange rate (L/s)
21.1	4.6	81	1.2	162
10.3	4.6	68	1.2	132

Further, comparison with the previous study (Schutrum et al., 1961) was also made and the results are shown in Table 3. Due to the differences in the door size and rotation speed, it is hard to compare the results directly but still they are comparable. In our measurements, the highest door rotation speed tested for the door model is 4.6 rpm (corresponding to 1.2 rpm for a full-size door); while the lowest door speed considered in Schutrum's study is 2 rpm. It would be much easier to compare with Schutrum's study if a higher door rotation speed was tested.

Table 3. Comparison of air exchange rate for a full-size door between our study and Schutrum's study.

Prototype full-size revolving door (our study) **D (diameter) = 2.6 m; H (height) = 2.4 m**			**Full-size revolving door (Schutrum et al., 1961)** **D (diameter) = 2 m; H (height)= 2.1 m**		
ΔT (°C)	N (rpm)	Air exchange rate (L/s)	ΔT (°C)	N(rpm)	Air exchange rate (L/s)
21	1.2	162	20	2	195
10	1.2	132	10	2	186

3.3 Energy performance comparison of a revolving door and sliding doors

Energy performance of a revolving door was compared with a sliding door for an office building for a mild climate (e.g., Gothenburg), with the input data of climate profile for a reference year, door usage profile for office buildings, empirical correlations for predicting air exchange rate, and the number of working days for the year of 2016. The comparison results are shown in Table 4 and Figure 3.

For a sliding door, four empirical models were used. The model proposed by Awbi (1996), Warren (1978), De Gids and Phaff (1982), Larsen and Heiselberg (2008) are suitable for predicting flow through an opening for the case of single-sided ventilation where there is only one opening in room/space; while the orifice equation is suitable for the case of cross-ventilation where there are two or more openings on opposite walls. For the revolving door, the correlation curves presented by Schutrum was used. Also, the opening time for how long the door is kept fully opened was determined by using the equation proposed by Yuill et al. (2000) with input of people flow per hour. According to Table 4, the average energy losses through a sliding door predicted by the first three models (for single-sided ventilation is) is 8300 kWh, while it is increased to the 28500 kWh for the scenario of cross-ventilation. This means that energy saving by using a revolving door is between 60%-90%, depending on the flow condition (single- or crossed ventilation). This is theoretical calculation and is made for extreme condition. In real cases, the flow condition is more likely in between the single- and crossed-ventilation.

For the sliding door, the model of Awbi (1996), De Gids and Phaff (1982) and Larsen and Heiselberg (2008) for single-sided ventilation gives similar results, see Table 4 and Figure 3. Since Warren's model (1978) treats the combined effect of wind and temperature by taking the maximum flow caused by each factor, i.e., wind and buoyancy force, $Q = \max(\frac{1}{3} * Cd * A * \sqrt{\frac{\Delta T * g * H}{T_{ave}}}, 0.025AU)$, the results will be the same to the Awbi's model (1996) if the stack force takes over wind effect, which is the case in our study. The equation for predicting flow driven by buoyancy force is the same in the Awbi (1996) and Warren's model (2008), and that is why the results by Warren's model (2008) are omitted in Table 4 and Figure 3.

Table 4. Yearly energy performance of a sliding door and a revolving door based on empirical predictions.

	Sliding door				**Revolving door**
Energy losses kWh/year	Awbi (1996)	De Gids and Phaff (1982)	Larsen and Heiselberg (2008)	Orifice equation	Schutrum et al(1961)
	9000	7900	8000	28500	3400

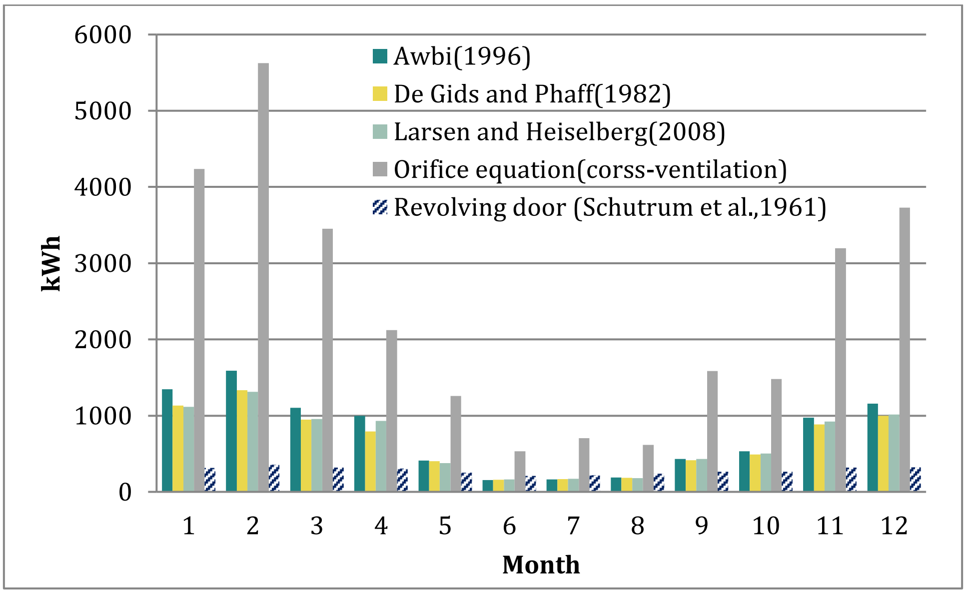

Figure 3. Energy performance of a sliding door and revolving door based on empirical predictions.

4 Discussion

The air exchange rate through a revolving door depends on the pressure differential due to wind and stack effect, door rotation speed, door area, door usage and the closeness of fit. Regarding air leakage through door seal (when the door is closed), temperature (stack effect) shows a very small influence on the door leakage, about 2 L/s at ΔT = 10 and 20°C, based on our measurements for the reduced scaled door model. Air leakage for a full-size door can be much larger in real life, especially for the case of a high-rise building with an open staircase to the top floor where the buoyance force is strong. The air-exchange rate due to door movement and related energy losses is much larger than that caused by air leakage through a door, and the door rotation speed has been shown to be more important than the temperature in our study.

There are several models, i.e., Schutrum et al (1961), Zmeureanu et al (2001) and Du et al (2014) available for predicting air exchange through a revolving door, and Schutrum's model is mostly cited and used. Although Du et al (2014)' study is the latest published study on revolving door; it gives much lower air exchange rate compared to Schutrum's study (1961). Du et al (2014) used a small door model (1:10) in their measurement and the door rotation speed was 100 rpm (corresponding to 10 rpm for a full-size door); the effect of door movement on temperature mixing close to the entrance cannot be ignored. The door used in Schutrum's study is from 1960s. Information and knowledge on the performance of modern doors are lacking. Further studies are needed to update the existing information and data for revolving door.

Wind is an important factor affecting the door leakage; the effect has not been identified in this project and it has been only studied at a small temperature difference in previous studies. Few tests were performed in this project to study the wind effect; however, we got opposite results of what we had expected. To understand how wind affects the air exchange for a revolving door, more tests for a full-size door, both closed and in use, are needed in the future. This could be a sperate research project due to complexity of wind effect.

The revolving door shows a great saving potential for space heating compared to a sliding door, and it saves about 5000 – 26000 kWh energy for one year for this specific case, corresponding to 60-90% energy reduction of energy losses through the door. Saving for the scenario of cross-ventilation is significant, however it seldom occurs. The saving potential also depends on the door area, sealing, usage and climate.

A revolving door can be considered as a more energy efficient entrance solution than a sliding door and swinging door, and energy saving in kWh becomes even more important when it comes to the low energy buildings. Therefore, further studies are needed to provide better models for predicting the air-exchange rate through opening for modern revolving doors.

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Appendics

Literature study

Due to limited space of the report, only the most important findings and studies are presented here. Air exchange through automatic doors depends on various parameters such as size of doors, frequency of door usage, building geographical location, wind velocity, height of building and indoor-outdoor difference in interrelated properties of air, i.e., pressure, temperature and humidity (Mshajian et al., 2015).

A general form for estimating air flow through automatic doors can be expressed as: $Q = C_A A R_P$, where C_A is air flow coefficient, introduced by Yuill (2000), and R_P is pressure factor. Yuill established a function of the airflow coefficient and the number of people using a door each hour, based on a large number of laboratory tests and field measurements. By knowing the people flow per hour and pressure difference across the entrance door, air leakage through the door can then be determined. It should be noticed that the laboratory measurements in Yuill' study (2000) are based on the blower door method, assuming the flow is unidirectional. However, when the flow is mainly driven by buoyance force, flow across the opening is bidirectional. Few studies are available for predicting flow rate through a large opening such as doors and windows, and the stack effect, wind effect including wind speed and direction has been addressed to different extents. Details of the empirical correlations for openings will be described in the air exchange calculation part.

For revolving doors, the studies found from the published literature are Schutrum et al (1961), Zmeureanu et al (2001), Allgayer (2007) and Du et al (2014). Schutrum (1961) preformed laboratory measurements for a full size door and developed empirical models for predicting air exchange through a revolving door. Zmeureanu et al (2001) investigated the air leakage characteristics of revolving doors of a large institutional building at different pressure differences; two wing and four-wing revolving door with worn and new seals were studied and curves of leakage varying with the pressure difference were presented. Allagyer (2007) conducted an in depth study of the air and heat transfer mechanism related to the door movement, by using a reduced scale door model (1:3) and using water as working medium. He concluded that although studies on air exchange through revolving doors have been done there is much about the physics of the air transfer that is unknown. Du et al (2014) carried out laboratory measurements for a reduced scale door model (1:10) and presented a method for scaling up the results. Among the above mentioned studies, the Schutrum's study (1961) is most widely used and referenced. It includes the correlation of air leakage through door seals as a function of pressure difference, and air exchange due to door movement as a function of door rotation speed and temperature difference between indoor and outdoor. Both the reference doors used by Schutrum et al., (1961) and Zmeureanu et al., (2001) are based on doors manufactured in the 60s-70s, information for the performance of a modern door is still lacking.

Laboratory measurement

Both the temperature measurements and tracer gas measurements were performed in this project to determine air exchange through the revolving door model. More details of these two methods and measurement data, i.e., description of the test room, temperature sensors (number and placement), tracer gas measurement and air exchange calculation can be found in the thesis work by Gavilan (2017).

Scaling method

To scale up the measurement data from a reduced-scale model to a prototype full-size door, these two models must be similar in terms of linear dimensions, shape and airflow pattern. Only when the independent dimension parameters are the same in scaled-model and prototype, correct scaling can be made. This project uses the same method as Du applied in their study (Du et al., 2014) to scale up the air exchange rate due to door movement to a full size door. The method is described below:

Geometric scale ratio $\lambda_{L:}$

$\lambda_L = D_p/D_m = 2$

where D is the diameter of the revolving door; the subscript "p" represents the prototype, "m" represents the reduced scale model. D_m = 1.3m, the door height H_m=1.2m.

Reynolds number (Re)

$Re = (\omega D/\nu)_p = (\omega D/\nu)_m$

Where ω is angular speed, in rad; ν is the kinematic viscosity of air. Air is used as the fluid in model and prototype, the angular velocity factor λ_ω can be written as follows:

$\lambda_\omega= \omega_P/\omega_m= (D_m/D_P)^2=1/4$

Based on the fan law and together with the condition of $D_m \approx H_m$, the airflow fator λv can be written as:

$\lambda v = V_P/V_m= (\omega_p D_p^3)/(\omega_m D_m^3)= 1/4 \times (2)^3=2$

where V is the volume flow rate in L/s.

Empirical predictions of energy performance for a sliding door and a revolving door

Calculation method

Energy performance of a revolving door and sliding door for an office building has been compared by making excel-calculation. The calculation involves empirical models for predicting air exchange through the entrance doors, and input of weather data (hourly and monthly averaged temperature, wind speed and wind direction for a reference year), people flow/hour, area of the opening and location of the entrance. The revolving door chosen in the calculation has a height of 2.4 m and diameter of 2.6 m, giving an opening area of 2 x 3.12 m^2. It is a good representation for the largest population of the revolving doors, according to the door manufacture, Assa Abloy. For the sliding door, the gross height is 2.1 m and gross length is 1.5, giving an opening area of 3.15 m^2, assuming to have the similar passenger capacity to the revolving door. The basic data for the reference door and operation time for the case study are shown in Table 5.

Table 5. Basic data for the reference doors for the case study of an office building.

	Revolving door (4-wings)	**Sliding door**
Dimension	D=2.6 m H=2.4 m	L = 1.5 m H = 2.1 m
Door rotation speed	3.6 rpm	/
Operation time	07:00-19:00 (working days)	07:00-19:00 (working days)

For a revolving door, air exchange includes two parts: one is through the door seal and the other one is due to door movement. Both two are calculated based on empirical correlations. While for a sliding door, only the air exchange flow through the door opening is calculated and air exchange through the door seal is not included in the total air exchange rate, due to the lack of information of test data or correlations. However, flow rate through an opening part is the dominant part for energy losses. Including or excluding the losses through the door seal will not make a big difference for the final results.

After determining the air exchange rate through the opening, air exchange through the door for one hour/day/month/year can be estimated via multiplying the air exchange flow rate by the time that the door is kept open.

The input data and the equations used for the calculation are presented in the following part.

Climate data

The climate data for Gothenburg is obtained from the IDA-ICE program; it contains both the monthly averaged and hourly averaged data. Calculations were made for both monthly averaged and hourly averaged data, and it shows a small difference on the yearly energy performance and the monthly averaged data were preferred. The parameters relevant to the energy performance calculation are shown in Table 6.

Table 6. Weather data for Gothenburg for a reference year (Source: IDA-ICE program).

Gothenburg Säve-1977	**Dry-bulb temperature, Deg-C**	**Direction of wind, Deg**	**Speed of meteorological wind, m/s**
January	-1.9	118.1	3.3
February	-2.9	99.3	3.3
March	2.2	139.2	3.5
April	3.4	180	4.9
May	11.2	143.7	3.3

June	15.7	160.5	3.8
July	15.7	177	3.8
August	15.5	140.8	2.9
September	11.2	180	4.6
October	9.4	172.3	4.2
November	4.2	145	5.1
December	1.6	135.4	3.8

Pressure differential

Stack pressure

Stack pressure is generated by the difference in temperature (density difference) between indoor and outside, and it can be calculated by the equation (Hagentoft, 2001) shown below:

$$\Delta P_s = h * 3456 * (\frac{1}{T_e} - \frac{1}{T_i}) \tag{1}$$

Where *h* is the vertical distance from the neutral height to the bottom of an opening; T_e and T_i is the temperature for outdoor and indoor in degrees of Kelvin. The neutral height can be assumed at the middle height of an opening.

Wind pressure (pressure coefficient)

$$P_w = C_P \frac{\rho {U_z}^2}{2} \tag{2}$$

Where C_p is a wind pressure coefficient, the value of C_p is an empirically derived parameter, largely based on the results of wind tunnel measurements. The C_p value is determined from Figure 4 in this project. A negative value of C_p means that there is a wind suction acting on the envelope. U_z is the wind velocity at a specific height, determined by equation (3).

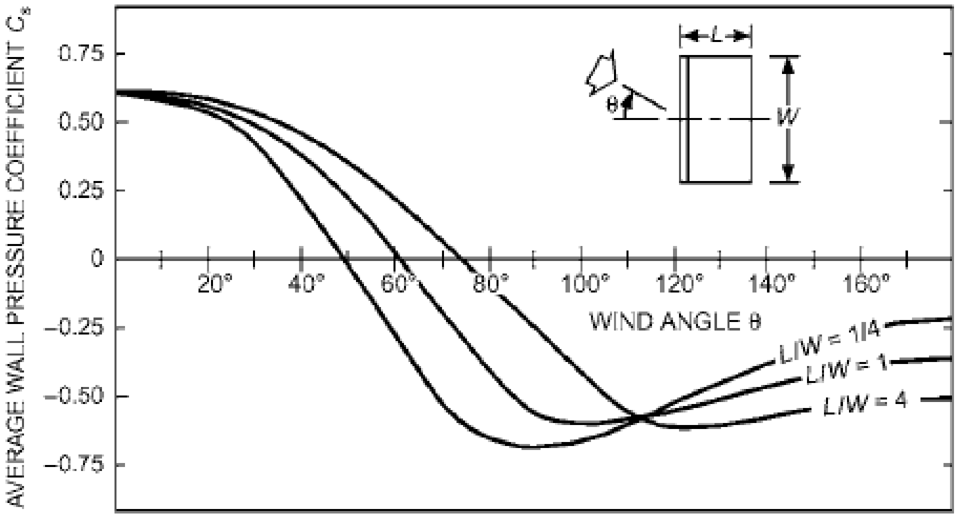

Figure 4. Surface-averaged wall pressure coefficients for tall buildings (Akins et al. 1979) (picture source: ASHRAE handbook).

$$U_z = U_m * k * z^a \quad (3)$$

Where U_m is the wind speed at a weather station at a height of 10 m, z is the building height, k and a are constants. The value of k and a can be found from Table 7.

Table 7. Values for the constant of *k* and *a* in equation (3) (Hagentoft, 2001).

Terrain coefficient	***k***	***A***
Open. flat country	0.68	0.17
Country with scattered wind breaks	0.52	0.20
Urban	0.35	0.25
City	0.21	0.33

Prediction of airflow through a sliding door

A sliding door is actually an open door when it operates. Therefore predictions for a sliding door are focused on a large opening, i.e., door and window.

The equations used for predicting flow through an opening in this project are:

$$Q = \frac{1}{3} * Cd * A * \sqrt{\frac{\Delta T * g * H}{T_{ave}}} \text{ (Awbi, 1996)} \quad (4)$$

$$Q = \max(\frac{1}{3} * Cd * A * \sqrt{\frac{\Delta T * g * H}{T_{ave}}}, 0.025AU) \text{ (Warren, 1978)} \quad (5)$$

$$Q = 0{,}5A\sqrt{0.001U^2 + 0.0035H\Delta T + 0.01} \text{ (De Gids and Phaff, 1982)} \quad (6)$$

$$Q = A_{eff}\sqrt{C_1 f(\beta)^2 |C_P| U^2 + C_2 H\Delta T + C_3 \frac{\Delta C_{p,opening}\Delta T}{U^2}} \text{ (Larsen and Heiselberg, 2008)} \quad (7)$$

$$Q = 0.6 * A * \sqrt{(\frac{\Delta P}{\rho})} \text{ (orifice equation)} \quad (8)$$

Where C_d is the discharge coefficient, and the value of 0.61 is commonly used for predicting flow through a large opening and is valid for a wide range of Reynolds number; A is the opening area; ΔT is the temperature difference, H is the door height, T_{ave} is the average temperature in kelvin; U is the average wind speed through the opening.

In equation (7), where C_1, C_2 and C_3 are constants and values are depending on wind direction and incidence angle, *f(β)* represents wind incidence angel; C_p is the pressure coefficient; U is the wind speed; ΔC_p is the pressure coefficient at the opening and is as a function of the incidence angel of the wind. More details of equation (7) can be found in Larsen and Heiselberg's study. In equation (8), Δp is the pressure differential across the opening.

Equations (4)-(7) are used for the case of single-sided ventilation, while equation (8) assumes the flow in space/room volume is cross-ventilation. Equation (8) gives much larger prediction of the flow through an opening than Equations (4)-(7).

All the above listed equations can be used for estimating flow through an opening; the flow can be driven by buoyancy force, or by wind, or by the combined effect of both two and that is usually the case in real life. Equation (4) only considers the stack effect, equation (5)-(6) considers both the temperature effect and wind speed; equation (7) is the most sophisticated equation so far for predicting flow through an opening, that includes temperature, wind speed, wind direction and incidence angle.

Prediction of airflow through a revolving door

Air exchange through a revolving door includes two parts: leakage through door seals and air exchange due to door movement. Measurements from previous study have shown that air leakage through door seals does not change significantly when door rotates. The correlation developed by

Schutrum et al. (1961) was used to calculate air exchange through a revolving door, considering the temperature effect and door rotation speed. Although Du's model (2014) also includes these two parameters, it is less accurate than the Schutrum's model due to the mixing effect caused by door movement on temperature.

Infiltration through door seals

Schutrum et al. (1961) measured leakage through door seals at different pressure differences (0-250 Pa) and presented measurement curves for both new and worn doors with two- and four-wings. Results for a new door with four-wings for those measurements are shown in Figure 5. Since the reference door used in Schutrum's study was made from 1960s, the data can not be really used to present the performance of a modern door. A new curve of infiltration varying with pressure difference needs to be made or re-constructed for modern doors. However, there is very limited data or published studies that can be found from literature. Karlsson (2013) referred a set of test data made by a door manufacture (Carne door) in his work; it states that at 75Pa pressure difference, the infiltration rate through door seals is 20 L/s. This data can be considered as good indication for modern doors. Both two doors (tested by the manufacture and studied by Schutrum) have identical dimensions.

According to the measurement data reported by Schutrum (Figure 5), the infiltration rate past door seal is about 40 L/s at the pressure difference of 75Pa, and the flow is almost doubled compared to the data for a modern door at the same pressure. By combining the infiltration curve presented in Schutrum's study and the single test point made by the door manufacture, the performance curve for a modern door was estimated and constructed. Figure 6 shows the estimated infiltration curve for a pressure difference up to 100 Pa. The best curve fit equation shown in Figure 6 is used in our infiltration calculation.

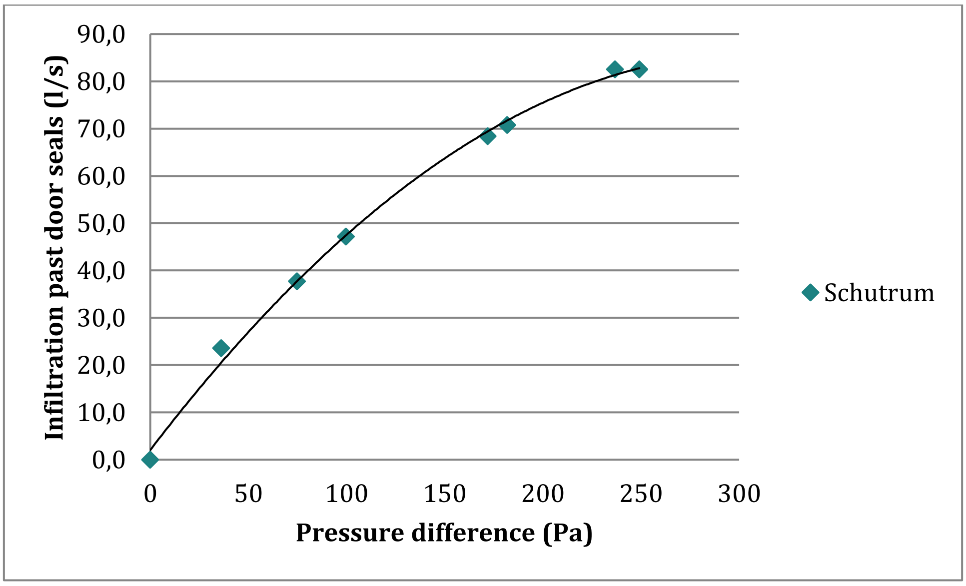

Figure 5. Infiltration through door seals from Schutrum's study (1961).

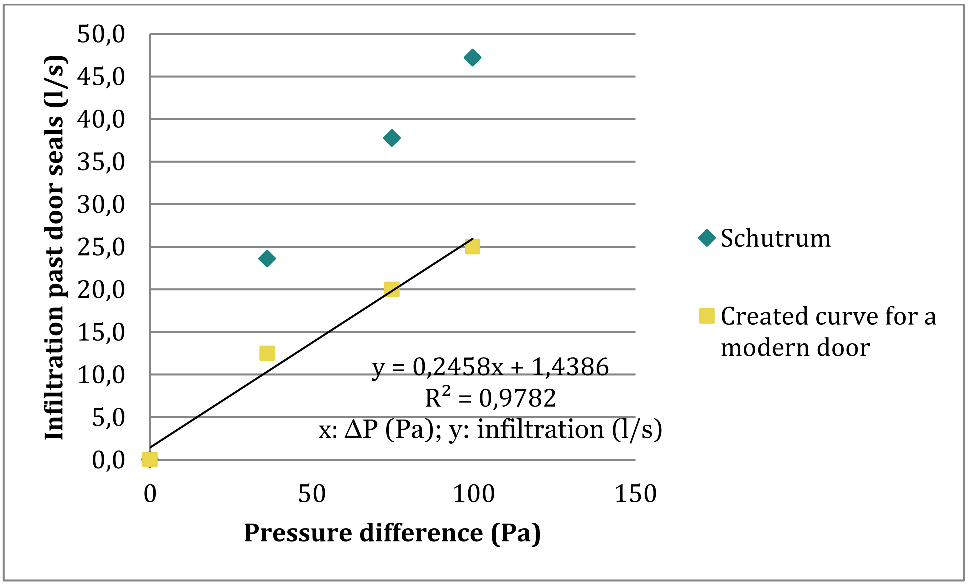

Figure 6. Estimated performance curve of a modern door.

Air exchange due to door movement

Schutrum et al (1961) presented a series of curves of air exchange due to door movement at different door rotation speeds and temperature differences between indoor and outdoor; see Figure 7. For example, at the temperature difference of 20 °C and door rotation speed of 4 rpm, air exchange due to door movement is approximately 250 L/s. To estimate air exchange due to door movement at specific door rotation speed and temperature difference, a regression equation was generated based on a set of data points extracted from Schutrum's curve (Figure 7). The data range used for regression analysis is for the door rotation speed 3-5 rpm and the temperature difference 5-20 °C, which is relevant to this project.

The regression equation includes the variable of the temperature difference and door rotation speed, has a form expressed as below

$$Q_{exchange\ due\ to\ door\ movement} = 126{,}43 + 5{,}01 * \Delta T + 7{,}226 * N \qquad (9)$$

It should be noted wind is not included in this equation. Schutrum et al (1961) concluded that the amount of air exchange in revolving doors depends upon the door speed and the temperature differential and somewhat upon the wind and indoor air velocities.

The total air exchange through a revolving door is the sum of leakage past door seal and air exchange due to door movement.

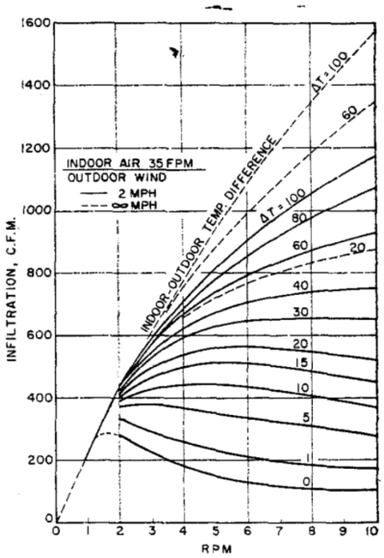

Figure 7. Air exchange due to door movement at different door rotaion speed and temperature difference between indoor and outdoor (Schutrum et al., 1961).

Door opening time for a sliding door

Neither a sliding door nor a revolving door operates all the time. The final air exchange through a door also depends on the door opening time (for a sliding door) or door usage (for a revolving door), i.e., how long time the door is kept fully opened or how often the door is used when there is a certain number of people passing through the door.

For a sliding door, Yuill et al. (2000) performed a large number of field measurements and developed an correlation of fractional open time (T_h) as a function of people flow per hour (P_h), expressed in equation (10). Profile of people flow per hour for office buildings will be presented later.

$$T_h = 1 - \exp(-0{,}002233 * P_h) \tag{10}$$

Door usage for a revolving door

Estimating the fraction of door usage (0-1) for a revolving door is a complex probability problem. It depends not only on people flow and door capacity but also sensors and the shape of the flow (Karlsson 2013). A simplified model used in Karlsson's study (2013) was adopted in this project to estimate the degree of door usage, see below:

$$Door\ capacity = N_c * N_{PPC} * RPM * 60 \tag{11}$$

$$R_{usage} = \frac{F_p}{door\ capacity} \tag{12}$$

where N_c is the number of segments; N_{ppc} is the number of people per segment; and F_p is the people flow (the number of people per hour). For a small revolving door up to 3 meters in diameter it is common that every segment/compartment can hold one person (Karlsson, 2013)

For example, for a small 4 wings revolving door (diameter up to 3m), $N_c = 4$, $N_{ppc} = 1$, revolving at a speed of 3,6 rpm has a capacity of 864 people per hour.

People flow per hour (door usage schedules)

Karlsson (2013) evaluated the energy performance of various entrances types on an office building based on IDA simulations, and created an office like door-usage schedule which is based on Swedish office times and office behavior. The same door-usage profile was adopted in the air exchange calculation; see Figure 8.

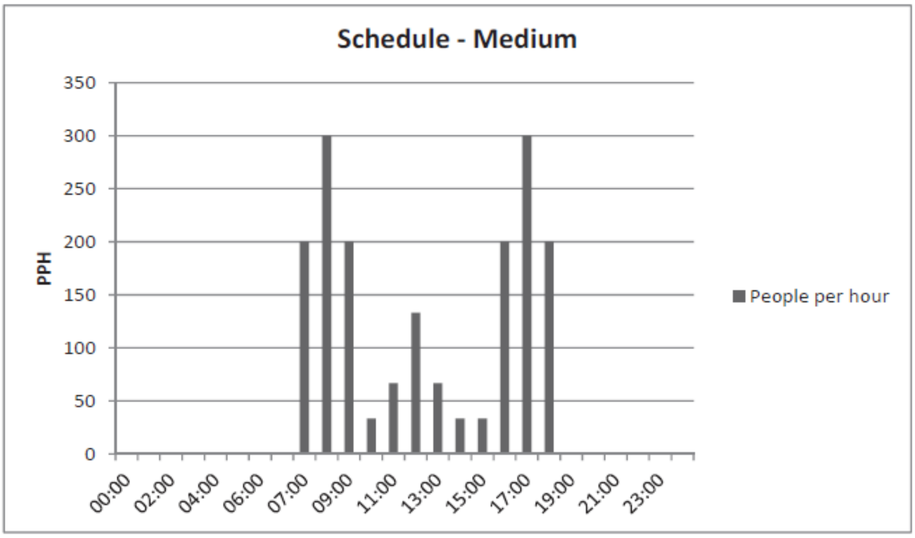

Figure 8. Door-usage schedule for office buildings (picture source: Karlsson, 2013).

Runt 35 procent av all energi i Sverige används i bebyggelsen. I forskningsprogrammet E2B2 arbetar forskare och samhällsaktörer tillsammans för att ta fram kunskap och metoder för att effektivisera energianvändningen och utveckla byggandet och boendet i samhället. I den här rapporten kan du läsa om ett av projekten som ingår i programmet.

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