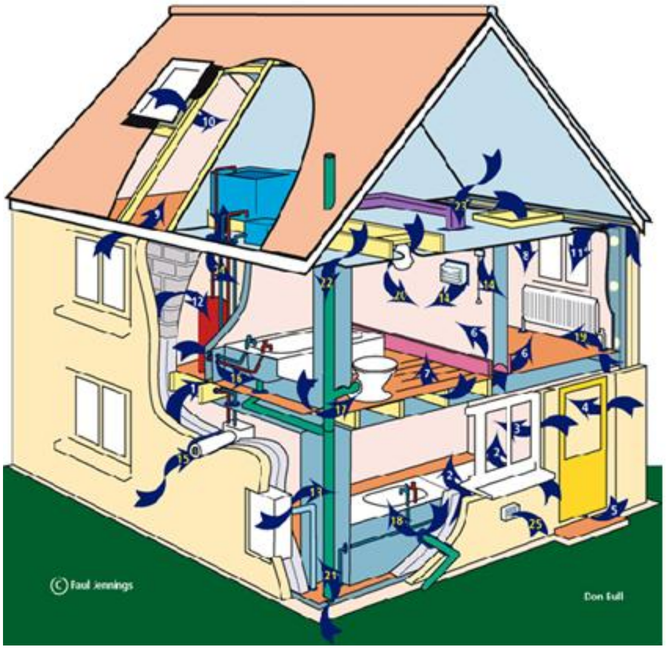

Classification of buildings with regard to airtightness

Master of Science Thesis in Structural Engineering and Building Performance Design

YANKE ZOU

Department of Civil and Environmental Engineering
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CHALMERS UNIVERSITY OF TECHNOLOGY
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Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover Page:
The image shows some typical air leakage paths existing in a single family detached house

Abstract

With the increasing demand on building energy efficiency and sustainability, airtightness plays a vital role when improving the building energy performance and indoor air quality. However, when attempting to calculate the heat losses by air infiltration, information on the airtightness of the building is scarce. A standard air permeability value of 0.8 l/s, m^2 at 50 Pa pressure difference is often used for conventional buildings and a value of 0.3 l/s, m^2 at 50 Pa pressure difference is used for passive houses in Sweden. However, the real value varies from less than 0.1 l/s, m^2 to more than thirty times the standard value. As a result, air infiltration heat loss calculations based on the standard value are not reliable. Therefore, a more accurate air leakage value has to be determined in order to yield more representative results.

In this study, various factors related to airtightness were identified through three steps consisting of literature review, questionnaires and interviews. Based on the findings, a database was established to classify the buildings with respect to airtightness and thus made it possible to predict the airtightness of Swedish single family houses.

A total of 374 buildings were investigated in order to determine the most influential factors affecting the airtightness. In addition, 185 airtightness measurements data on Swedish single family houses were subjected to statistical analyses using the F-test and the Student’s T-test. The statistical results showed that the building airtightness was significantly affected by these factors, for instance, energy efficiency focus, use of an installation layer, year of construction and number of storey etc. By contrast, predominant wall materials, foundation type only had small impact, which were not statistically determined.

Furthermore, three predictions of q_{50} value on Swedish single family houses were conducted. According to the predicted results, the first two examples showed good agreements with real measurement data. The difference in percentage is 0.7% and 16% respectively. However, due to the lack of information on the key airtightness related factors, a remarkable deviation occurred between the predicted value and the average value of real measurement data in example three. The difference in percentage is 57%. Therefore, more measurement data and information needs to be fed into the database in order to refine the prediction.

Key words: energy efficiency, airtightness, air infiltration, database, Swedish single family house, classification, prediction

Contents

Preface

The aim of this thesis is to classify the buildings with respect to airtightness and the classification will be further used for predicting the air permeability value of a Swedish single family house. The results from classifications and predictions will somehow unveil how the building airtightness varies in relation to the different building characteristics and provide a more reliable air permeability value for heat losses calculation due to air infiltration.

This thesis was carried out at department of Civil and Environmental Engineering, Chalmers University of Technology under supervision of assistant professor Paula Wahlgren, to whom I would like to express my sincere gratitude. With her profound scientific expertise, she has guided and inspirited me to overcome the difficulties throughout my thesis study.

I also would like to thank the airtightness test engineers who had involved in my project and answered my questionnaires, which undoubtedly help me to structure the database. In addition, I especially appreciate Owe Svensson and Hans Wetterlund for their generous supports and informative consultations during the interviews and other means of communication. I also appreciate Professor Johan Claesson for his kind help on the statistical analysis part.

Finally, I wish to express my gratitude to my parents, for their endless love and encouragement to me. Thanks also to my friends and classmates during the two years of education at Chalmers.

Yanke Zou

邹堰柯

Göteborg, Sweden, July, 2010

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Notations

ACH50 or n_{50} [1/h]	Air infiltration rate at 50 Pa pressure difference
$A_{air\ gap}$ [m^2]	Area of the air gap
A_E [m^2]	Area of the buildings envelope
A_{inf} [m^2]	Infiltrated area by air
L [m]	Thickness of the building components
NL [-]	Normalized leakage area
Ra [m^3]	Air flow rate
Sg [Pa • s/m3]	Air gap resistance
S_e [Pa • (m^3/s)^2]	Air flow resistance
V [m^3]	Volume of building
b [m]	Height of air gap
d [m]	Thickness of wall, floor and ceiling
k [m^2]	Permeability
q_{50} [l/s,m^2]	Air permeability at 50 Pa pressure difference
μ [kg/ms]	Dynamic and kinematic viscosity of air
ΔP [Pa]	Pressure difference over the building envelope
ρ_a [kg/m^3]	Density of air

1 Introduction

1.1 Background

With the increasing demand of slowing down the change of global warming and reducing the energy consumption, sustainable design covers all range of engineering fields. For construction industry, the healthy, sustainable and energy efficient building is required to be built in order to make contribution to the sustainability.

Recent research studies by, for example, Emmerich et al. (2005), Byggforsk (2003), Emmerich et al. (1998) show that substantial heat losses are caused by building infiltrations. In addition, Sandberg et al. (2007a) also conducted some investigations and declared that heat losses due to building infiltration can be larger than those caused by transmission through the building envelope. As a consequence, building thermal discomfort will occur and people normally compensate this by increasing the indoor temperature. Unfortunately, this would inevitably lead to more energy consumption. Furthermore, poor airtightness also introduces some other problems, for instance, disturbance of HVAC[1] system. In this case, the system cannot function properly since the pressure difference over the building envelope is jeopardized by the air leakage. Unconditioned and uncontrolled outdoor air intake will increase the risk of spreading of gas and outdoor air pollutants into the building. Moreover, moisture convention caused by leakage through the building envelope can also lead to severe moisture problems especially when the building is overpressure. The warm air can escape from the building envelope and meet with cold outer layers and condensation can occur. Mold and rot can grow in this area eventually. In addition, the uninsulated attic space is also a problematic area, mould and rot growth can be found as well due to the moisture transportation from inside building envelope. This has been shown by Hagentoft et al. (2008) and Samuelsson (1995).

Therefore, airtightness is one of the most important aspects which have to be carefully considered both in the design and construction phase. As a matter of fact, in Sweden, there are now specific airtightness requirements for passive houses. However, for conventional houses the previous airtightness requirements in the Swedish building code (BBR) have been removed. The existing information on airtightness for energy consumption calculation is insufficient and scarce. This is quite strange when comparing with other neighbouring countries, for instance Denmark and Norway and their demanding on airtightness is increasing. When information about the building airtightness is needed, there are normally three options available. Firstly, measure the airtightness directly. However, this is often not economical and practical. Secondly, make a rough estimate of the building airtightness by using standard air permeability of 0.8 l/s, m^2 at 50 Pa from former BBR[2] code. However, the actual value sometimes ranges from less than 0.1 l/s, m^2 to thirty times larger than standard one. As a consequence, calculations for energy declaration based on this assumption are not quite reliable. In order to avoid these mistakes occurring, a more feasible and reasonable way of using airtightness data is to establish an intelligent database, which

[1] Heating, ventilation and air conditioning

[2] Swedish Building Regulation

covers wide range of building characteristics. By having this database, it is possible to obtain a more accurate air permeability value rather than standard one.

1.2 Purpose

The aim of this project is to investigate what kind of airtightness related factors have to be taken into account in order to structure an airtightness database for buildings. By having this database, it is possible to classify the buildings with regard to the airtightness. The project will also provide explicit perspectives on the airtightness situation in Sweden and other countries and make it possible to show the differences between them.

In addition, a basic statistical model will be established in order to predict the air permeability of Swedish single family house. By having this prediction, heat loss calculation by air infiltration for this type of building will become more reliable when considering the airtightness issue.

1.3 Objective and Method

The method of processing this project consists of following steps. Firstly, comprehensive literature studies will be executed to discover some available airtightness classifications and to identify the airtightness related factors. Secondly, in order to acquire more knowledge on the airtightness related factors, communication by means of interviews and questionnaires with airtightness test engineers will be conducted. In addition, participation of the blower door test is needed since this project also has a practical focus on how to achieve an airtight building in reality. Lastly, some available airtightness measurement data from test authority, for instance, SP [3] and WSP[4] will be provided by the test engineers. By feeding these data into the database, it is feasible to classify the buildings with respect to airtighness and to predict the air permeability value of Swedish single family houses.

[3] SP Technical Research Institute of Sweden

[4] WSP Group- Engineering Consultants

2 Available airtightness data and classification

2.1 Airtightness measurement data from Australia

As known to most of us, Australia has mild and warn climate due to its geographic location. The annual temperature is on average higher than some other countries situated to the north of the equator. Therefore, air infiltration does not significantly influence the heating demand. The local governments have not put much effort on improving the building airtightness during the last several decades. As a result, old houses were suffering from large amount of air leakage. However, the previous situation had been changed mainly attributing to the world energy crisis and the green house effect. After 1980s, in southern part of Australia, the local government built some new houses so-called ‘solar village’ with high demand on airtightness. In addition, all of these houses are typical single detached houses. Some classifications and house information is shown in Table 2.1 and Figure 2.1 respectively.

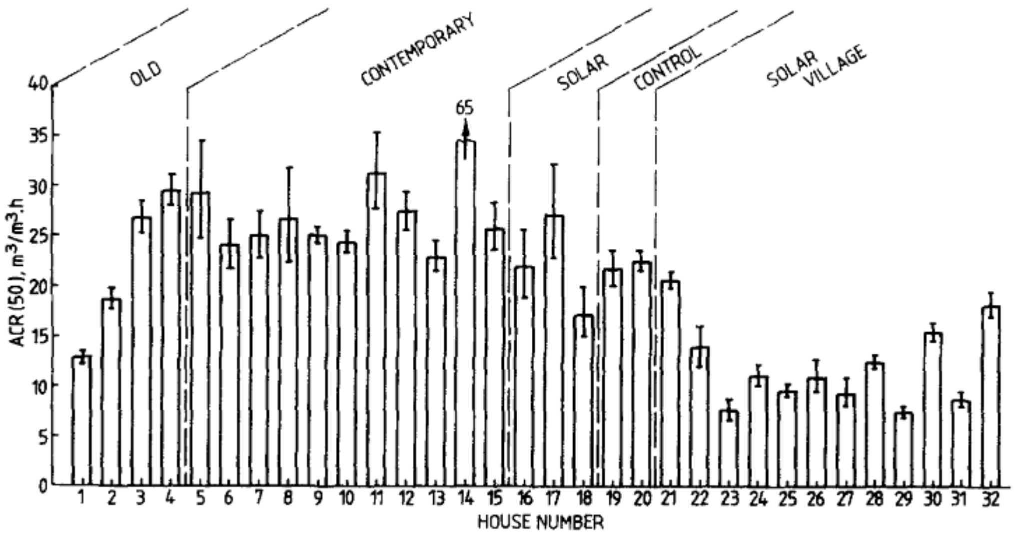


Figure 2.1 Air tightness measurement data (Biggs et al. 1986)

As it can be seen in Figure 2.1, the average ACH (50) value is approximately 26.3 h^{-1} for contemporary house and 12.2 h^{-1} for solar village house. According to K. L. Biggs (1986), house 14 is the leakiest one mainly due to its unusual and leaky form of fixed ventilation. The fixed ventilation openings take the form of wide, unobstructed slots above each window. Measurements indicated that the air leakage due to this was greater than the total leakage of any house in the study. In addition, the ceiling construction was also very leaky and it consists of plasterboard sheet fixed to the battens between exposed ceiling beams. The length of cracks between ceiling and the roof space arising from this form of construction has almost the same order as the sum of all other visible crack in the building envelope (Biggs et al. 1986).

Table 2.1 Airtightness measurement data (Biggs et al. 1986)

House No.	Type of house	No. of vents	Floor area (m^2)	Surface area (m^2)*	Volume (m^3)	$Q(50)$ ($m^3 h^{-1}$)	Exponent, n
1	Cavity brick, timber floor, insulated ceiling	12	136	469	399	5170	0.61
2	Cavity brick, timber floor	12	116	381	331	6230	0.65
3	Timber frame clad with 'weatherboards', timber floor	12	83	273	221	5940	0.64
4	Brick veneer, timber floor	14	113	345	292	8640	0.62
5	Brick veneer, timber floor	12	105	319	252	7390	0.61
6	Brick veneer, timber floor	12	105	319	252	6080	0.59
7	Brick veneer, timber floor	12	105	319	252	6320	0.59
8	Brick veneer, timber floor	12	105	319	252	6760	0.62
9	Brick veneer, timber floor (split level)	12	135	374	315	7920	0.58
10	Brick veneer, timber floor	12	112	338	270	6600	0.58
11	Brick veneer, timber floor	14	135	396	324	10,200	0.63
12	Brick veneer, timber floor	12	107	325	253	6990	0.60
13	Brick veneer, timber floor	11	110	226	264	6080	0.61
14	Cavity concrete masonry, concrete floor, flat roof, ventilation slots above windows	†	157	297	360	23,300	0.76
15	Cavity brick, concrete floor, flat roof, ventilation slots above windows	†	144	311	329	8520	0.57
16	Double brick (urea formaldehyde in cavity), concrete floor, flat roof, ventilation slots above windows	†	144	253	329	7270	0.63
17	Double brick (urea formaldehyde in cavity), concrete floor, fixed ventilation via unfilled mortar joints, doors and windows weatherstripped	12	95	190	217	5920	0.62
18	Brick veneer with glass fibre insulation in walls and over ceiling, concrete floor	0	105	209	252	4390	0.63
19	Timber frame with fibre-cement sheeting, particle-board floor	18	95	295	228	5000	0.59
20	Brick veneer, particleboard floor	4	72	266	172	3900	0.57
21	Double brick (urea formaldehyde in cavity), particle-board floor	2	72	251	163	3380	0.57
22	Brick veneer, concrete floor	1	72	179	172	2430	0.57
23	Timber frame with fibre-cement sheeting, concrete floor	1	95	295	228	1800	0.57
24	Timber frame with fibre-cement sheeting, concrete floor	3	84	202	226	2550	0.63
25	Timber frame with fibre-cement sheeting, concrete floor	1	84	202	226	2190	0.59
26	Double brick (urea formaldehyde in cavity), concrete floor	3	92	214	251	2800	0.68
27	Double brick (urea formaldehyde in cavity), concrete floor	2	92	214	251	2370	0.67
28	Timber frame with fibre-cement sheeting, concrete floor	3	102	282	269	3380	0.55
29	Mixed brick veneer and timber with fibre-cement sheeting, concrete floor	1	89	228	258	1930	0.75
30	Timber frame with fibre-cement sheeting, concrete floor	2	90	225	239	3710	0.59
31	Mixed brick veneer and timber frame with fibre-cement sheeting, concrete floor	1	82	172	196	1710	0.67
32	Double brick (urea formaldehyde in cavity), particle-board floor (split level)	3	97	341	284	5180	0.60
33	Single room of brick-veneer construction, timber floor, insulated ceiling	4	36	131	87	750	0.59

*Excludes floor area when floor is concrete.
†Non-standard fixed ventilation.

According to Biggs et al. (1986), the average ACH (50) value of solar village houses (12.2 h^{-1}) is significantly lower than other groups. This is mainly owing to the widely use of less permeable materials and more attention to critical air leakage paths had paid. For instance, the elimination of fixed wall vents, sliding aluminium windows with adhesive tape mounting both inside and outside the window frame and in most houses with concrete intermediate slab, weather-stripped exterior door. In the older house group, the weatherboard and brick-veneer house 3 and 4 has a permeability value which is similar to the contemporary houses. However, the cavity-brick houses (1 and 2) are substantial less permeable than other old houses. This is because of that the visible construction cracks were effectively sealed, and the windows were tight fitting when closed. In other solar houses which were not belonging to the solar village house, the ACH (50) value is almost the same as the contemporary group due mainly to the presence of several fixed wall vents in houses 16 and 17 and to the unweatherstripped windows in house 18 (Biggs et al. 1986). In conclusion, the amount of service penetration and the quality of workmanship on the critical leakage paths definitely have large impact on the airtightness.

2.2 Airtightness measurements data from Estonia

According to Kalamees (2007), Estonia also realized that the airtightness has dramatic impact on the energy consumption and environmental impact of the building. Therefore, the local test authority from Tallinn area had performed several blower door tests on 32 timber framed single family detached houses during 2003-2005. In addition, most of these houses were relatively new, built approximately two to three years in prior to the test. After the completion of the test, researchers categorized the houses into several groups with regard to different airtightness related factors. The measurement data and classifications are shown in Table 2.2 below.

Table 2.2 Airtightness measurement data (Kalamees 2007)

Results of air tightness measurements

	Number of houses	Air leakage at 50 Pa ($m^3/(h\,m^2)$)		Air change rate at 50 Pa, n_{50} (1/h)		Effective Leakage Area at 4 Pa (cm^2/m^2)	
		Average	St. dev.	Average	St. dev.	Average	St. dev.
All measured data	32	4.2	3.3	4.9	3.5	326	273
One-storey house	9	1.9***	0.8	2.3***	0.7	105***	59
Two-storey house	23	5.1***	3.5	5.9***	3.5	413***	271
House built under professional supervision	23	3.0*	1.8	3.5**	2.1	218**	194
House built without professional supervision	9	7.2*	4.5	8.4**	3.7	602**	243
Constructed on site	17	5.3*	4.0	6.0*	3.9	427*	307
House with pre-fabricated wall or room elements	15	2.9*	1.8	3.5*	2.1	211*	166
Natural ventilation	4	10.1*,*	5.2	11.0**,**	2.4	689**,**	185
Mechanical exhaust ventilation	16	3.5*	2.0	4.4**	2.9	273**	238
Balanced ventilation with heat recovery	12	3.1*	2.0	3.5**	2.1	277**	254

*Significant, $P<0.05$; **Highly significant, $P<0.01$.;***Extremely significant, $P<0.001$.

Number of storey

According to Table 2.2, it is apparent that two-storey houses are on average leakier than one-storey houses according to the air leakage value at 50 Pa (l/s, m^2). This is mainly due to its longer air gap exists in joints between ceiling and walls and between floor and walls in two-storey buildings in comparison with one-storey ones. However, there are some exceptions, for examples, the first three two-storey houses are even less permeable than one-storey house as it can be found in Figure 2.2. This is probably due to the strong awareness on airtignhtness issues during the construction phase. Nevertheless, good airtightness can be achieved as long as more attention is paid by builders. For instance, they have to be excessively careful and rigorous when dealing with the problems in the leaky areas.

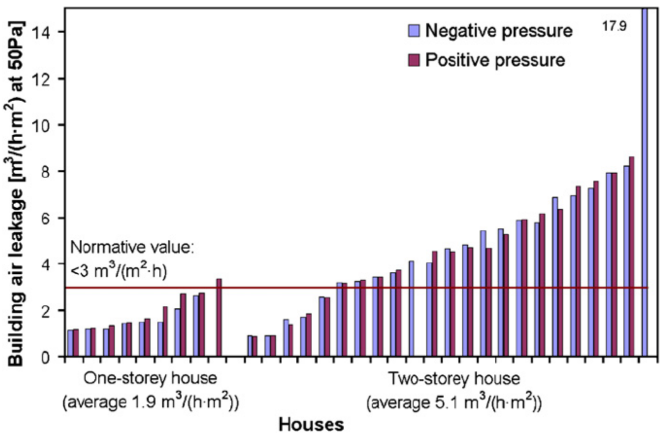


Figure 2.2 Airtightness in relation to house storey (Kalamees, 2007)

Construction method

As shown in Figure 2.3, the houses that are built by prefabricated elements are more airtight than those that are constructed in-site; however, Kalamees (2007) reached a conclusion that the construction method only has minor impact on airtightness. When they are taking into account the cross dependency effect of other factors, such as, number of storey and workmanship, they have stronger effect than construction method. For instance, one-storey houses are always more airtight than two-storey houses no matter what kind of construction method has been used.

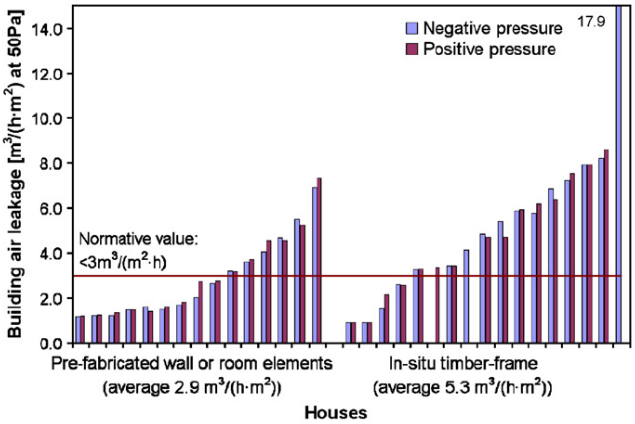


Figure 2.3 Airtightness in relation to construction method (Kalamees, 2007)

Workmanship

According to Kalamees (2007), some house owners in Estonia wish to build houses by their own efforts because of the cheaper price than if it was built under professional builders. It is undoubtedly that the former one will result in bad airtightness. As shown in Table 2.2, the houses that were built without professional supervision on airtightness (7.2 l/s, m2) are on average leakier than those that were built by professions (3 l/s, m2). Therefore, the involvement of well educated and experienced builders, both in design and in construction phase, is of great importance when aiming to construct an airtight building.

Ventilation type

Normally, the houses with natural ventilation are leakier than those with mechanical exhaust ventilation or balanced ventilation. During the last decades, natural ventilation was the most common way to ventilate the houses by opening windows and doors. Apart from this, natural ventilation also occurs when there is a driving force, i.e. wind force, temperature difference to let the air flow penetrate through the holes and cracks in the building envelope. Therefore, to have a desirable indoor environment, infiltration makes up the ventilation in house with natural ventilation and bad airtightness is formed up consequently. Comparison between the impacts of these two ventilation systems on airtightness is shown in Figure 2.4.

On the contrary, the buildings with mechanical exhaust ventilation are leakier than the ones with balanced ventilation according to Table 2.2. When using balanced ventilation system, the volume of inlet air and outlet air is roughly the same, excessive infiltration will increase heat loss and cause disturbance to ventilation system. As a result, the ventilation system cannot function properly. On the other hand, the building will have higher risk in under pressure condition than over pressure condition from moisture viewpoint. This is mainly due to that the heated moist air meeting cold surfaces and condensation occurring within the building fabric. The building materials will suffer from moisture damage. Therefore, a building with balanced ventilation has to be built significantly more airtight than a building with mechanical exhausted ventilation, in order to reduce the risk of moisture damage and heat losses (Abel et al. 2007).

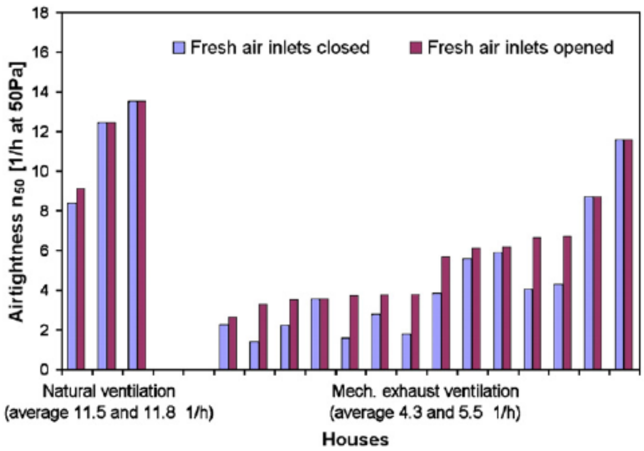


Figure 2.4 Airtightnss in relation to ventilation type (Kalamees, 2007)

2.3 Airtightness measurements data from the USA

2.3.1 Single family dwellings

During the last decades, approximately 13000 of the single-family houses were subjected to the blower door test and most of these measurement data come from Alaska, Alabama, Vermont and the Rhode Island region. In comparison to other countries, the unit of measurement in USA is in terms of normalized leakage area (NL) which is defined as the total leakage area [cm^2] normalized for floor area [m^2]. The ratio between NL and n_{50} can be roughly set to 17.5 with standard deviation of 2.3. Based on the statistically analyses of data, Sherman et al (1994) found that the NL value is dominated by these factors including house age, number of storey and basement type.

Number of storey

Most of the U.S. housing stocks are in one and two storey, single family dwellings. Approximately 56% of the measurements are of multi-storey dwellings and those buildings are 11 % leakier (i.e. NL=1.8) than single-storey houses (i.e. NL=1.6).The difference is, therefore, statistically significant, and it is concluded that there is a difference between single and multi-storey dwellings (Sherman et al. 1994).

Foundation type

According to Sherman et al (1994), the dwellings had been divided into two categories: houses that had floor leakage to outdoor (crawlspace and unconditioned basements) and those that had no floor leakage to outdoor (slab-on-ground and fully conditioned basement homes). Approximately 80% of the houses had floor leakage at NL= 1.75 and are slightly leakier (5%) than the rest of houses that had no floor leakage at NL = 1.64.

Year of construction

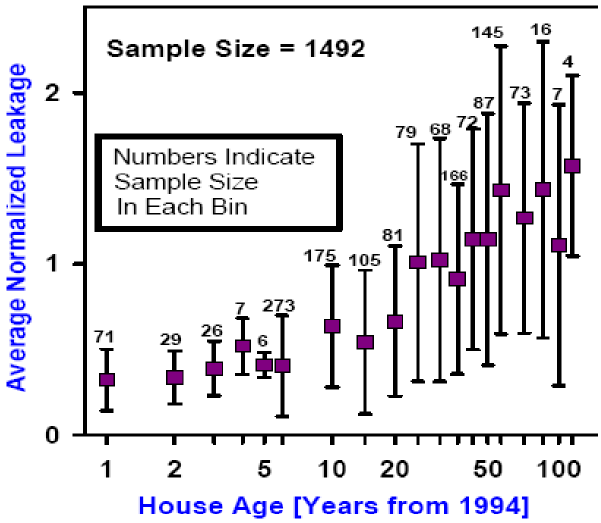


Figure 2.5 House age versus NL value Sherman et al (1994)

As shown in Figure 2.5, the breakpoint can be found in the year of 1980. The houses that were built after 1980 did not show any leakage trend correlating to the year of erection. By contrast, the remaining houses that were built prior to 1980 have a clear leakage trend with increasing age. The newly built houses tend to be more airtight than older ones.

2.3.2 Commercial and institutional buildings

It is common to say that the new buildings are tighter than the old buildings and the number of storey would have significant impact on the airtightness. However, Persily(1998) gathered some measurement data for commercial and institutional buildings either from USA or some other countries, which are shown in Table 2.3 below. Some different perspectives can be found from his research.

According to Table 2.3, 69 out of 139 buildings were tested within the program of Florida Solar Energy Centre and fall into four different types which include office, school, industrial and retail. The rest of buildings were tested by some other countries.

Table 2.3 Summary of commercial buildings (Persily, 1998)

Dataset	Country/State	Number of Buildings	Mean Number of Stories	Mean Age (Years)	Range of Ages (Years)
NIST Offices	USA	8	6.1	18.3	8 - 23
NRC Offices	Canada	8	18.5	27.5	24 - 34
BRE Offices	UK	10	NA[1]	17.2	7 - 35
FL Offices	USA/FL	22	1.0	25.8	4 - 67
NY Schools	USA/NY	13	NA	NA	NA
NRC Schools	Canada	11	1.0	31.7	25 - 46
FL Schools	USA/FL	7	1.0	27.4	8 - 33
NRC Retail	Canada	10	NA	31.4	18 - 44
FL Retail	USA/FL	6	1.0	21.8	4 - 32
Industrial	Sweden	9	NA	NA	NA
FL Industrial	USA/FL	9	1.1	24.9	4 - 57
FL Other	USA/FL	25	NA	NA	NA
Other	Canada	1	5	10	10

NB. FL= Florida NY = New York NIST = National institution of standards and technology (US)

BRE = Building research establishment (UK) NA = Not available

Year of construction

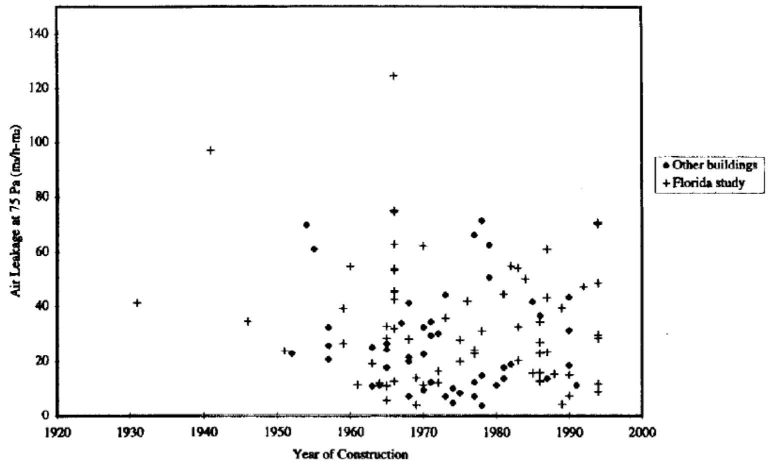


Figure 2.6 Year of construction versus air leakage at 75 Pa ($m^3/h\ m^2$) (Persily, 1998)

Normally, based on the conventional wisdom, the newly built constructions are more airtight than older ones. However, according to Figure 2.6, there is no clear correlation between the airtightness and the year of construction for rest buildings, since the air permeability values are randomly distributed in the diagram. This is probably due to the fact that the data were collected from various countries and their requirements on the airtightness are quite differed from each other during a specific period, which could result in large variances. Alternatively, the author should compare the data within one country rather than mix them together.

Wall material

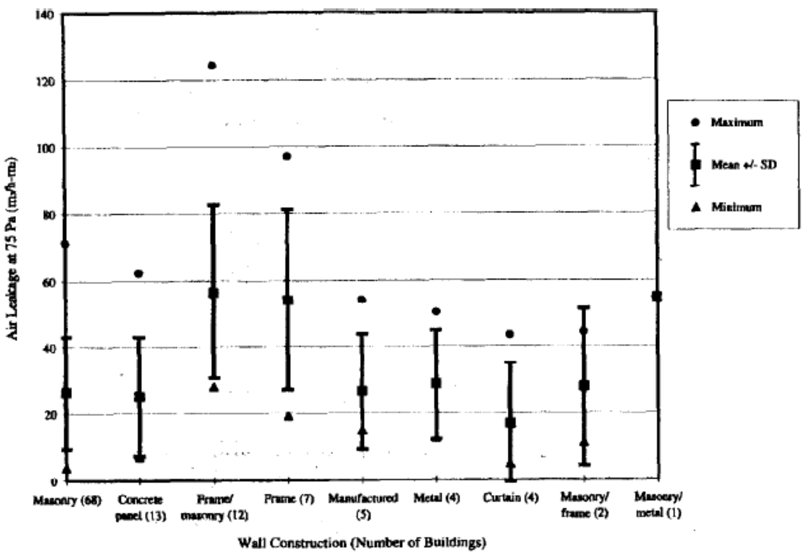


Figure 2.7 Wall material versus air leakage at 75 Pa ($m^3/h\ m^2$) (Persily, 1998)

As it can be seen from Figure 2.7, masonry, concrete panel, manufacture, metal, curtain, and masonry/frame building were similar in airtightness. All of them have a mean air permeability value around 25 $m^3/h\ m^2$. In addition, the frame buildings (55 $m^3/h\ m^2$) and frame/masonry buildings (57 $m^3/h\ m^2$) appear to be leakier than other types of the buildings because of some extremely leak samples (up to 100 $m^3/h\ m^2$ and 125 $m^3/h\ m^2$). Moreover, the masonry/metal building also has 55 $m^3/h\ m^2$ whereas only one sample is presented. There is no obvious correlation between wall construction and the airtightness. In conclusion, it is suggested that frame buildings tent to be leakier than other types according to Persily (1998), but no reasons were provided by them. Nevertheless, it is difficult to draw a conclusion that the type of construction has a significant impact on building airtightness.

Number of storey

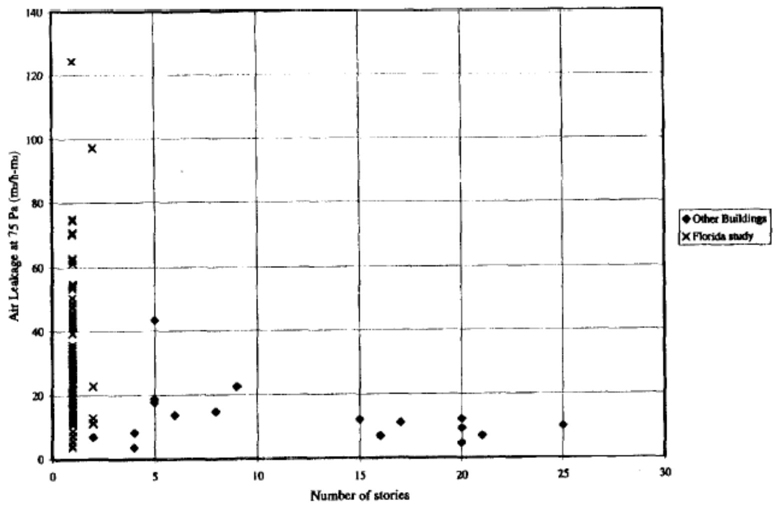


Figure 2.8 Number of storey versus air leakage at 75 Pa ($m^3/h\ m^2$) (Persily, 1998)

According to Figure 2.8, the air permeability value connected to the number of storey. The more storeys the building has, the worse airtightness it becomes. This is mainly because of that the taller building requires more careful design and construction process to satisfy the higher demands of structural complexity, such as increased wind loads and with the control of rain penetration. A one or two-storey building does not need to have such a high demand and they include more wall types of construction than the taller office buildings. These factors probably result in poor airtightness of the lower buildings (Persily, 1998).

In addition, it is quite different when referring to Kalamees (2007) and it stated that the less number of storeys, the better building airtightness. Therefore, it is suggested to separate the single family dwelling and commercial building when someone tries to compare the building airtightness with respect to the number of storey.

2.4 Airtightness measurement data from Finland

From year 2002 to 2004, the corporative research project called Moisture–proof healthy detached house was carried out by Tampere University of Technology and Helsinki University of Technology. In this project, 100 Finnish timber-framed buildings were undergone the blower door test to estimate their airtightness. In addition, in 2005, a three year project called airtightness, indoor climate and energy efficiency of residential building was initialized and the airtightness of 70 heavyweight detached houses and 60 multi-storey apartments were studied by using the blower door test as well. The measurement details are described in *table 2.4* and *table 2.5* respectively.

2.4.1 Single detached house

Table 2.4 Average depressurization test of detached single family Finnish houses (Korpi et al. 2006)

	Amount of houses	Average air change rate at 50 Pa [1/h]	Standard deviation	Minimum value [1/h]	Maximum value [1/h]	Average air permeability [l/sm^2]
Autoclaved aerated concrete	10	1,5	0,6	0,5	2,2	0,5
Lightweight aggregate concrete	6	3,4	1,2	2,0	5,3	1,1
Brick	10	2,8	1,2	0,7	5,4	0,8
Shuttering concrete block	10	1,6	0,8	0,5	3,2	0,5
Concrete element	9	2,5	1,2	1,1	4,7	0,7
Log	16	6,1	3,7	1,0	16,2	1,6
Log - airtight seam insulation	7	4,1	2,0	1,0	6,5	1,2
Log - conventional seam insulation	6	8,3	4,4	3,1	16,2	2,1
Log - additional int. insulation layer	3	6,8	3,9	3,4	11,1	1,7
Timber-framed	100	3,9	1,8	0,5	8,9	1,1

The houses that are listed in Table 2.4 are located in Tampere and Helsinki region. The age of all tested houses is relatively new and the construction year range from 1996 to 2006. In addition, a large percent of the houses (approximately 82%) were built after year 2000 which can be seen in Figure 2.9.

According to the Table 2.4, the houses that are made of autoclaved aerated concrete (1.5 h^{-1}) and shuttering concrete block (1.6 h^{-1}) are the most airtight among the entire categories, followed by the house that are made of concrete element (2.5 h^{-1}), brick (2.8 h^{-1}) and light aggregate concrete (3.4 h^{-1}) respectively.

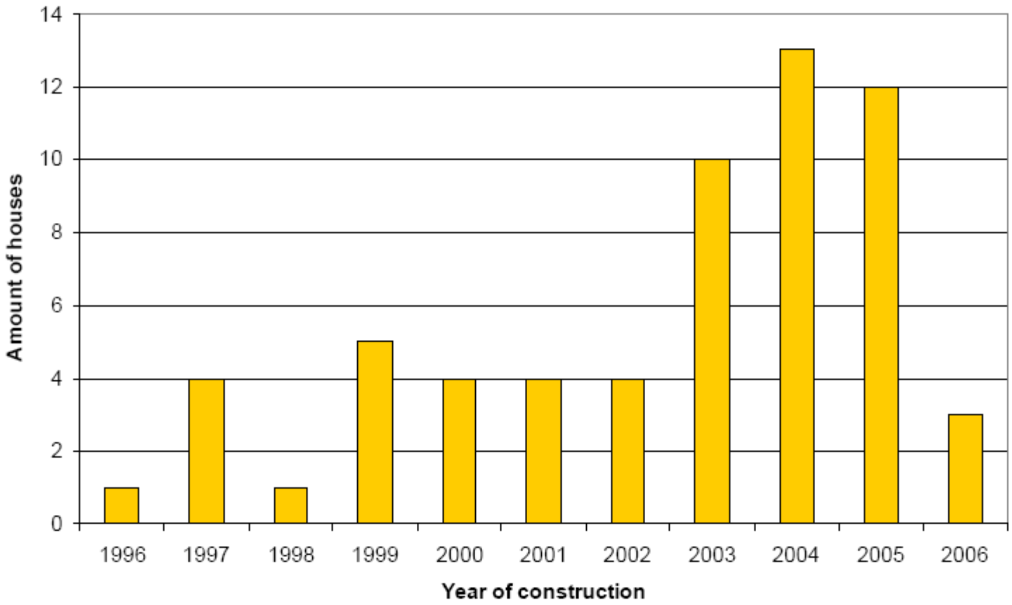


Figure 2.9 Year of construction of studied houses (Korpi et al. 2006)

In addition, the constructions that are made of wooden materials are on average leakier than those that are made of heavy materials. The log houses are the leakiest which have n_{50} value of 6.1 h^{-1} and the average n_{50} for timber-framed house is 3.9 h^{-1} as shown in Figure 2.10. The difference between the log house and concrete element house is quite noticeable. On the other hand, when comparing the airtightness by using q_{50} value, the margin between timber-framed houses, log houses and concrete element one becomes smaller. As it can be seen from Figure 2.11, log and timber house has a q_{50} value of 1.59 l/s, m^2 and 1.08 l/s, m^2 whereas autoclaved aerated concrete house has a q_{50} value of 0.5 l/s, m^2. This is because of that the ratio between the volume and building envelope area of the concrete houses are on average higher than log and timber-framed house [6]. The q_{50} value is decreased as a consequence of smaller V/S ratio of the log and timber-frame house. The relation between the n_{50} and q_{50} is shown in equation (2.1) below.

$$q_{50} = n_{50} \cdot \frac{V}{A_E} \cdot \frac{1}{3.6} \qquad (2.1)$$

Where V – Volume (m^3)

A_E – Envelope area (m^2)

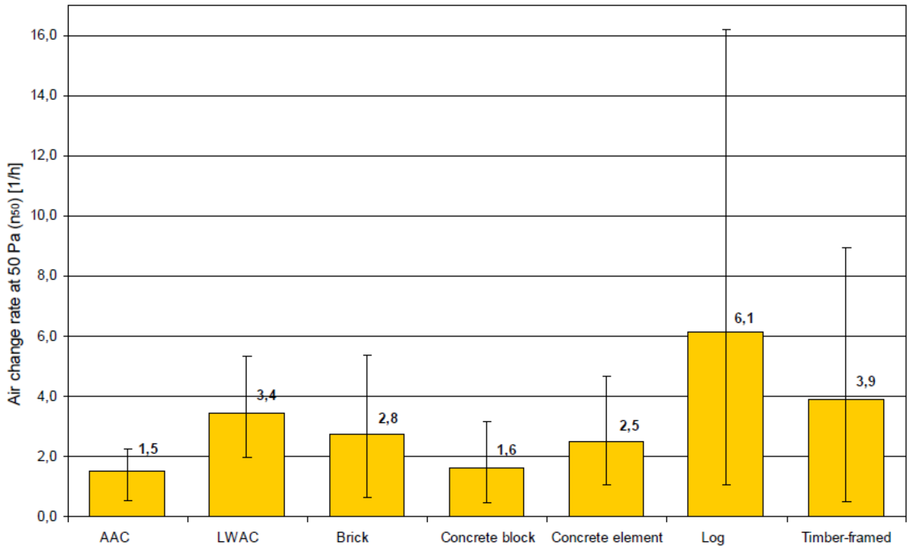


Figure2.10 Air change rate at 50 Pa (1/h) for different houses (Korpi et al. 2006)

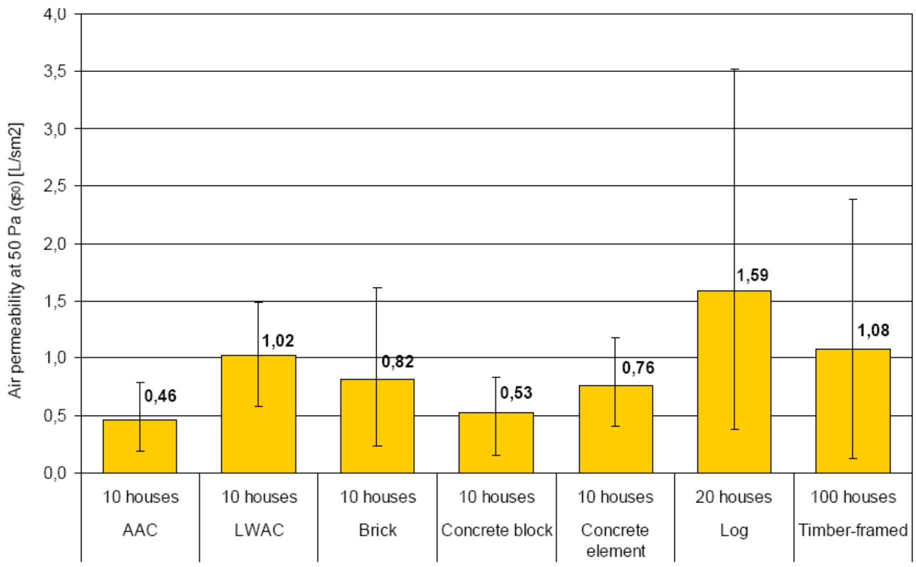


Figure 2.11 Air permeability at 50 Pa (l/s m^2) of different houses (Korpi et al. 2006)

According to Korpi et al. (2005), there remains some other factors which can affect the airtightness beside wall materials, for instance, the timber-framed houses that were built on-site (average 4.5 h^{-1}) were not as tight as prefabricated elements (average 3.3 h^{-1}). Secondly, one-storey houses have n_{50} value of 3.7 h^{-1} which is slightly tighter than two-storey houses (average 4.1 h^{-1}). Coincidentally, these two findings are consistent with Kalamees (2007). Thirdly, the houses in which the thermal insulation was polyurethane were on average more airtight than houses with other kind of insulation materials or vapour barriers (Korpi et al. 2005).

Table 2.5 Air change rates of houses with concrete or timber-framed ceiling structure (Korpi et al. 2006)

Building wall materials	Amount of houses with concrete ceiling structure	Average air change rate at 50 Pa [1/h] of these houses	Amount of houses with timber-framed ceiling structure	Average air change rate at 50 Pa [1/h] of these houses
Autoclaved aerated concrete	9	**1,5**	1	**2,2**
Shuttering concrete block	3	**1,2**	7	**1,8**
Concrete element	2	**1,2**	8	**2,9**
All these houses	**14**	**1,4**	**16**	**2,3**

In addition, the ceiling structure of the houses seems to have impact on the airtightness. According to Table 2.5, the buildings with timber-framed ceiling (2.3 h^{-1}) are on average leakier than the ones with concrete ceiling (1.4 h^{-1}). This is mainly because of the joints between the exterior walls and ceilings are the most common leakage path and thus it is difficult to make joints between solid walls and the thin air barrier layer in timber ceiling as airtight as expected (Korpi et al. 2006).

2.4.2 Multi-storey apartment

The two universities also performed several blower door tests to three different types of multi-storey apartments. The first type of building in which the external walls were made of concrete element while the intermediate walls were made of hollow core slab. The second type is concrete built with intermediate floor cast in situ. The third group were timber-framed buildings. Comparison between those three types of buildings is shown in Figure 2.12 below.

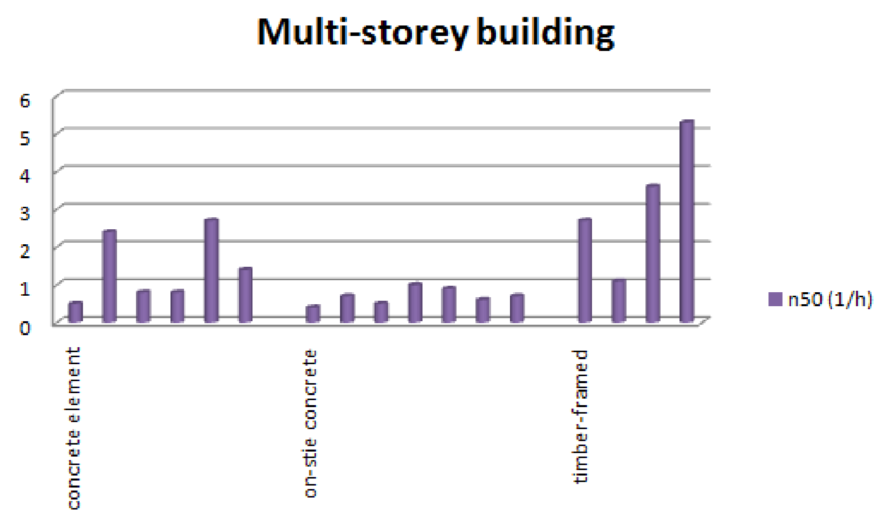


Figure 2.12 Comparison between the concrete elements, timber-framed multi-storey buildings

According to (Korpi et al. 2006), the average n_{50} value of all multi-storey apartments is 1.6 h^{-1} in comparison with 3.7 h^{-1} of single detached family houses. The findings are in line with Persily (1998). Multi-storey buildings tend to be more airtight than single family house probably owing to the fact that the multi-storey buildings have to be designed and built more carefully to satisfy the higher demand of structure complexity as it has been discussed previously.

In addition, when comparing the different building types in Figure 2.12, the lowest average n_{50} values were found in concrete built with cast in situ intermediate concrete floor (0.7 h^{-1}). This is presumably due to that the cast in situ intermediate floor gives possibilities to make the joints between walls and floor attaching together better than the joints between the prefabricated ones. Furthermore, the average n_{50} value of apartment in concrete element house was 1.6 h^{-1} and in timber-framed was 2.9 h^{-1}. Yet timber-framed construction has the worst airtightness among the entire categories.

2.5 Airtightness measurements from New Zealand

In 1982, a survey of 40 houses' airtightness in wellington city, New Zealand was completed by Bassett and it used the blower door test to measure the air leakage characteristics of 40 houses with different ages and construction types. More interesting thing was that Bassett classified the houses into several groups with regard to shell complexity, in which the summation of the perimeter lengths of bottom and top plate together with vertical lengths of exterior corners and the boundaries of changes of ceiling pitch that divided by building envelope area is defined as shell complexity (Bassett, 1983). The results are shown in Figure 2.13.

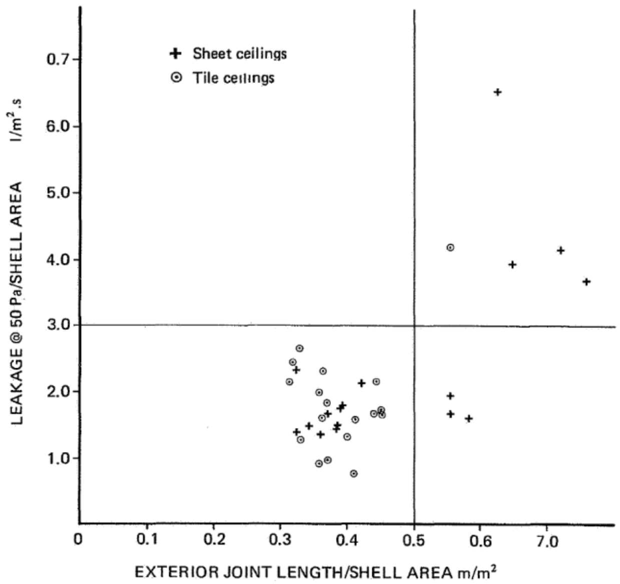


Figure 2.13 Building shell complexity versus q_{50} (Bassett, 1983)

Obviously, the house with less shell complexity as shown in Figure 2.13 has lower air permeability value. The vertical straight line stands for the average shell complexity while the horizontal straight line represents for the average q_{50} value. There are eight houses of above average shell complexity and five of them have higher q_{50} value than average level but the other three are under average q_{50} value. All other houses in which the shell complexities are lower than average level (0.5 m/m^2) are on average more airtight than others. In addition, no houses in which the shell complexities are lower than the average level are found to have higher air permeability than the airtightness average level. Therefore, it is reasonable to say that there is a high degree of association between the shell complexity and airtightness (Bassett, 1983).

2.6 Comparison of airtightness requirements and situation

In order to present a comparative analysis among some European countries, a total number of 1094 n_{50} values were studied by the collaboration between 7 European countries.

Table 2.6 Summary of n_{50} value for 7 European countries (Papaglastra et al. 2009)

Country	Source	Number of available n50 values	Types of buildings tested	mean n50	min n50	max n50	stdev	stdev/ mean	median
Belgium	Belgium Building Research Institute (BBRI)	21	18 houses, 1 industrial, 2 offices	4,99	0,50	22,50	5,10	1,02	3,70
Greece	National and Kapodistiran University of Athens, Group Building Environmental Research (NKUA)	39	39 houses	6,38	1,87	13,10	3,15	0,49	2,64
The Netherlands	Netherlands Organisation for Applied Scientific Research (TNO)	218	110 houses, 108 appartments	1,48	0,06	6,20	1,03	0,70	1,26
France	Centre d' Etudes Techniques de l' Equipement de Lyon (CETE de Lyon)	644	317 houses, 242 appartments, 10 industrial, 5 offices, 4 hotels, 5 information, 7 multiple use halls, 4 sports, 4 whole appartment buildings, 46 others	3,38	0,04	60,96	4,42	1,31	2,55
Norway	Stiftelsen SINTEF (SINTEF)	17	17 houses	1,09	0,17	2,79	0,86	0,79	0,74
Finland	Tampere University of Technology, Department of Civil Engineering Helsinki University of Technology, HVAC laboratory	128	70 houses, 58 appartments	2,54	0,30	16,20	2,33	0,92	2,05
Germany	BlowerDoor GmbH, Energie- und Umweltzentrum (EUZ)	27	13 houses, 3 industrial, 2 offices, 2 homes for eldrly people, 2 shops, 1 hospital, 1 school, 1 library, 2 other	1,21	0,01	4,70	1,07	0,88	1,00

According to Table 2.6, the mean n_{50} value ranges from 1.09 (followed by Germany and the Netherland) for Norway to 6.38 for Greece (Belgium close at 4.99). Among the entire groups, the Norwegian buildings are the most airtight. It is mainly due to its cold climate, where the house builders have to construct airtight house in order to overcome the heat loss caused by air infiltration. In addition, Greek buildings are leakier than other countries' building which probably due to two major factors. One reason is its warmer climate that the building does not suffer from the draught severely. Instead, it has higher average temperature during the whole year than the other European countries. Therefore, the natural air flow through the cracks and holes is needed in order to cool down the indoor temperature. Another factor is that the studied buildings in Greece are on average older (large amount of house are built before 1970s) than those in other European countries, which is compared in Figure 2.14. Generally, the quality of workmanship and awareness of airtightness was not major design factors during that period. Moreover, Finland has quite similar location and climate condition to Norway, but the airtightness of these two countries is not on the same level. Unfortunately, the reason has not been mentioned by Papaglastra et al (2009), further investigation is worthy to be conducted to figure it out.

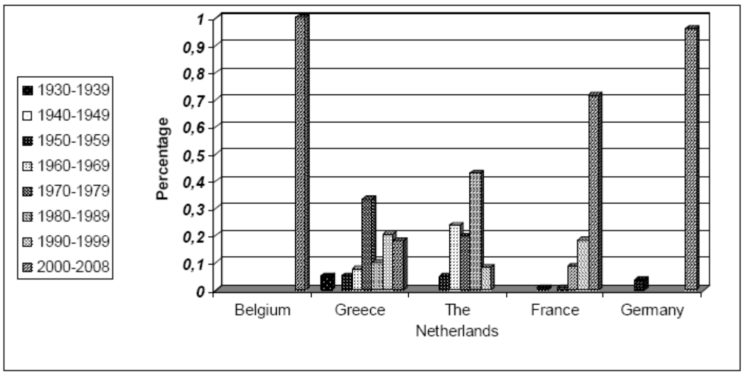
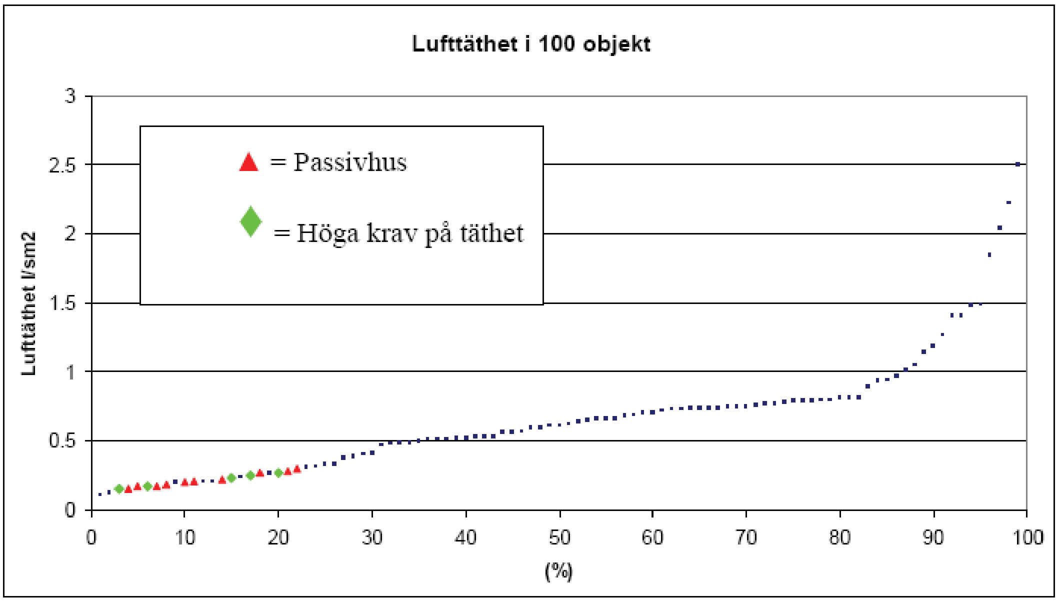


Figure 2.14 Year of construction of different countries (Papaglastra et al. 2009)

Table 2.7 Comparison of n_{50} value around the world (Kalamees, 2007)

Country, measurement time	Number of houses	Air change rate at 50 Pa, n_{50} (1/h)		Remarks
		Average	Min–max	
Belgium, 1995–98	51	7.8	1.8–25	
Canada, 1985–95	222	3.1	0.4–11	New conventional houses
	47	1.2	0.13–2.6	R2000 low-energy houses
Estonia, 1999–2000	19	9.6	4.9–32	
Estonia, 2003–05 (current study)	31	4.9	0.7–14	Built in 1993–2004
Finland, 1979–81	16	6.0	2.2–12	Common pre-fabricated timber-frame wall-element houses
	28	3.5	1.0–7.5	Special attention is paid for the air tightness
Finland, 1981–98	171	5.9	1.6–18	Mostly reclamations cases
Finland, 2002–04	100	3.9	0.5–8.9	Timber-frame envelope
Norway, 1980	61	4.7	2.0–8.0	
Norway, 1984	10	4.0	3.3–5.4	Built in 1980, low-energy houses.
Sweden, 1978	205	3.7	St. dev. 1.24	Built during 1960s-1970s
Sweden	44	1.02		Timber-frame envelope
United Kingdom	471	13.1	2–30	
USA	12,902	29.7	0.5–84	Built in 1850–1993

In addition, the similar studies were also conducted in Finland. The information in Table 2.7 mainly shows the airtightness measurement data around the world during the last three decades. Apparently, when comparing the airtightness globally, Canada and Nordic countries achieved good airtightness compare to other countries. In addition, there is a clear correlation between the n_{50} value and the awareness of airtightnss or project goal. For example, 28 houses that are built in Finland with high focus on airtightness are significantly more airtight than the common pre-fabricated timber-framed wall element houses (16 samples) between 1979 and 1981. The same phenomenon can be traced in Canada and Norway respectively. It is mainly due to that there was a special focus on the airtightness during the construction phase. The buildings that were built with timber-frame in Sweden are considered to be good examples.



Luftt ähet i 100 objekt = airtightness in 100 objects, Luftt ähet = airtightness

Passivhus = passive house, H öga krav p å t ähet = high demands on tightness

Figure 2.15 Airtightness measurement data from SP (Svensson et al. 2009)

In recent years, high energy efficiency of the building becomes a major concern within the Swedish building industry. Therefore, a lot of engineers and house builders put much effort on improving the airtightness in order to decrease the heat loss caused by air infiltration. At the same time, engineers from SP have also conducted a broad study on airtightness. In this study, both light and heavy constructions have been investigated which consisting of block flats, single family detached houses and schools. As it can be seen from Figure 2.15, the air permeability of approximately 90% buildings is between 0.2 and 1.2 l/s, m^2 at pressure difference of 50 Pa. In addition, the air permeability of passive house and the houses with special focus on airtightness are even lower than 0.3 l/s, m^2. Since the value of 0.8 l/s, m^2 has been removed from former BBR code, it is not an accurate value for heat loss calculation. Alternatively, it is more feasible to ask the house builder or owner directly with information on whether the building was built to be passive type or not. By having this information, the q_{50} value could be more accurate than assumption.

2.7 Summary of literature review

Generally, there are three factors that will affect airtightness significantly which include: year of construction, number of storey and quality of workmanship. It is reasonable to say that the new buildings are more airtight than old buildings because of the improved construction technology and more rigorous design on the airtightness. On the other hand, attention should be paid for older buildings. If the buildings had been subjected to the retrofitting work, then there is no explicit difference between new constructions and old ones. This can be proved by referring to Biggs et al (1986). The older houses did not differ significantly from the modern ones.

For number of storey, the more stories the building has, the leakier it becomes. This rule will only validate in the range of single family houses as mentioned in Kalamees (2007) and Sherman et al (1998). Multi-storey buildings and commercial buildings as mentioned in Korpi et al (2006) and Persily (1998) have even lower air permeability than one-storey houses mainly due to its more careful design and construction method. For workmanship, there is no controversy to say that the involvement of experienced project supervisor and well educated builder on airtightness will build much more airtight buildings than those constructed by builder with poor airtightness knowledge. In addition, the quality of workmanship is quite related to the energy efficient focus. If the building is aiming to be a passive type, then the excellent workmanship on critical air leakage path is undoubtedly required. As a consequence, the passive house is more airtight than the conventional one.

In addition, it is worthy to mention some other factors, such as: building materials, foundation type, ventilation type and envelope complexity etc. Before the world energy crisis, people did not pay much attention to energy performance of the building. Thus the airtightness was not considered as one of primary factors both in design and construction phase. When stepping back to that period, the airtightness was highly associated with wall materials. Generally, the houses made of heavy materials such as, concrete and brick were more airtight than those made of timber material. However, the airtightness of recently constructed buildings is not allied to this issue noticeably. Some examples can be found in timber-frame houses built in Nordic countries after year of 2000 as discussed in section 2.6. Therefore, the construction materials have to be combined with year of construction when someone tries to compare their airtightness. Furthermore, it is inconvincible to reach a conclusion that ventilation and foundation type has dramatic impact on the airtightness solely based on Kalamees (2007). Lastly, the envelope complexity also has impact on airtightness according to Bassett (1982). Therefore, it is worthy to investigate all of these potentially relevant factors further by asking professions and thereafter constructing the database.

Some airtigtness related factors from literature reviewing are summarized in Figure 2.16.

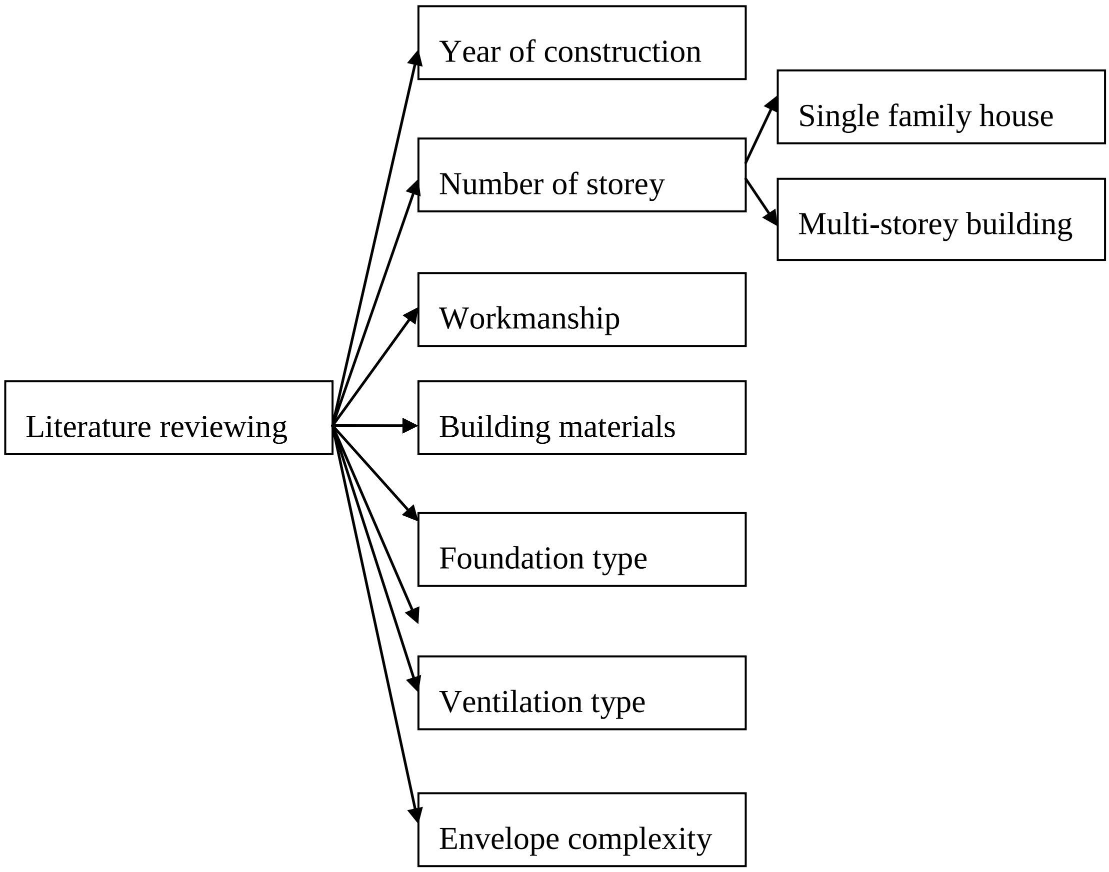


Figure 2.16 Summary of the airtightness related factors from literature review

3 Communication with airtightness test engineers

3.1 Purpose

To predict the building's air permeability more accurately, the most feasible and reasonable way was to ask experienced airtightness test engineers directly with information on, for instance, year of construction, the predominant material used for building, number of storey etc. Based on their feedback, it became possible to structure the database and put them into further use. Therefore, a questionnaire concerning the general perspectives and interviews of detail issues on the airtightness should be conducted in order to retrieve the useful information from engineers.

3.2 Method

As mentioned in the introduction part, various methods of estimating the building airtightness were optional, for example, experiments, literature reviews and surveys. The latter one was more likely to reveal the key point of issue than other two methods. Therefore, questionnaires were considered as principal way of collecting relevant information. In addition, interviews with airtightness test engineers should also be conducted in order to explore useful information to a much deeper level.

To ensure that all the interviews would yield satisfied results, seventeen questions were raised in the questionnaire. Most of them were directly related to the different potential relevant factors that would have impact on the building airtightness. By having these questions, the test engineers can be assessed on his or her familiarity on the building aittightness without face to face communication.

Interviews were planned to be conducted with two engineers from SP and WSP separately. All of them had long working experiences in the field of the building airtightness. The first occasion was held to help the writer to have better understanding of building airtightness and to evaluate whether all the questions were worthy to be raised in questionnaire. The second one was held to help the author to structure the database and to provide the airtightness measurement data which would be fed into database afterwards.

3.3 Results and discussion

3.3.1 Feedback from questionnaire

The questionnaire has been sent to five airtightness test engineers and all of them have at least 5 years working experiences in the field of airtightness. Some of them had performed hundreds of blower door tests for various building types which consisting of single family detached house, multi-storey building and school building. In addition, one of them has been working as a consultant on airtightness with approximately 30 years experiences.

The questionnaire mainly includes 17 questions which are directly linked to the building airtightness (see Appendix 1). The first two questions are raised to ask test engineers some common leakage paths and suspected airtightness related factors.

According to their responses, there are three major leakage paths widely existed in Sweden based on their experiences. They are consisting of gaps around windows, service penetrations and gaps around wall to floor or ceiling joints. In addition, the quality of workmanship and wall materials were the most critical factors which could affect airtightness dramatically.

Furthermore, there are eight Yes/No questions in questionnaire, all of them are designed to ask participants whether those factors would have an impact on the airtightness. The responses are shown Table 3.1.

Table 3.1 Responses of questionnaire

Factor	Number of participants	YES	NO	Uncertain
Wall materials	5	5	0	0
Workmanship	5	5	0	0
Foundation type	5	5	0	0
Construction method	5	4	0	1
Year of construction	5	4	0	1
Number of storey	5	4	0	1
Building type	5	3	0	2
Ventilation type	5	1	1	3

As it can be seen form Table 3.1, five participants both have agreements on following factors consisting wall materials, workmanship and foundation type. Therefore, they are reasonable to be put into the database for conducting classification. At the same time, number of storey, construction method and year of construction obtain four votes from participants. Thus it is worthy to put them into the database as well. The rest factors have to be further checked with airtightness test engineers during the interviews. Feedbacks from questionnaire are illustrated in Figure 3.1 as shown below.

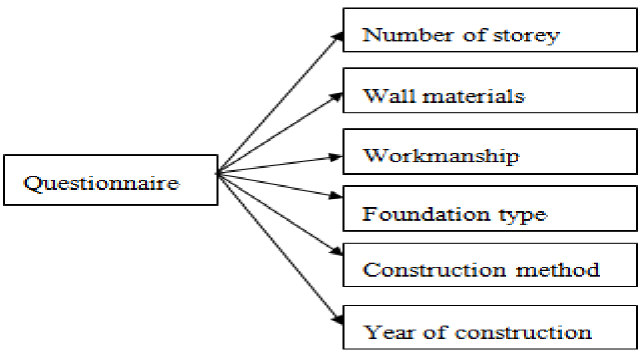


Figure 3.1 Summary of airtightness related factors from questionnaire

3.3.2 Feedback from interviews

To set up the database, direct communication with engineers is another effective way of retrieving useful information. Therefore, three interviews were held with two airtightness professions. The first one was held at SP, during this occasion, the questionnaire was discussed with an engineer. Based on his expertise, most questions were reasonable to be raised in questionnaire. However, there was still one exception that the impact of building materials on airtightness in questionnaire was not a clear question. It was mainly due to the fact that the question itself make participant feeling confused. The building materials include wide range of substances, such as, wall materials, sealing materials and insulation materials. Therefore, the question must be revised in order to clarify which specific materials did the author means. Afterward, the building material in questionnaire was changed to stand for predominated wall materials, such as, concrete, light-weight concrete, timber etc.

The second interview was also held at SP. During this occasion, the structure of database was discussed. Most of airtightness related factors such as, year of construction and number of storey listed in the database (see Appendix B) had either come from the answers of questionnaire or literature reviewing. Based on the test engineers' assessments, all of these factors were worthy to be investigated. Apart from this, he also added some other factors which would be of interest. For example, the total joint length of the building may has an influence on airtightness according to his expertise. Therefore, the way of evaluating the effect of joint length becomes an interesting topic. After the discussion, a simplified method had been worked out. The width, height, length of the building were planned to be put into the database to account the total joint length between the connection of wall and floor, wall and ceiling. In addition, the application of an installation layer was another interesting topic during the discussion. The buildings that were designed to be built with installation layer were more airtight than ones without installation layer. Therefore, this factor was also integrated in the database. Furthermore, the way of evaluating workmanship was also discussed. It is quite fair to say that the buildings built with superior workmanship will yield an airtight building. Thus, how to estimate this factor was of great importance. One solution was to rank the different projects' awareness and level of builders' education background on airtightness in a quantitative way. However, problems would occur if we conducted further investigation based on this idea. It was not feasible for the author to collect such big amount of relevant information on those two points within a short period. Therefore, this solution had been rejected. Another interesting thesis topic on this matter is Eliasson (2010). Alternatively, the project goal was considered as a simplified and rough estimation on the quality of workmanship. If one building was aiming to be built as an energy efficient building or there was a target value on airtightness, then good quality of workmanship must be achieved in order to satisfy the demand. As a result, a factor so-called 'energy efficient' was decided to be put into the database.

The third interview was held with one engineer form WSP. During the discussion, he stressed that the joint between wall and floor or ceiling of the buildings contribute the largest air leakage source. As a consequence, the larger building was likely to be leakier than smaller one because of its longer joints length. Thus it was interesting to conduct investigation on relation between the total joint length and airtightness. At the same time, the building type also became of interest. Apart from this, he also pointed out that the ventilation type would affect the airtightnss somehow. Furthermore, some outcomes yielded from the database were also discussed with him, especially on the construction method and foundation type. Since the discussions in this section only show how the author retrieves useful information either from questionnaire or interviews for constructing the database, more details from interviews and questionnaire will be further discussed in chapter 5 in combination with outcomes obtained from the database.

Some interesting airtightness related factors from interviews are summarized in Figure 3.2 below.

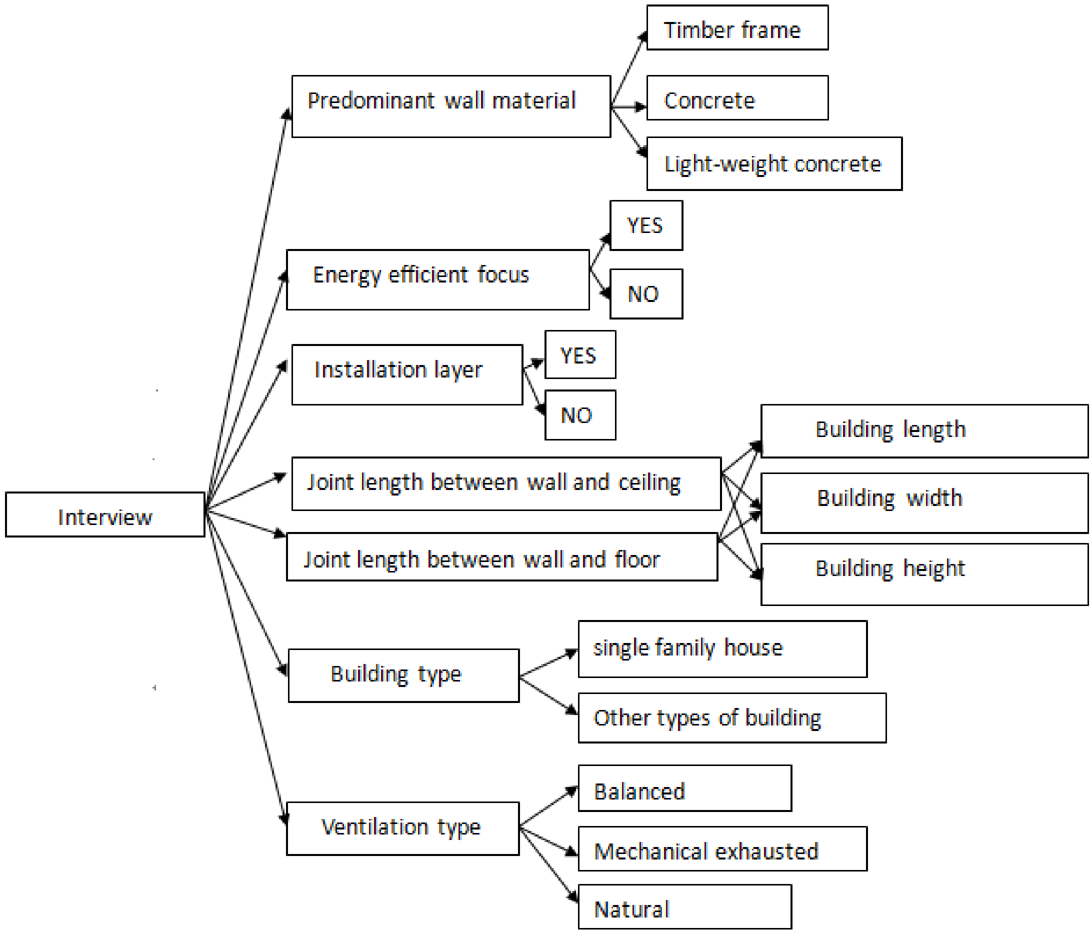


Figure 3.2 Summary of airtightness related factors from interview

4 Field measurement – the blower door test

4.1 Background

With the increasing demand on energy efficiency and sustainability, building airtightness becomes a crucial factor when aiming to construct a low energy and environment friendly building. Therefore, a diagnostic testing of building on airtightness both during the construction phase and operation is necessary. There are several ways of testing the air leakage value of a building. All of these methods have originated from the same principle by introducing a pressure difference over the building envelope. The fan pressurization method, commonly referred to as the blower door test is one of the most common ways of estimating the building's airtightness.

4.2 Principle

4.2.1 Purpose

The blower door is used as a diagnostic tool to test the airtightness and to help locating air leakage path. The measurements are used for various purposes which include: documenting the air tightness of building, estimating natural infiltration rates of building, measuring and documenting the effectiveness of sealing (The Energy Conservatory, 2007).

4.2.2 Equipment

The measurement equipment generally consists of a sealing frame with a fan, a pressure gauge and a set of computer system for recording and processing the test results. The fan with an air flow meter is temporarily mounted into sealing frame which can be used as exterior doorway. In addition, a pressure gauge is connected to the tubes. During the test, the fan will generate a specific pressure difference over the building envelope and the sensor will simultaneously measure the air flow through the fan and its effect on the air pressure difference across the building envelope. The measurement result will automatically be recorded by the computer. The illustration of measurement principle is shown in Figure 4.1.

4.2.3 The EN 13829:2000

The EN 13829:2000 standard is one of various standards that are approved by a number of European countries for estimating the thermal performance of buildings. Before the test, some prerequisites should be fulfilled as described below.

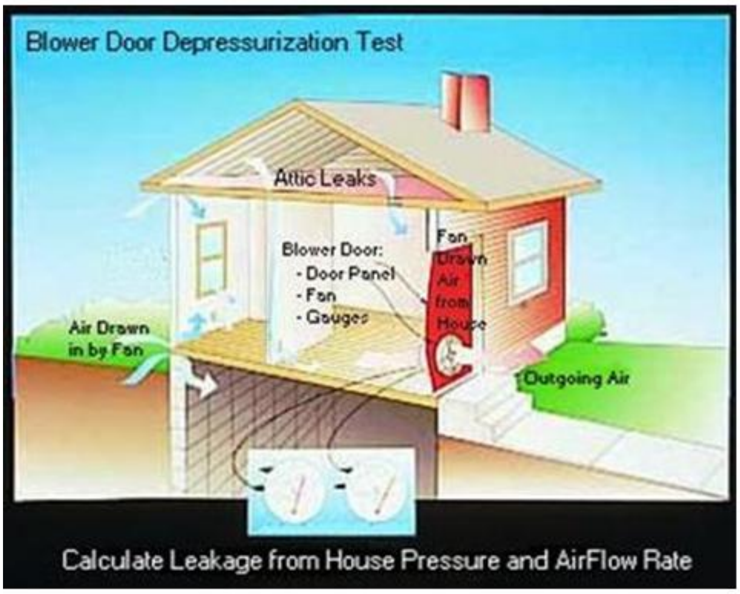


Figure 4.1 Principle of blower door test (The Energy Conservatory, 2007)

4.2.3.1 Measurement condition

Since the wind velocity and air temperature will have effects on the zero flow pressure difference (baseline pressure), before the test, following requirements should be fulfilled. According to EN 13829:2000, the temperature difference of between indoor and outdoor, in K, multiplied by the height of the building envelope, in m, if the result is larger than 500 m· K, then it is hard to reach an eligible zero flow pressure difference. In addition, if wind speed exceeds 6 m/s, zero flow pressure difference can not be reached as well. The average pressure difference should be measured both before and after test by connecting the pressure measuring device to measure the pressure difference over a period of 30 seconds. It is recommended that if either of these two average values of zero-flow pressure difference is greater than 5 Pa, then the test result will not be approved.

4.2.3.2 Envelope area

Since the envelope area will directly influence the value of air permeability at 50 Pa, the way of counting this area should also comply with the standard. The envelope area A_E of building or measured part of building is the total area of all floors, walls and ceiling bordering the internal volume subject to the test. This includes walls and floors below external ground level. Overall internal dimensions should be used to calculate this area. No subtraction should be made for the area at junction of internal walls, floors and ceiling with exterior walls, floors and ceilings (EN 13829:2000). This is illustrated in Figure 4.2.

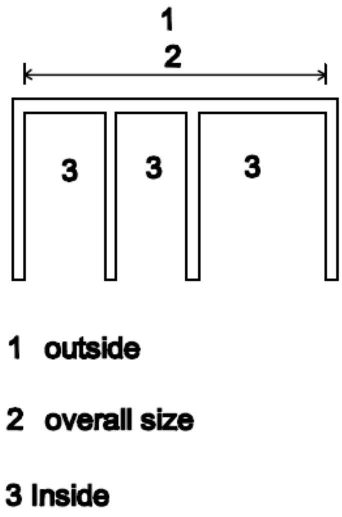


Figure 4.2 Definition of envelope area (EN 13829:2000)

4.2.3.3 Pressurization and Depressurization

According to the EN 13829:2000, it is recommended that two sets of measurements data should be made, one for pressurization and another for depressurization. But it is also allowable to have only one measurement data either for pressurization or depressurization. Referring to Geurts (2009), the results from two sets of tests are not the same although they are measured by using the same range of pressure and it is inevitable. The difference probably caused by the characteristic of building envelope and it has been investigated by Owe Svensson in 2008. From his experiences, the uncompleted building often shows higher depressurization result than pressurization one. For the finished building, the result is opposite. Whether the envelope is completely finished plays a vital role. Therefore, both pressurization and depressurization test is recommended to be conducted. The mean value of these two data is more reasonable to represent the actual airtightness.

4.3 Field test

Since this thesis has a practical focus, participation of the field tests is required. The measurement is executed by using Minneapolis Blower door and the illustration of this equipment is shown in Figure 4.3.

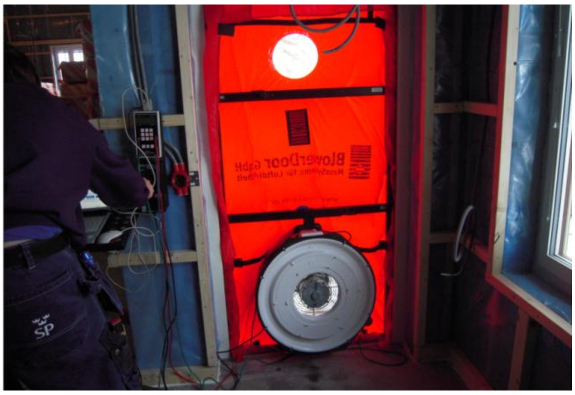


Figure 4.3 Test equipment

4.3.1 Description of the building

The building is located in Frölunda area, southern part of Gothenburg. It will be used as a recuperation centre for handicapped people after erection and it has only one storey with approximately 400 m^2 floor area in total. Generally, the wall is made of timber frame and concrete is used for its floor construction. The foundation type is slab on groud. Before the test, the technician estimated that the total area of building envelope is about 1416 m^2. In addition, the external wall from inside to outside mainly consists of gypsum board, wooden stud, air barrier, mineral wool, wind protection, nail batten, air gap and external cladding. The roof from outside to inside including outer facing, air gap, wind protection, wooden beams, mineral wool, air barrier, nail batten, air gap and inner facing. The fabric of external wall and roof are shown in Figure 4.4 and Figure 4.5 respectively.

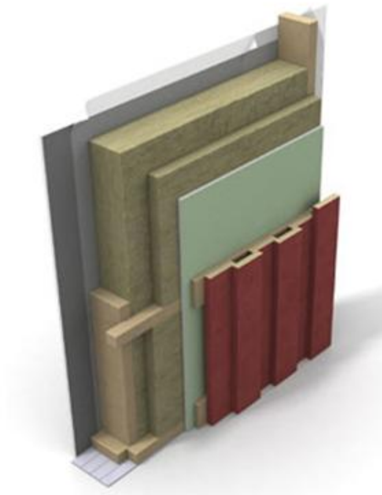


Figure 4.4 External wall construction [Paroc 2010]

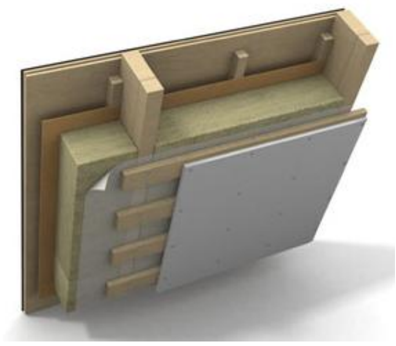


Figure 4.5 Roof construction [Paroc 2010]

4.3.2 Preparation

Before the test, following preparations according to EN 13829:2000 have to be done. All the windows and doors must be closed including door to attic if this space is not conditioned. In addition, all the interior doors must be kept open in order to maintain the total air volume of the building envelope. Furthermore, all intentional openings and service penetrations must be effectively sealed before the test, which is shown in Figure 4.6 and Figure 4.7 below.

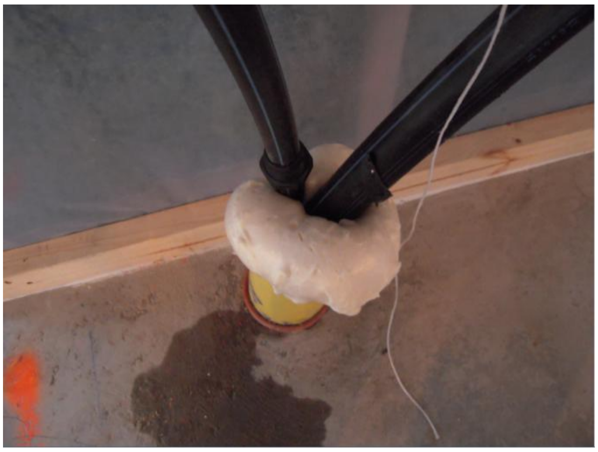


Figure 4.6 Seal the gap around service penetration

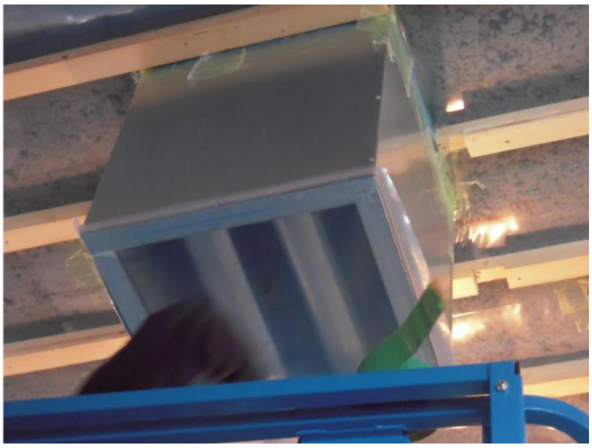


Figure 4.7 Seal the ventilation opening using plastic foil

4.3.3 Measurement

To measure the airtightness of construction, method B of the EN 13829:2000 standard was adopted. The measured outdoor temperature is -2 ℃, wind speed was 3.1 m/s and atmospheric pressure was approximately 10220 Pa. After all preparations had been done, the technician performed four sets of measurements. One group was with tape sealing the gaps around the exterior doors either for pressurization and depressurization and another group was without tapes sealing around the exterior doors. In calculation, the average value of pressurization and depressurization result was approved.

4.3.4 Results

With tapes sealing, the visible gaps around the exterior door is

$A_E = 1416\ m^2 \quad R_a = 170\ l/s \quad q_{50} = \frac{R_a}{A_E} = 0.12\ l/s,m^2$

Without tapes sealing, the visible gaps around the exterior door is

$A_E = 1416\ m^2 \quad R_a = 210\ l/s \quad q_{50} = \frac{R_a}{A_E} = 0.15\ l/s,m^2$

Those two q_{50} values are less than 0.8 l/s, m^2 by the former Swedish building regulation of Boverket, BFS 2002: 199:212. However, the builders and contractors also have a target on the airtightness which should not exceed 0.2 l/s, m^2 at 50 Pa pressure difference. Therefore, the construction company fulfilled the requirement precisely.

4.3.5 Investigation of leakage path

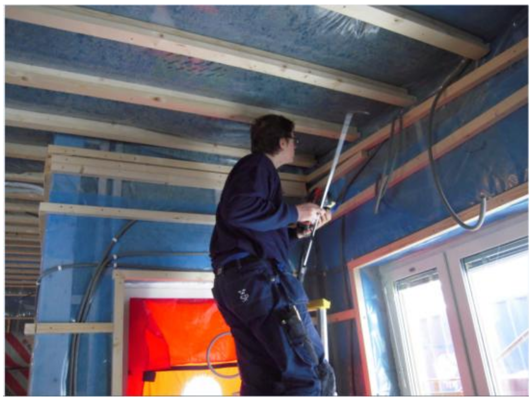


Figure 4.8 Detection by using air velocity meter

Figure 4.9 Detection by using infrared camera

There are mainly two ways of localizing the leakage paths. One way is to use air velocity meter to measure the velocity of penetrating air around the junction between walls and ceiling which is shown in Figure 4.8. If the velocity is too high, then it is recommended to tighten this area by using, for example, tapes or foam sealant. Apart from this, the gap around exterior door is another critical leakage path. The measured air speed at this part is always significantly higher than other paths. To avoid the leakage, more attention should be paid here. Another detection method is to use infrared camera to check the junction between walls and ceiling by introducing an under pressure in the building, then leakages can be easily traced by the camera. This is mainly due to the fact that the cold outdoor air penetrating into the building and cools the surface area around the leakage path, making them 'visible' in the camera (Petersson et al 1980). The dark colour in the middle of the camera (see Figure 4.9) indicates the temperature difference between the leaks and adjacent areas.

Some typical air leakage areas in the building are summarized in Table 4.1 below.

Table 4.1 Summary of leaky area

Leakage location	Problems description
Roof surface	Tears and holes on the surface of the plastic foil which are often caused by bad quality of workmanship when mounting the plastic foil on the insulation layer. Sometimes the builders forget to mend it.
Junction between roof and wall	Joints between roof and wall are not effectively sealed by tapes
Junction between wall and slab	When the plastic foil meets with ground floor, there are not always arrangements of sealing strip along the connection. Therefore, cold air can easily penetrate into the building through gaps between the connections.
Connection around windows	The plastic foil sometimes does not fold into the window reveal and no tapes are used to seal the inner corners around the window frame
Gaps around exterior doors	The gaps around exterior doors are not effectively sealed by the sealant
Junction between the steel column and roof	Small gaps around the steel column, sometime the builder forget to tape it.

4.3.6 Discussion

Figure 4.10 Seal the leaky areas

Figure 4.11 Maintain the integrity of plastic foil

Figure 4.12 Workmanship around the window frame

Since the air permeability of 0.2 l/s, m^2 had been set to be the project goal on airtighness, the measured building can be regarded as extremely tight. Generally, there are several reasons which make contributions to such tight building. First, the plastic foil between the mineral wool insulation and wooden stud is kept unbroken, especially between the ceiling and wall. Once the technician detect holes, the builder will tape it immediately (see Figure 4.11). Second, window frame has been effectively sealed by gun applied sealant which also applied to the gaps around the exterior door (see Figure 4.10). Third, the plastic foil is folded into the window frame and the inner corners of window frame are sealed by using tapes (see Figure 4.12). In conclusion, those builders put much effort on preventing the air leak into the building, thus, the workmanship and involvement of well educated builders become a dominant factor of such achievement. Apart from this, the foundation type of this house also has minor affect. Since neither basement nor crawl space is included in the construction, the building is likely to be easier to achieve good airtightness. Furthermore, it is worthy to mention that the willing and ambition of winning the future contract is another important reason for those builders to strive for airtight building. In other words, they want to be more competitive in the market.

5 Database

5.1 Description of the database

5.1.1 Construction process

The database is designed to classify the buildings with regard to airtightness, thus the structure of database and the selection of airtightness related factors are of great importance. To construct the database, there are three steps including literature reviewing, questionnaire and interviews. The intention of each step is trying to discover the most relevant airtightness related factors, thus make classifications reasonable. The process of constructing the database is shown in Figure 5.1 below.

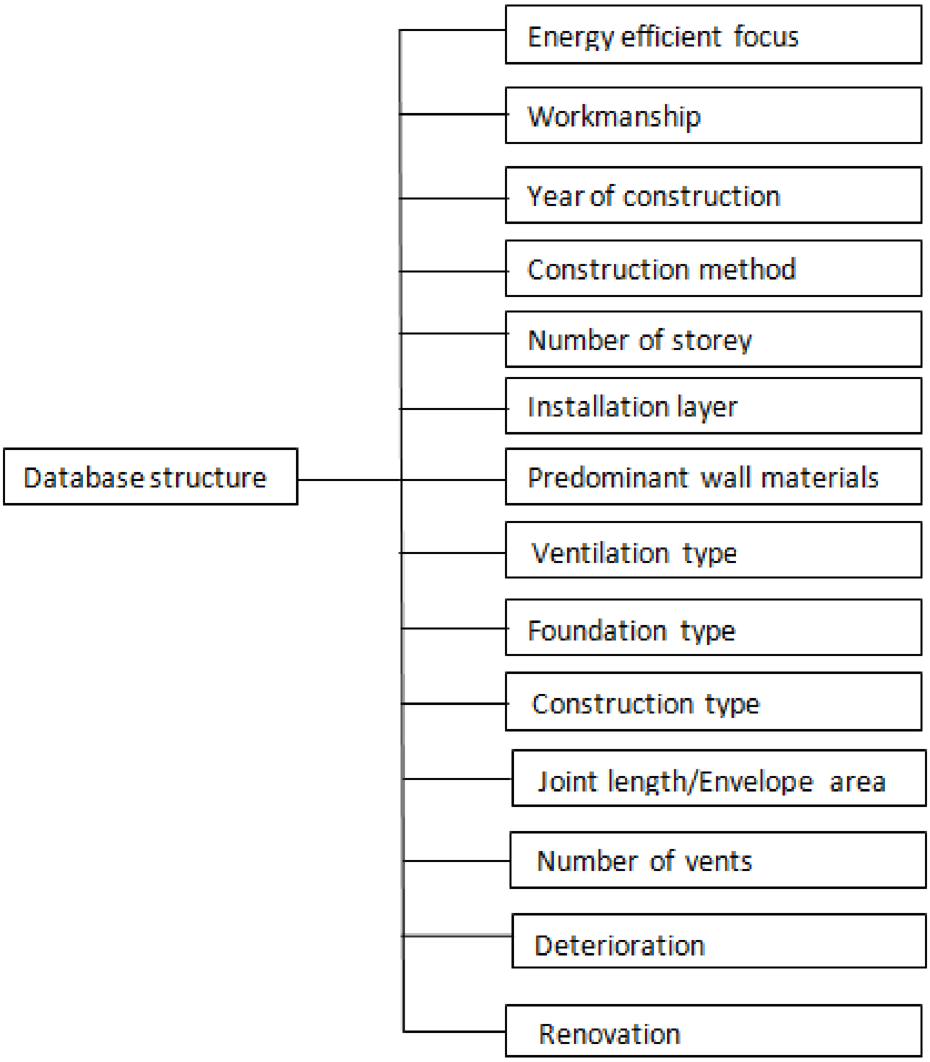


Figure 5.1 Structure of the database

5.1.2 Data collection

After completion of the database structure, data collection is processed. There are 374 measurement data over six countries. The data were collected through various sources including publication (See Appendix C) and reports provided by the airtightness test engineerd from SP. In addition, Sweden contributes to the large percent of data mainly due to two facts. One is the shortage of data source from other countries' tests caused by the author's limited accessibility. Another reason is that the project is considered to focus on investigating the building airtightness situation in Sweden, especially for the single family detached houses. As a consequence, 185 out of 374 buildings are accounted for the Swedish single family houses. The remaining buildings are made up by various building types, such as, industry buildings, multi-storey apartments and school buildings etc. More details about database can be seen in Appendix B.

5.2 Classification and discussion

5.2.1 Classification and survey of airtightness related factors

In order to provide a clear perspective on how the airtightness is affected by the building characteristics, the measurement data from the database were assessed regarding to various aspects, for instance, project goal, number of storey and the year of construction etc. The influences of different variables are described as follows:

Project goal and workmanship quality:

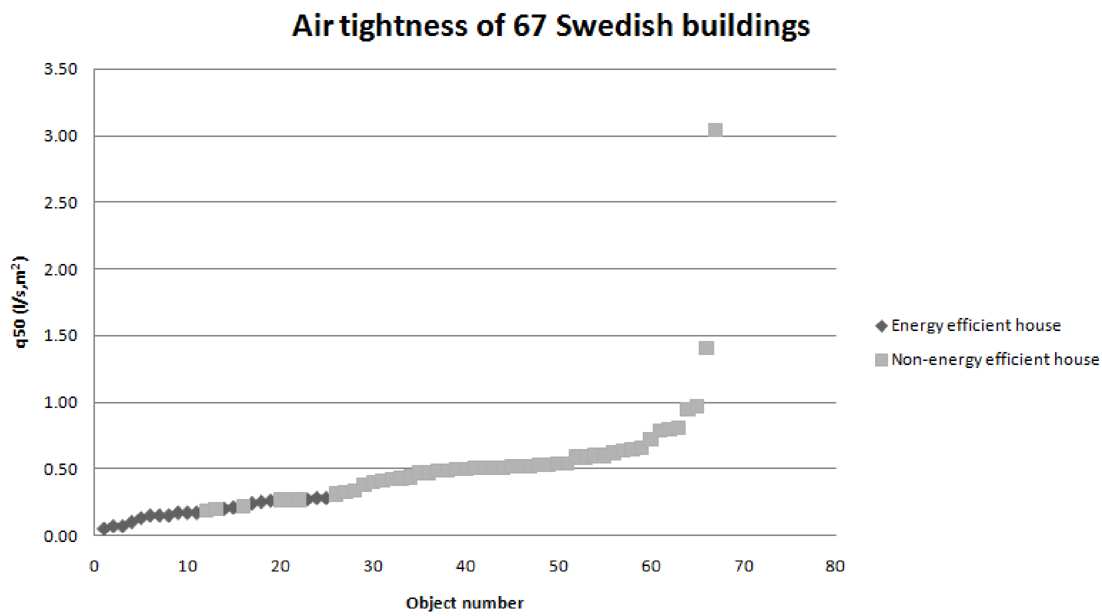


Figure 5.2 The influence of project goal of Swedish buildings

There are mainly two groups of buildings as shown in Figure 5.2, the dark circles indicate the houses that were aiming to be an energy efficient buildings while the remaining buildings were built with conventional building technology. It is quite obvious that the energy efficient buildings are more airtight than non-energy efficient ones. This is mainly because of strong awareness of the airtightness and involvement of well educated builders in the project. On the other hand, all energy efficient buildings fulfil the requirement of 0.3 l/s, m^2 for Swedish passive house.

In addition, the quality of workmanship was also assessed. As mentioned in chapter 3, the way of evaluating this factor has been simplified. There are three levels of workmanship quality according to Figure 5.3 and they are evaluated by airtightness test engineers. For instance, if the building is aiming to energy efficiency, then good quality of workmanship must be carried out in order to match that demand. On the other hand, the sample size here is not the same as shown in Figure 5.2. This is because of the lack of information on workmanship quality for remaining buildings. Nevertheless, the results reveal that good quality of workmanship will result in good airtightness undoubtedly and vice versa.

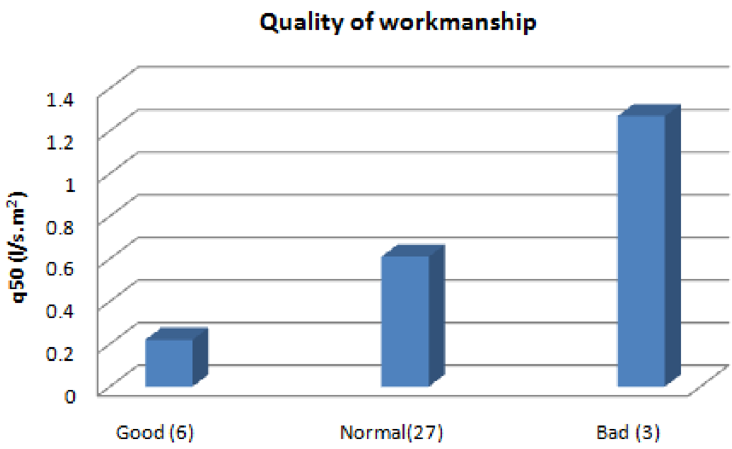


Figure 5.3 Quality of workmanship

Year of construction:

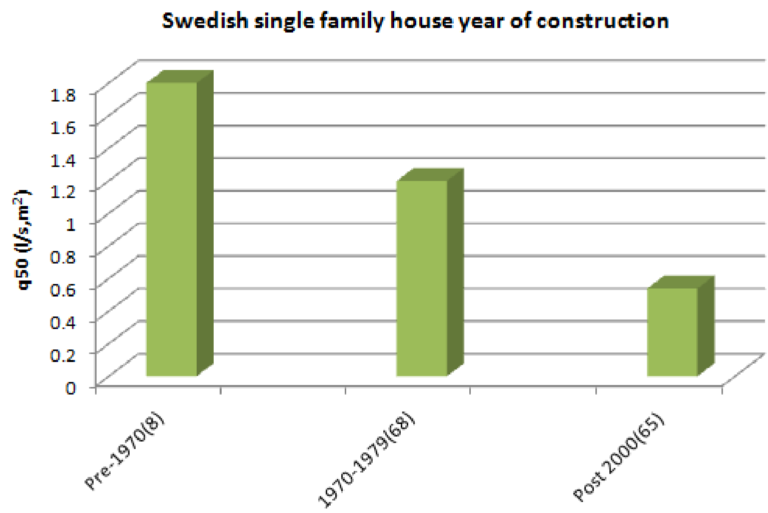


Figure 5.4 Year of construction versus q_{50}

As it can be seen from Figure 5.4, there is a clear correlation between the year of construction and q_{50} value. The houses are categorized into three age groups with 10 years interval and the numbers in the parentheses indicate the amount of samples. The

q_{50} value is decreasing gradually along the increasing year. Newly built houses are more airtight than old ones. In addition, the breakthrough occurred after 1979 where the difference between the post-2000 group and the 1970s group are quite noticeable. The average q_{50} value of the post-2000 group is approximately two and three times smaller than the buildings built during 1970s and pre-1970s respectively. Unfortunately, there is a shortage of the samples from 1980s and 1990s. Otherwise, it is possible to see how they differ from other age groups.

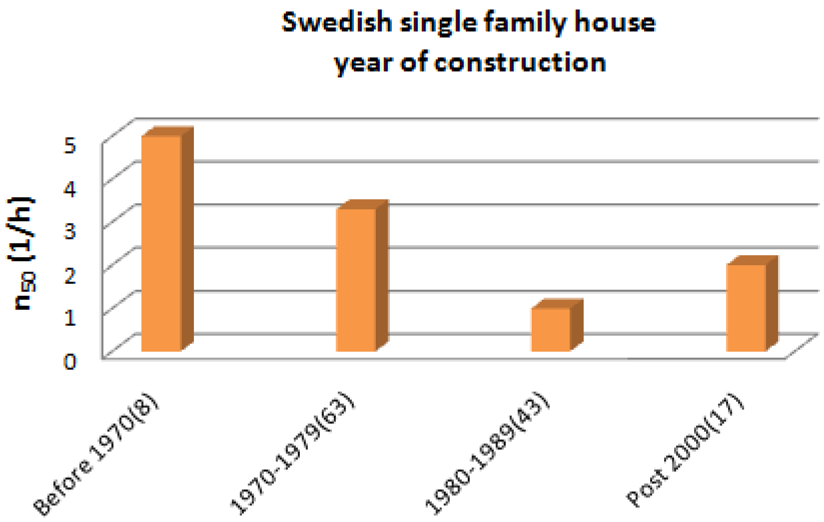


Figure 5.5 Year of construction versus n_{50}

As mention above, due to the lack of the q_{50} data from year 1980 and year 1989, it is not possible to compare this age group with others. Fortunately, the available n_{50} data during 1980s provides an opportunity to compare these different age groups. The correlation between n_{50} and q_{50} is discussed in Equation 2.1. As it can be seen from Figure 5.5, the houses are divided into four groups with 10 years interval. The building airtightness had been dramatically improved especially during 1980s. This is quite consistent with Sherman et al (1998) and it is presumably because of the influence of the world energy crisis. After this period, house builders put much effort on improving airtightness. Furthermore, it is strange that the n_{50} value of the post-2000 group is worse than the 1980s groups. The reason is that all the houses built in 1980s had a special focus on the airtightness according to Nilsson (1993), where 1 1/h was set to be the target value for the airtightness.

In addition, the results also are consistent with early research by Kronvall et al (1993), Figure 5.6 shows that the building airtightness were improved gradually along with the year of construction. The improvement becomes more noticeable between 1976 and 1988, during which the buildings are dramatically more airtight than former age groups.

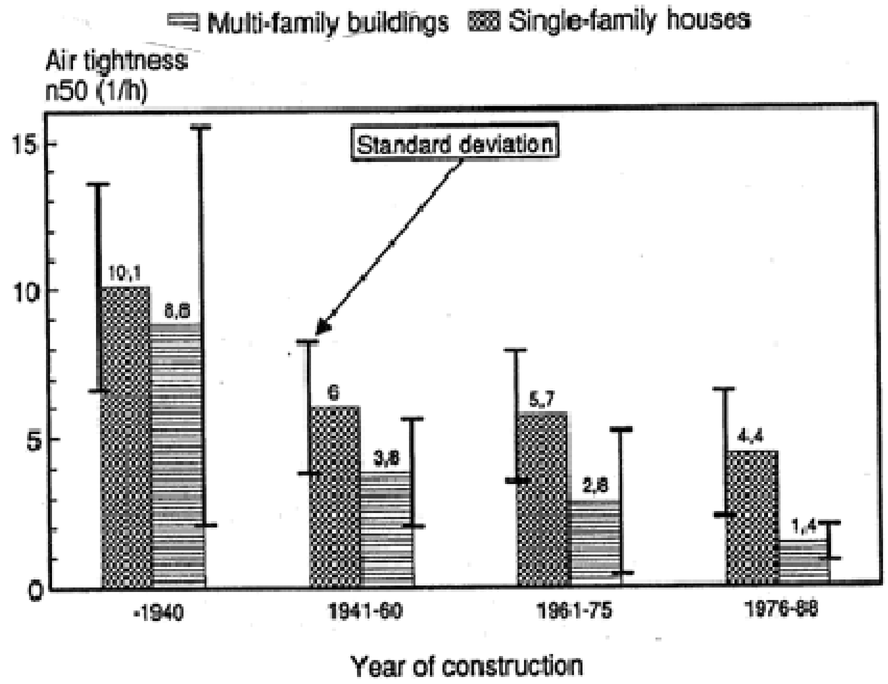


Figure 5.6 Airtightness of a sample of 50 single-family houses and 30 flats in multi-family houses of different ages in Sweden (Kronvall et al. 1993)

Predominant wall material:

During the discussion, the test engineers concluded that the buildings built with heavy material are usually more airtight than the ones built with light materials. This is mainly because of that the heavy materials are better linked together than light materials, especially along the connection between wall and floor or ceiling. On the other hand, when light materials meet with heavy materials, for instance, if someone looks closely to the connection between a sill and a concrete floor, there is a rugged connection strip which can allow enormous air leakage. The database categorized the buildings into two age groups with different materials and the results are shown in Figure 5.7 and Figure 5.8 respectively. According to Figure 5.7, the concrete construction (0.8 l/s, m^2) is the most airtight, followed by light-weight concrete (1l/s,m^2) and timber frame construction (1.4 l/s,m^2).

Apart from this, there is also a clear trend that heavy buildings are more airtight than light-weight ones after 2000s. However, the masonry block buildings are on average leakier than timber-frame ones according to Figure 5.8. This is mainly due to the fact that the plastic foils were widely applied on timber-frame houses and also the strong awareness of the airtighness during the construction, which can improve the airtightness dramatically. On the other hand, there were no special requirements on airtightness for masonry block buildings according to Pallin (2008), which result in relatively leakier constructions. Nevertheless, it is not advisable to compare the building airtightness solely based on the predominant wall materials. Alternatively, it is more feasible to combine with other information, for instance, workmanship quality and project goal. This is because of that these two factors are more dominant than predominant wall materials during this period.

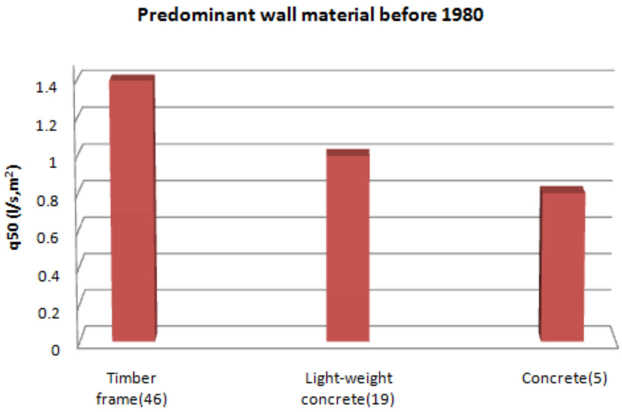


Figure 5.7 The influence of wall material before 1980

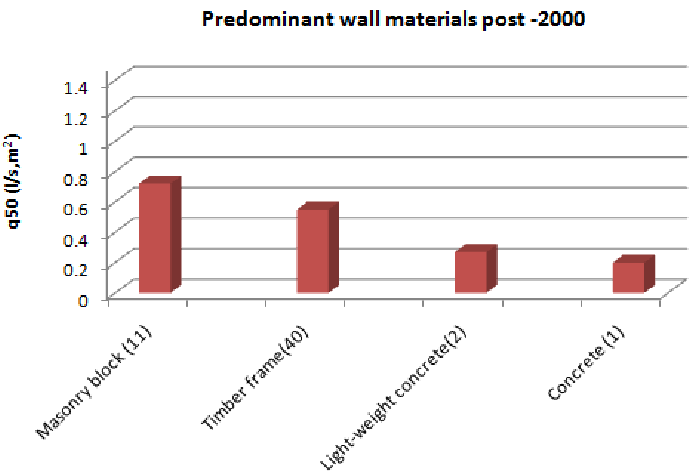


Figure 5.8 The influence of wall material after 2000

Construction method:

During the interviews, the test engineers suggested that it is difficult to ensure tightness between the prefabricated elements. In addition, the surface smoothness of the prefabricated element also plays a vital role on the airtightness. If no one in factory realizes that the airtightness is a crucial factor when aiming to construct energy efficient building, then it will lead to bad workmanship quality on the surface smoothness. As a consequence, the air can easily penetrate into the buildings through the rugged connection between these elements.

When taking an overall perspective on the influence of construction method, in general, the site-built constructions (1 l/s, m^2) are on average more airtight than the prefabricated ones (1.2 l/s,m^2), as it can be seen from Figure 5.9. It is worth mentioning that the discoveries are quite consistent with airtightness test engineers' experiences.

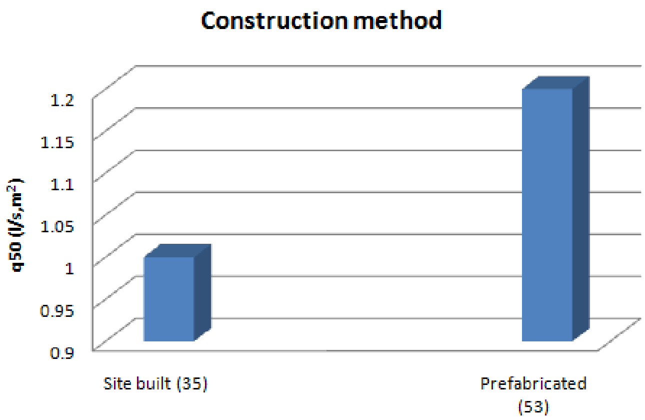


Figure 5.9 Overall influence of construction method

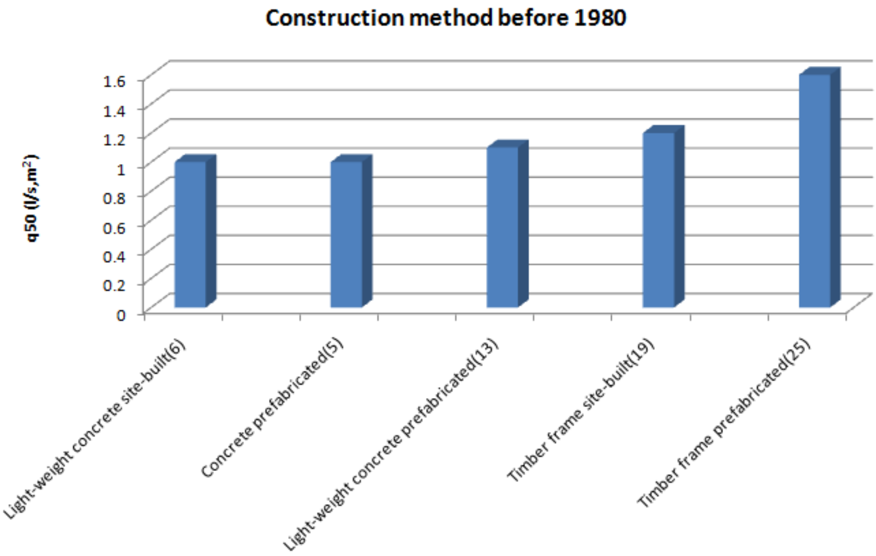


Figure 5.10 The influence of construction method before 1980

In addition, it is also interesting to take the cross dependency effect of other factors into consideration, such as, year of construction and predominant wall materials. As it can be seen from Figure 5.10, light-weight concrete site-built (1 l/s, m^2) and concrete prefabricate construction (1 l/s, m^2) are among the most airtight, followed by light-weight concrete prefabricated (1.1 l/s,m^2), timber frame site-built ((1.2 l/s,m^2) and timber frame prefabricated (1.6 l/s,m^2). However, the differences between the first four groups are not very noticeable. Therefore, the construction method only has a small effect on the airtightness during this period. The predominated wall materials appear to be more influential on airtightness. The heavy buildings are usually more airtight than light buildings regardless of the construction method. Furthermore, Figure 5.11 shows the impact of construction method on airtightness after year 2000. It is obvious that the site-built buildings are more airtight than prefabricate ones. Meanwhile, it is also clear that the site-built timber-frame houses are even more airtight than the site-built light-weight ones. The main reason is that most of the site-built timber houses were constructed to be energy efficient, which makes them extremely airtight. The workmanship and project goal again become more dominated on airtightness rather than the construction method.

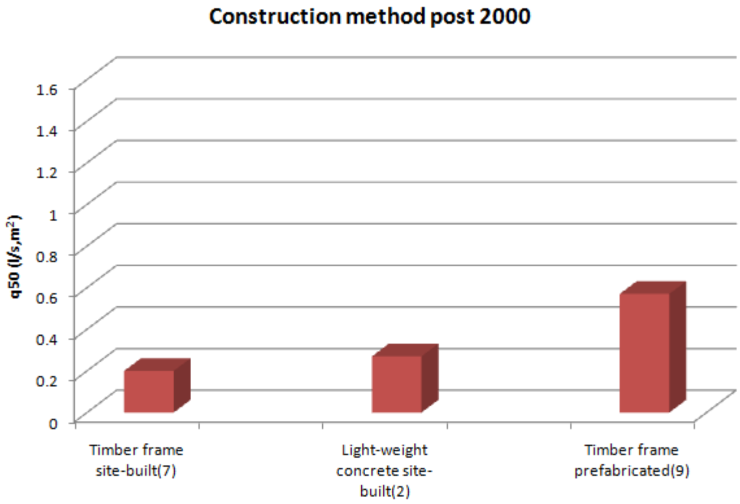


Figure 5.11 The influence of construction method post 2000

Number of storey:

The impact of number of storey focus on discussing the Swedish single family houses, since large amount of measurement data come from this building type. The results are shown in Figure 5.*12*.

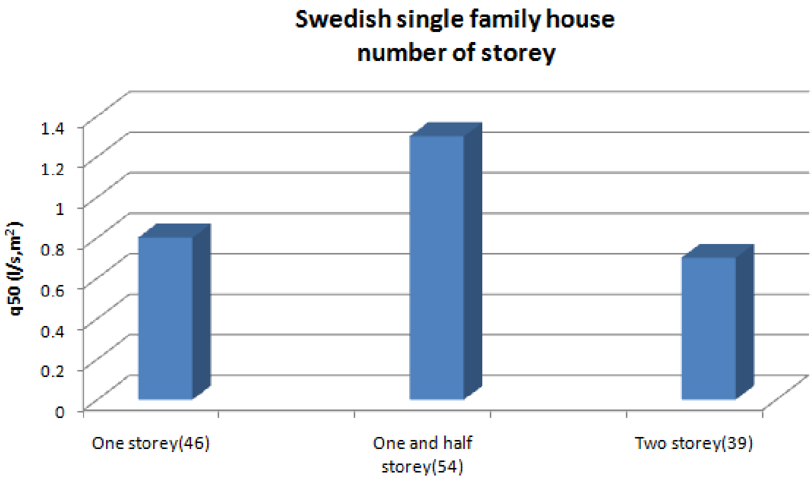


Figure 5.12 The influence of number of storey

According to Figure 5.12, the airtightness of one-storey houses (0.8 l/s,m^2) and two-storey houses (0.7 l/s,m^2) are roughly equivalent while one and half storey house (1.3l/s,m^2) is the worst case. This is probably due to the presence of knee wall construction (Figure 5.13) in Sweden. According to Mattsson (2007), this part could be quite tricky to make airtight unless excessive efforts have been put on it. The plastic foil, below the attic floor, has to be jointed to the plastic foil in the knee wall in order to form a continuous air- and vapour- tight layer. The presence of joists makes this difficult and time consuming. An alternative method is to install pieces of solid wood between the joist and then terminate the foil at the upper and lower edge of these pieces. In this case it is not necessary to cross the joist with plastic foil.

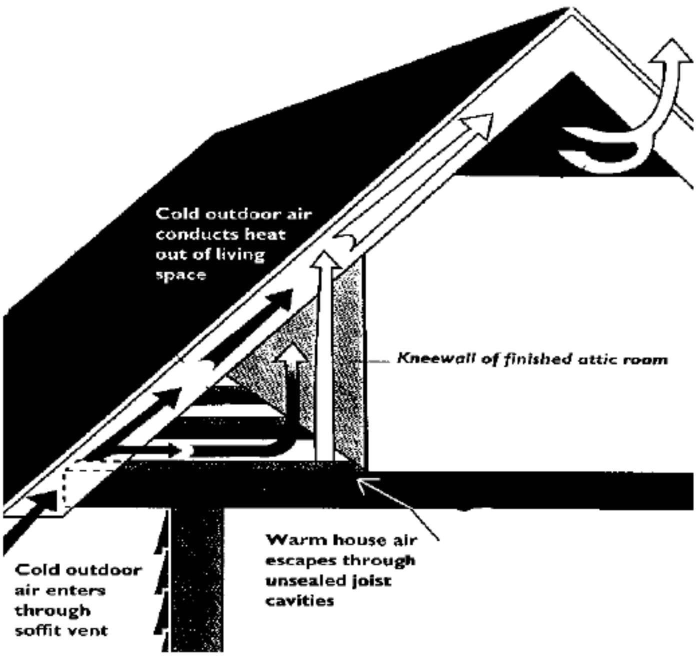


Figure 5.13 Knee wall construction (Pierce, 2000)

In addition, some Swedish semi-detached houses (Eliasson, 2010)) are also assessed and they are mainly categorized into three groups. According to Figure 5.14, there is a clear correlation between the airtightness and number of storey. The more number of stories, the worse airtightness it has. One-storey houses are almost always the best case on the airtightness.

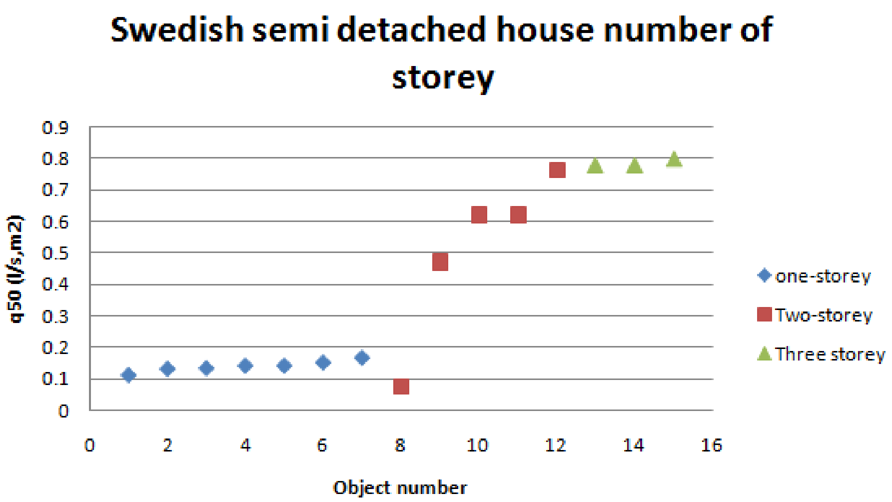


Figure 5.14 The influence of number of storey for Swedish semi-detached house

As discussed above, the number of storey appear to be very sensitive to the airtightness not only in Sweden, but for some other countries. In order to provide quantitative analyses on this issue, a simple calculation model is studied to show how the airtighness varies with respect to the increasing numbers of storey.

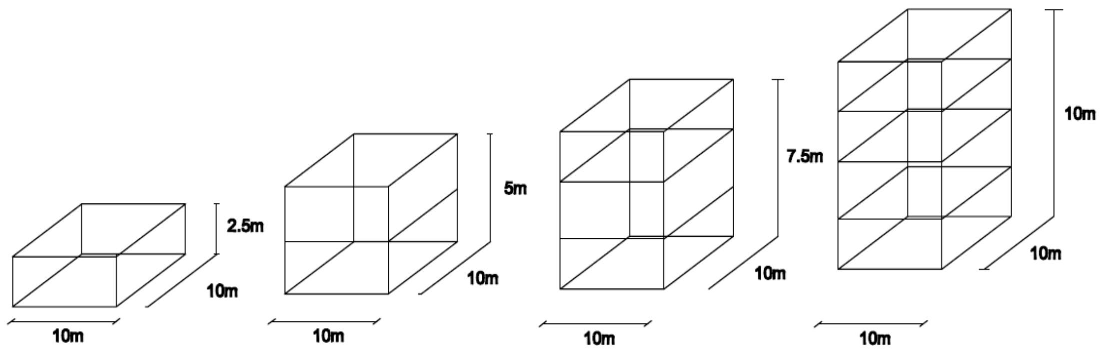


Figure 5.15 Dimension of four buildings

According to Figure 5.15, four regular block buildings are considered as simplified models for calculations. They have the same floor area but different height. The dimension of the window is assumed to be 1.5m*3.6m. For each floor, four windows are installed on each façade. This information is summarized in Table 5.1.

Table 5.1 Summary of four buildings' characteristics

Number of storey	Joint length (m)	A_E (m^2)	Joint length + window frame length (m)
1	90	300	130.8
2	140	400	221.6
3	150	500	312.4
4	240	600	403.2

Note: Assume each facade has three windows on each floor, the dimension of window frame is assumed to be: width*length = 3m * 2.1m

To calculate the air flow rate through the walls, ceiling and joint length, some equations from Hagentoft (2001) will be used.

Air flow through the permeable materials:

$$R_a = A_{\text{inf}} \cdot \frac{k}{\mu} \cdot \frac{\Delta P}{d} \qquad (5.1)$$

Where R_a (m^3/s) – Air flow rate

A_{inf} (m^2) – Infiltrated area by air

k (m^2) – Permeability

μ (kg/m• s) – Kinematic viscosity of air d (m) – Thickness of wall and ceiling

Table 5.2 Some assumed values for calculation

$k (m^2)$ Fiber board (low density)	μ (kg/m• s) at 10℃	ΔP (Pa)	d (m)
6.7*10e-12	17.5*10e-6	50	0.3

To calculate the q_{50} value caused by air flow through the walls and ceilings, the values from Table 5.1 and Table 5.2 are inserted to Equation 5.1

Table 5.3 q_{50} *values caused by air flow through walls and ceilings*

Number of storey	Ra (l/s)	A_E (m^2)	q50 (l/s,m^2)
1	12.8	300	0.043
2	19.1	400	0.048
3	25.5	500	0.051
4	31.9	600	0.053

Air flow through the air gap:

$$S_g = \frac{12 \cdot \mu \cdot L}{b^2 \cdot A} \qquad (5.2)$$

Where: S_g (Pa• s/m^3) – resistance of air gap

L (m) – Thickness of the building component

b (m) – Height of air gap

A (m^2) – Area of air gap

μ (Ns/m^2) – Kinematic viscosity of air

$$S_e^{'} = \frac{1.8 \cdot \rho_a}{2 \cdot A^2} \qquad (5.3)$$

Where: $S_e^{'}$ [Pa/(m^3/s)] – Air flow resistance

ρ_a [kg/m^3] – Density of air

A (m^2) – Area of air gap

$$R_a = \frac{1}{2 \cdot S_e^{'}} \left(\sqrt{S_g^2 + 4\Delta P \cdot S_e^{'}} - S_g \right) \qquad (5.4)$$

Where: R_a [m^3/s] – Air flow rate

ΔP [Pa] – Pressure difference over the building envelope

Table 5.4 Some assumed values for calculation

b (mm)	L(m)	Air gap area (m^2) at 1 m length	ρ_a (kg/m^3)	μ (kg/m• s) at 10℃	Ra per 1 m (l/s,m)	ΔP (Pa)
0.2	0.3	1*0.2*10e-3	1.25	17.5*10e-6	7.6*10e-2	50

Table 5.5 q_{50} values caused by air flow through the joint length and window frame length

Number of storey	Joint length (m)	Ra (l/s)	q_{50} (l/s,m^2)	Joint length + window frame length (m)	Ra (l/s)	q_{50} (l/s,m^2)
1	90	68.4	0.23	130.8	99.4	0.33
2	140	106.4	0.27	221.6	168.4	0.42
3	190	144.4	0.29	312.4	237.4	0.47
4	240	182.4	0.3	403.2	306.4	0.51

The results from calculations are plotted in Figure 5.16.

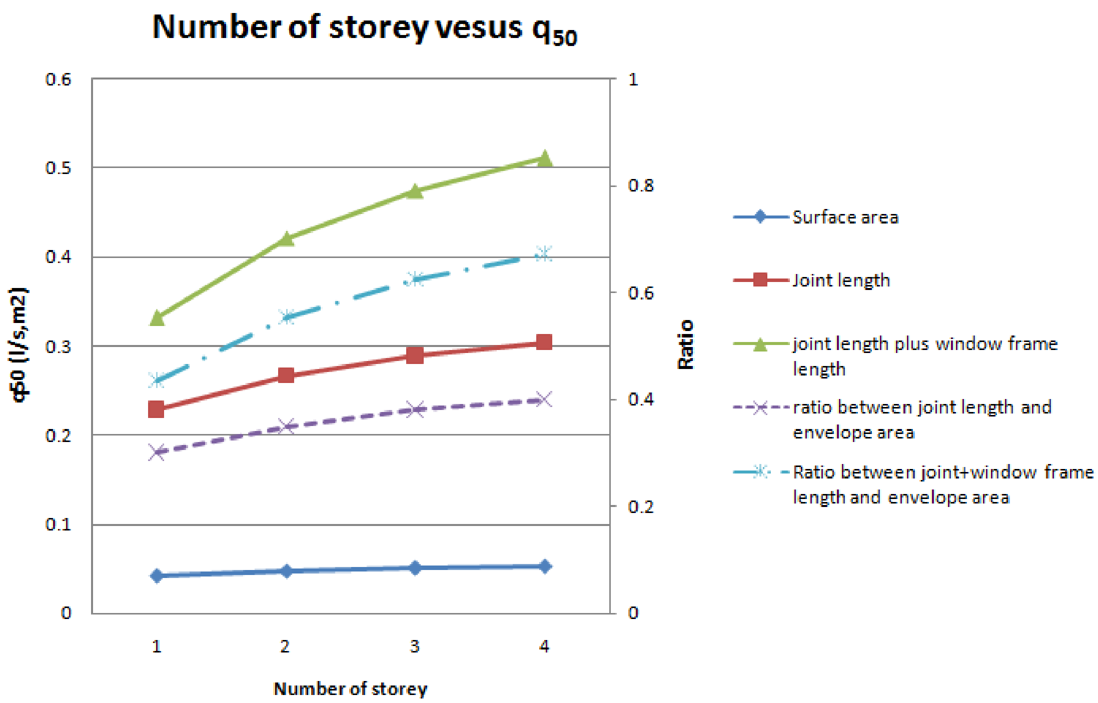


Figure 5.16 Relationship between number of storey and q_{50}

As it can be seen from Figure 5.16, the q_{50} value slightly raises with increasing amount of surface areas, while the q_{50} value steadily grows with increasing amount of the joint length. In addition, when taking window frame length into consideration, the q_{50} value becomes even worse than former two cases. It rapidly ascends with increasing amount of joint and window frame length. Furthermore, it is noticeable that the ratio between the joint length/joint adds window frame length and envelope area behaves the same trend as the q_{50} value. In other words, the airtightness is proportional to the ratio between the joint length and surface area. The higher ratio the building has, the leakier it becomes.

Coincidently, 11 one-storey Swedish single family houses from the database were assessed and their perimeter length of bottom and top plate together with vertical lengths of exterior corners were taken into consideration. According to Figure 5.17, the vertical dotted line stands for the average ratio between joint length and envelope area. The horizontal dotted one represents the average q_{50}. Apparently, the buildings with the ratio between joint length and envelope area are below the average level tend to be more airtight than those with ratio above the average level. Two houses have q_{50} value of 0.07 l/s, m^2 and 0.05 l/s, m^2 in comparison with other eight houses. However, there is one exception that the ratio between joint length and envelope area is 0.29 and its airtightness (0.2 l/s, m^2) is below the average level. Nonetheless, there is high degree of association between the airtightness and joint length to envelope area ratio.

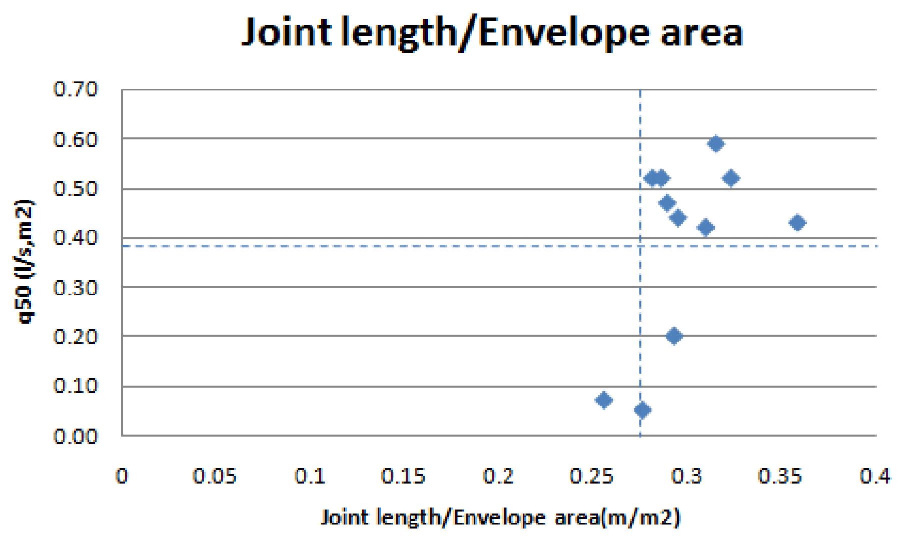


Figure 5.17 The influence of ratio between joint length and envelope area

Foundation type:

As mention in previous chapter, the foundation type has influence on the airtightness. Therefore, 117 Swedish single family houses from the database were assessed regarding to different foundation types. They were also divided into two age groups, pre-1980s and post-2000s. The results are shown in Figure 5.18 and Figure 5.19 respectively.

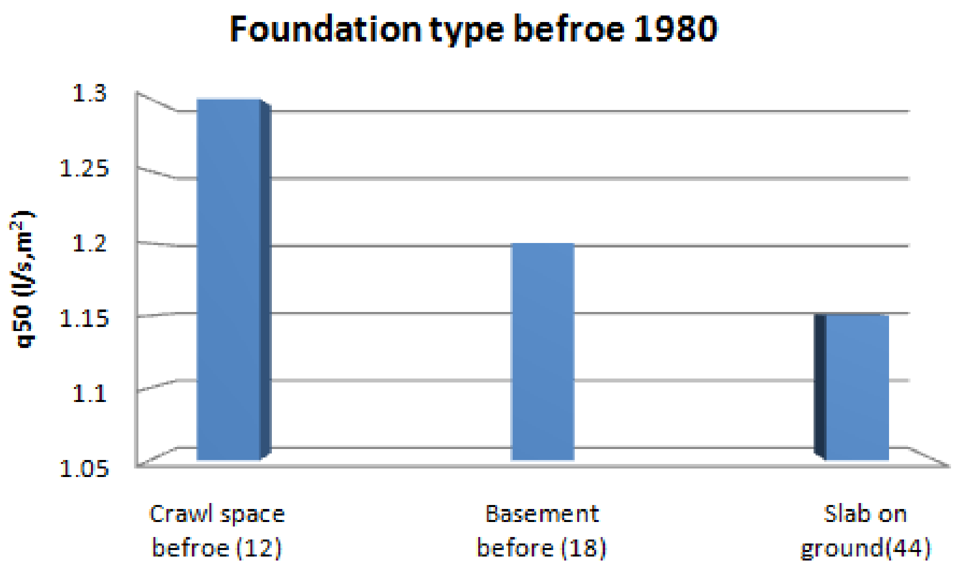


Figure 5.18 The influence of foundation type before 1980

According to Figure 5.18, the buildings with crawl space (1.3 l/s, m^2) are the worst. Based on the consultation from test engineer, this is probably because there was usually no arrangement of plastic foil between the floor joist and insulation before 1980, which makes air penetrating into the building through crawl space easily. In addition, the foundation type also shows small impact on the airtightness of post-2000 group as shown in Figure 5.19. However, the differences between foundation types are quite small after year of 2000. It is apparent that buildings with slab on ground (0.48 l/s, m^2) are on average more airtight than the one with basement (0.53 l/s, m^2) or crawl space (0.53 l/s, m^2). However, there is only one sample of basement type. The real differences between basement type and other two types of foundation need to be further assessed by feeding more data into the database.

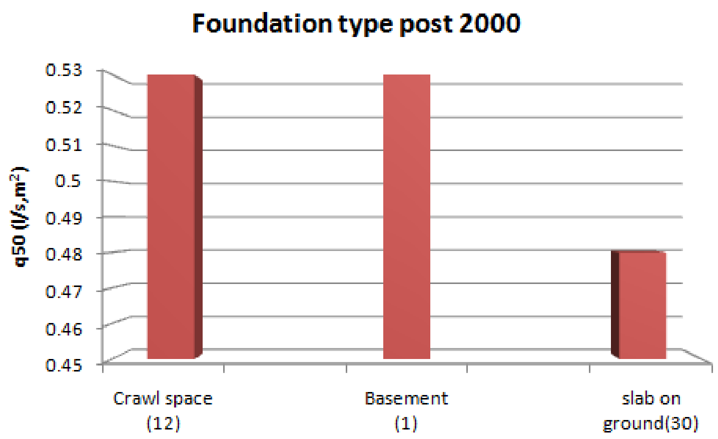


Figure 5.19 The influence of foundation type after 2000

Ventilation type:

According to the feedback from questionnaire, the buildings with mechanical exhaust ventilation or natural ventilation has more leakage areas in the external walls and roof than the buildings with balanced ventilation. According to Figure 5.20, the buildings with balanced ventilation (0.7 l/s, m^2) are the most airtight, followed by the buildings with mechanical exhausted ventilation (1 l/s, m^2) and with natural ventilation (1.5 l/s, m^2). The results are in line with Kalamees (2007) and it states that the air leakage is a crucial factor on the performance of the ventilation systems. Therefore, ventilation standards set the requirements for airtightness. For instance, the National Building Code of Finland Part C3 provides that to guarantee a proper function of ventilation devices, airtightness of a building envelope is recommended to be n_{50} = 1 1/h. The Belgian ventilation standard NBN D50-001 set the airtightness criteria for dwellings with mechanical ventilation $n_{50} < 3$ 1/h and in the case of the balanced ventilation with a heat recovery: $n_{50}<1$ 1/h (Kalamees 2007).

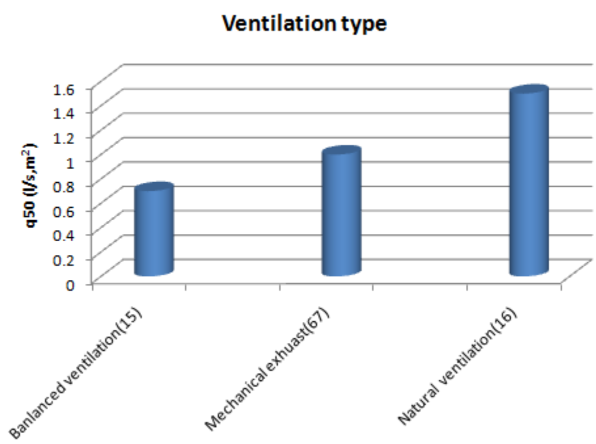


Figure 5.20 The influence of ventilation type

In order to analyze how the impact of ventilation type is related to year of construction, the ventilation type is also subdivided into two age groups including pre-1980 and post-2000. As it can be seen from Figure 5.21, the differences between the three categories within the pre-1980 group are not remarkable, however, there is still a clear trend that the balanced ventilation type is the most airtight (1 l/s, m^2), followed by mechanical exhausted (1.3 l/s, m^2) and natural ventilation (1.5 l/s, m^2). By contrast, the ventilation type seems to be more influential after year 2000. According to Figure 5.22, the building with balanced ventilation (0.13 l/s, m2) is more airtight than mechanical exhausted one (0.63 l/s, m^2). This is probably due to the fact that the higher demand on indoor air quality and energy efficiency is set to be the project goal in recent built construction, which inevitably requires an extremely airtight building envelope to ensure the balanced ventilation system functioning properly.

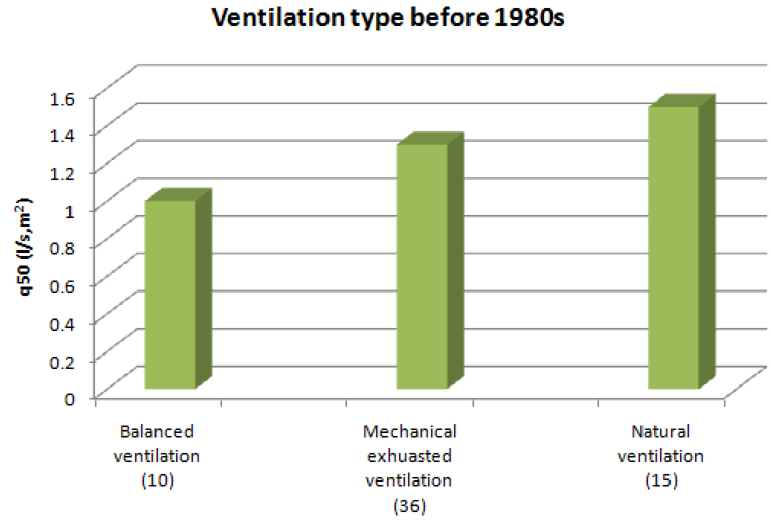


Figure 5.21 The influence of ventilation type before1980

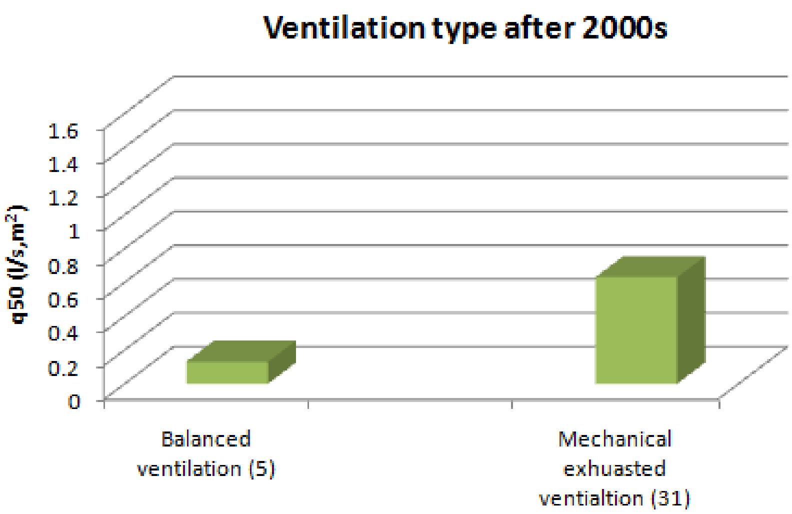


Figure 5.22 The influence of ventilation type after 2000

Construction type:

219 Swedish buildings with various construction types are collected in the database. The construction type is defined by the function of the building in this report. According to Figure 5.23, single family detached houses are slightly leakier than other building types. The differences between industrial buildings, row houses and school buildings are not very noticeable, all of their average q_{50} values are around 1.1 l/s, m^2. In contrast, multi-storey buildings appear to be leakier than others. However, there is only one sample, thus it cannot represent the real characteristic of this building type before 1980s. In conclusion, the construction type in Sweden before 1980 does not show a remarkable influence on the airtightness.

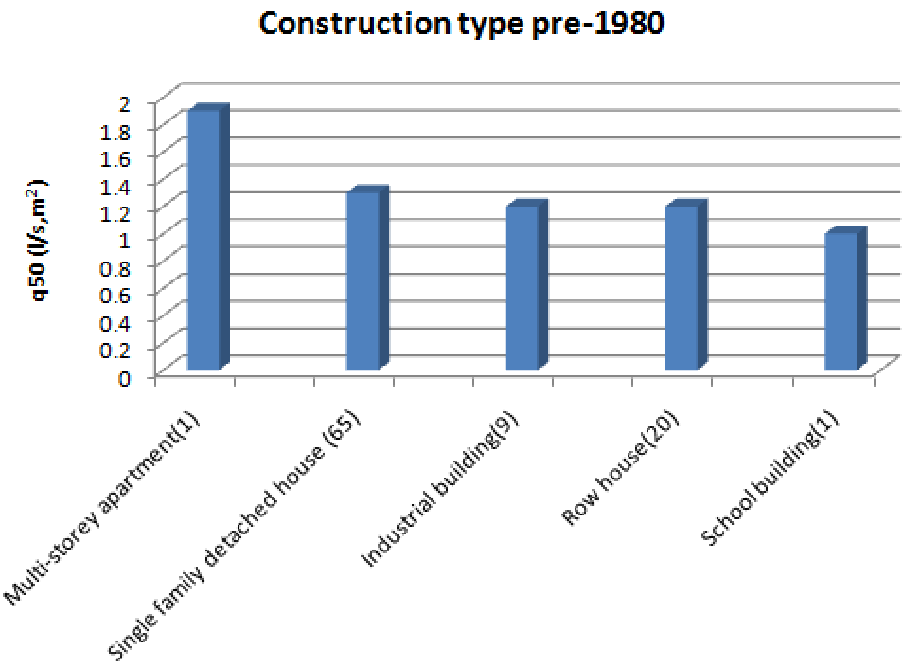


Figure 5.23 The influence of construction type before 1980

In addition, the construction type is also compared for the post-2000 group as it can be seen from Figure 5.24. Single family houses are the worst case on the airtightness. This is probably due to the large variability on the workmanship quality of single family houses, larger percentage of the houses were built by workers with poor knowledge on the airtightness, thus it results in normal or rather bad quality of workmanship. Only a small amount of houses were constructed with strong focus on the airtightness. At the same time, multi-storey buildings were constructed to be energy efficient according to airtightness test engineer's investigation, which inevitably leads to the superior workmanship quality and low q_{50} value.

Furthermore, when comparing the two figures, it is quite noticeable that the q_{50} value of each building type is significantly reduced after year 2000. Thus, workmanship quality and year of construction is more influential on the airtightness than construction type.

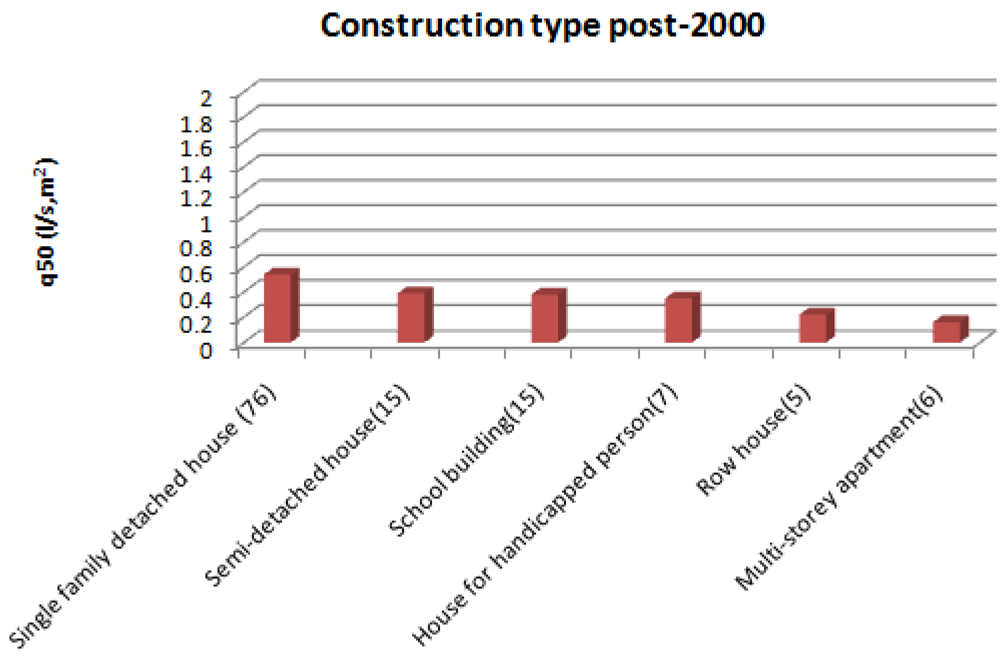


Figure 5.24 The influence of construction type after 2000

When referring to other studies, the measurement data from Litvak et al (2001) also provides an opportunity to assess the impact of the construction type on building airtightness. As shown in Figure 5.25, the offices and halls tend to be more sensitive to air leakage than hotels and education buildings. According to Litvak et al (2001), this is probably owing to their more complex technical ceilings which make them difficult to be airtight.

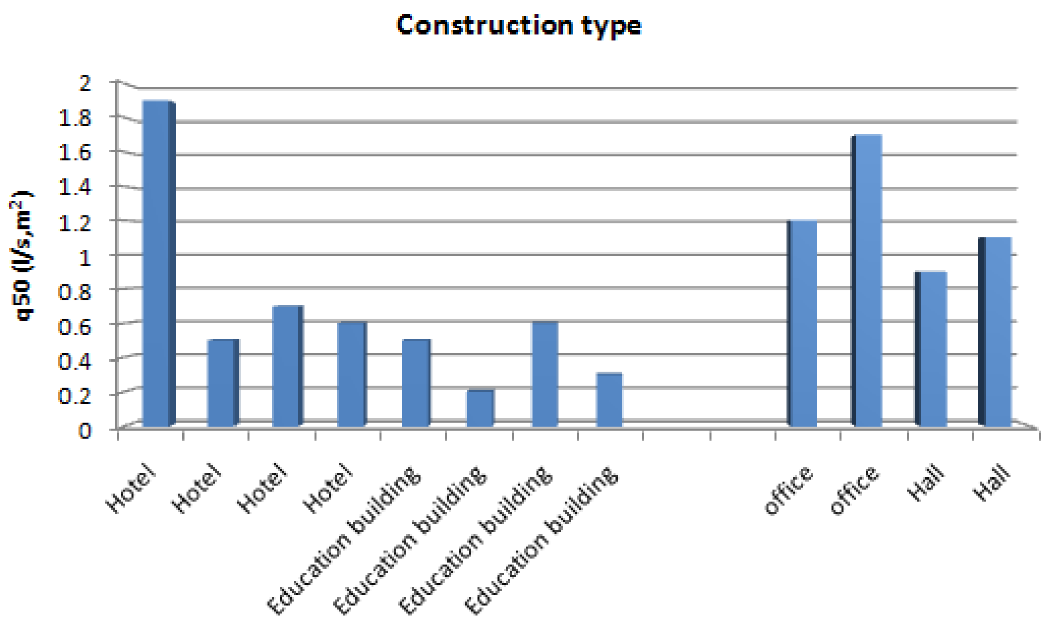


Figure 5.25 The influence of construction type

Apart from the classifications presented above, some other interesting factors are also discussed. It will be of help to the readers to know how these factors are linked to airtightness.

Installation layer:

During the interviews, the test engineer stressed that the use of an installation layer in building envelope will help to improve the building airtightness. It is mainly due to the fact that the installation layer avoids the cables or pipes from directly going through the air barrier, such as, plastic foil, thus it reduces the risk of air penetrating into the building from the gaps around the electrical cables and installation pipes. As it can be seen from Figure 5.26, the buildings with installation layer (0.31 l/s,m2) are more airtight than the those without installation layer (0.73 l/s,m2). In addition, according to Petterson et al (1980), electrical installations and holes for pipes passing through the construction often give rise to problems with regard to the insulation and airtightness performance. Air movements often occur both in the conduits provided for electric cables, and in the ducts formed between the conduits and the insulation material. Electric cables laid in the vicinity of the eaves are particularly sensitive. In cases where electrical installations have been placed not in the external wall but in an inner wall, the insulation and airtightness performance has generally been better. The scheme of installation layer is shown in Figure 5.27, where the plastic foil is not broken by electrical cables and installation pipes. Therefore, the application of installation layer is of great importance when aiming to construct an airtight building. The results are consistent with Eliasson (2010) as it can be seen Figure 5.28. It is quite noticeable that the air leakage rates do not exceed 0.4 l/s, m^2 for the buildings constructed with installation layer. By contrast, most of the buildings without installation layer have air leakage rates above 0.4 l/s, m^2, up to 0.8 l/s, m^2.

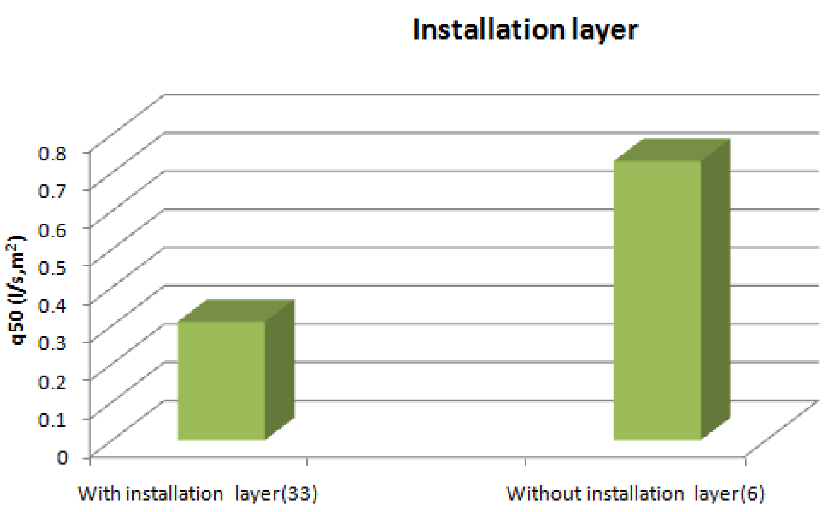


Figure 5.26 The influence of installation layer (measurement data by SP)

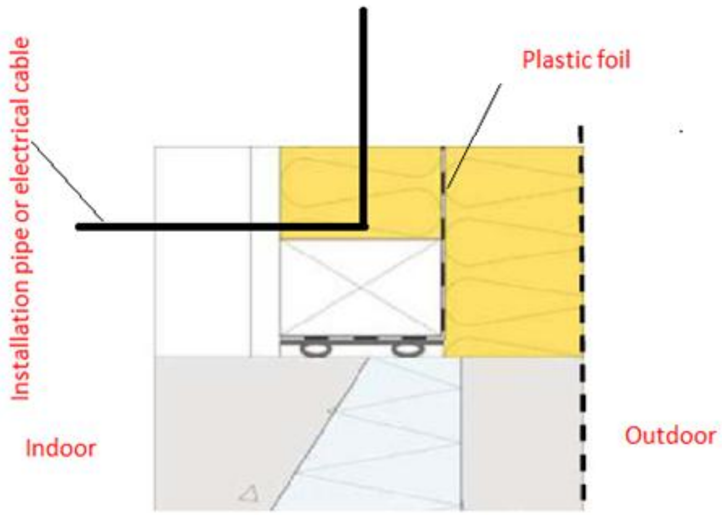


Figure 5.27 Illustration of installation layer (Eliasson, 2010)

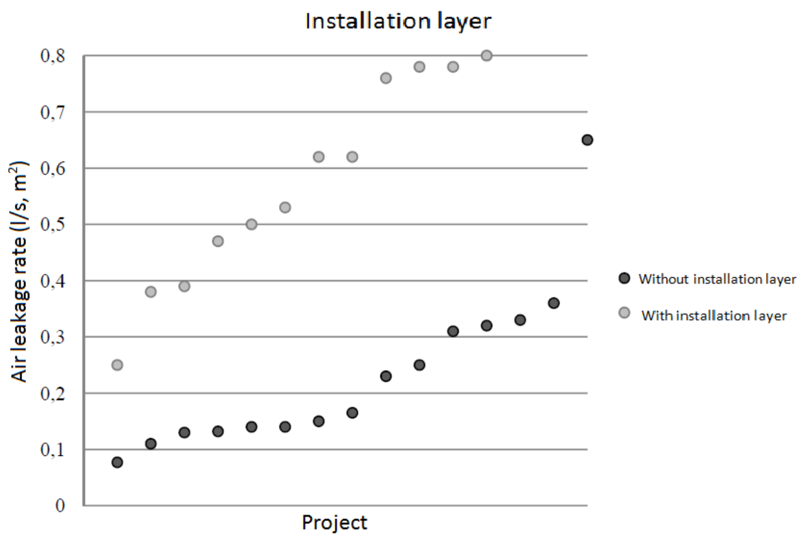


Figure 5.28 The influence of installation layer (Eliasson, 2010)

Number of vents:

The measurement data from Biggs et al (1986) provides an opportunity to estimate the impact of amount of vents on airtightness. As shown in Figure 5.29, the horizontal dotted line represents the average air leakage rate while the vertical dotted one indicates the average amount of vent. There is a clear trend that most houses that exceed the average number of vents level appear to be more sensitive to air leakage. By contrast, houses equipped with fewer amounts of vents are on average more airtight than former ones. All of their q_{50} values are under the horizontal dotted line. Therefore, it is reasonable to say that there is a high degree of association between the amount of vents and the airtightness. According to Biggs et al (1986), the improvement on the airtightness of the Australian houses was achieved largely by the elimination of fixed wall vent since it takes the form of wide, unobstructed slots above each window. As a consequence, air can easily penetrate into the building through this leaky path.

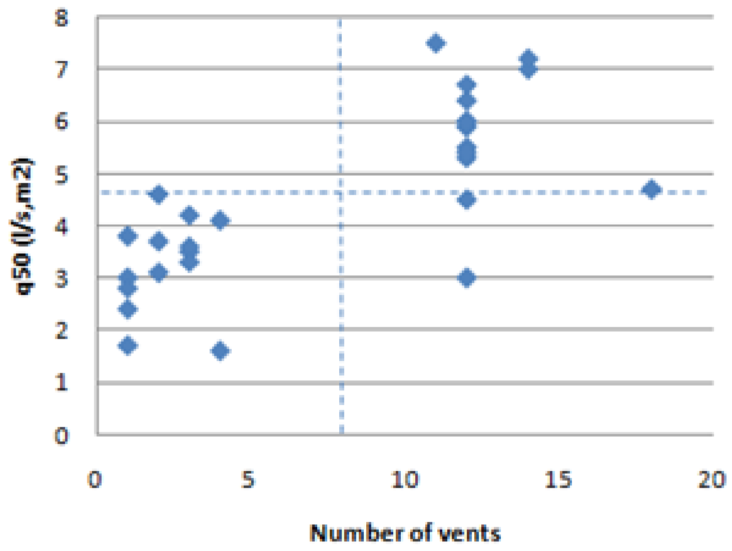


Figure 5.29 The influence of the number of vent (*data source from* Biggs et al. 1986)

As discussed above, installation layer and number of vents has a strong influence on airtightness and all of them can be classified into the service penetration category. Therefore, if someone tries to construct an airtight building, excessive attention must be paid to the critical leaky areas. The use of an installation layer, right choice of sealing materials and rigorous surveillance on the leaky area is of great significance during the construction phase.

Deterioration:

Based on the conventional wisdom, someone would say that the building airtightness degrades along with its increasing operation time. However, the real situation can only be proved by facts. In this section, two cases come from German and Sweden will be discussed to observe how the airtightness varies regarding degradation.

There were forty one Swedish single family houses constructed during 1980s and all of them were subjected to blower door test right after the completion. In 1993, another set of tests were conducted to these houses again (Nilsson et al, 1993). According to Figure 5.30, the results show that most of the houses' airtightness is not or slightly changed. However, there are four houses (2, 16, 24, 38) where the airtighness are significantly changed. This is mainly because of that the house owner made some changes in the attic spaces by their own efforts, thus it makes the airtigtness worse than before. In addition, the airtightness of house number four had been improved dramatically mainly owing to the retrofitting work. The house had been effectively sealed again which made a lower n_{50} value than before (Nilsson et al, 1993). Therefore, the building airtightness will not be changed a lot by its natural degradation, unless some parts are changed or mended by house owner according to this investigation.

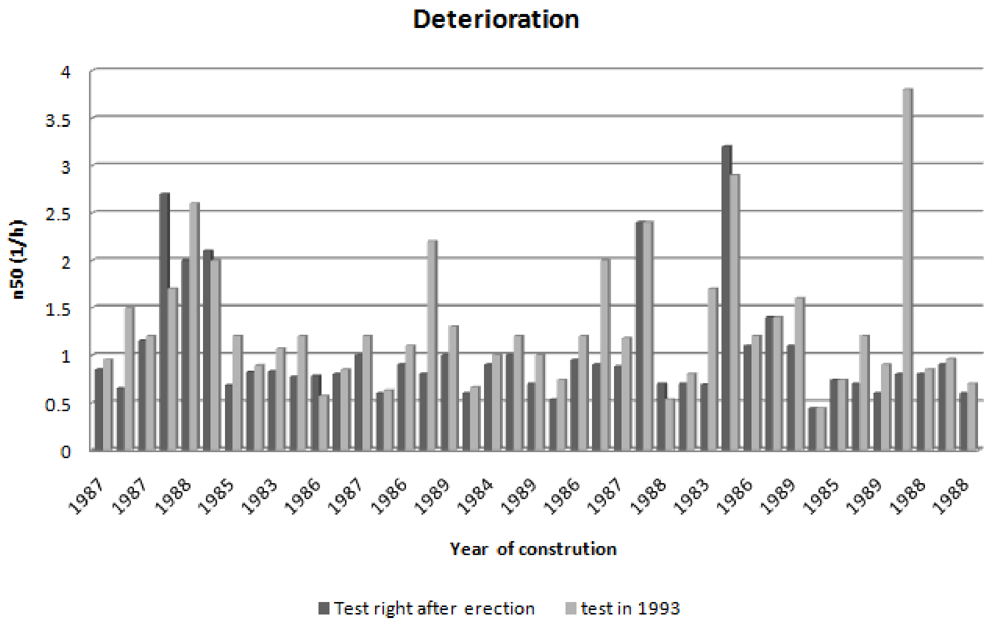


Figure 5.30 The influence of deterioration

Coincidently, some other investigations on the deterioration of the building airtightness were also conducted in Germany. There are two sets of blower door measurements in 2000 and 2002 respectively. According to Figure 5.31, the average infiltration rate of all fifty two row houses measured right after the erection was 0.37 1/h, while the average n_{50} value of thirty one houses was 0.46 1/h which were measured again two years later. However, there are five exceptions which exceed the Germany passive house requirement (n_{50}=0.6 1/h). Unfortunately, no reason can be traced according to Klutting et al (2009). Nevertheless, these two sets of measurements prove that the airtightness of the most houses had slightly changed during two years and all of them still fulfil the German requirement.

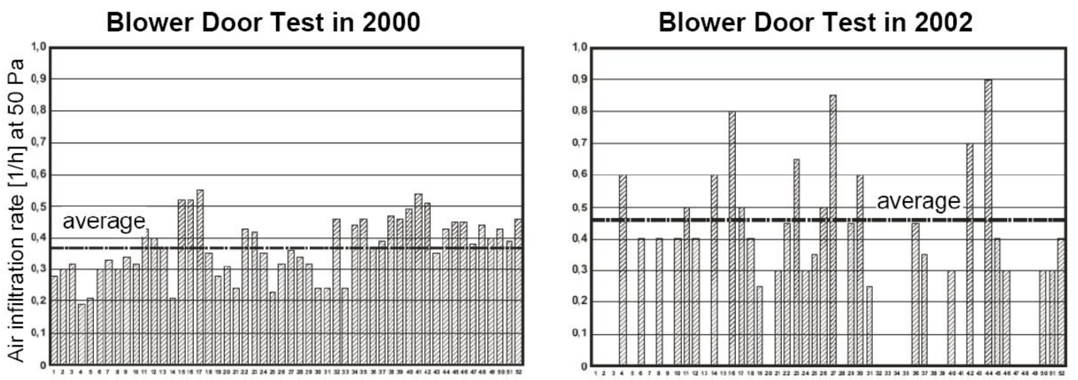


Figure 2: Results of airtightness measurements at 31 passive houses in Stuttgart, Germany measured right after the construction phase and 2 years later.

Figure 5.31 The influence of deterioration (Klutting et al. 2009)

Renovation:

As mention before, the airtightness will not be changed dramatically by building's natural deterioration unless some parts of the house has been mended or changed. Therefore, in order to have a clear perspective on how the airtightness will be affected by renovation is of interest. Ten row houses from the UK were studied according to Johnston et al (2006). Their airtightness is quite high in comparison to the Swedish buildings. The average q_{50} value for the UK buildings is 3.2 l/s, m^2 which is considerably higher than the recommended value from the Swedish building code. Generally, these houses were subjected to the retrofitting work consisting of two steps. The first one involved the injection of expanding polyurethane foam into various voids within the building envelope. Beside this, the wall cavity around the windows and door was also injected with expanding polyurethane foam before the installation of the replacement windows frame. The second one was conducted by using hand-held smoker generators to identify the leakage path and the expanding polyurethane foam was used to seal these leaky areas afterwards (Johnston et al 2006). As it can be seen from Figure 5.32, the airtightness of these houses had been significantly improved except house number eight, nine and ten. Unfortunately, no details could be found from Johnston et al (2006). Therefore, renovation could improve the buildings' airtightness somehow, but the effectiveness varies with different house units.

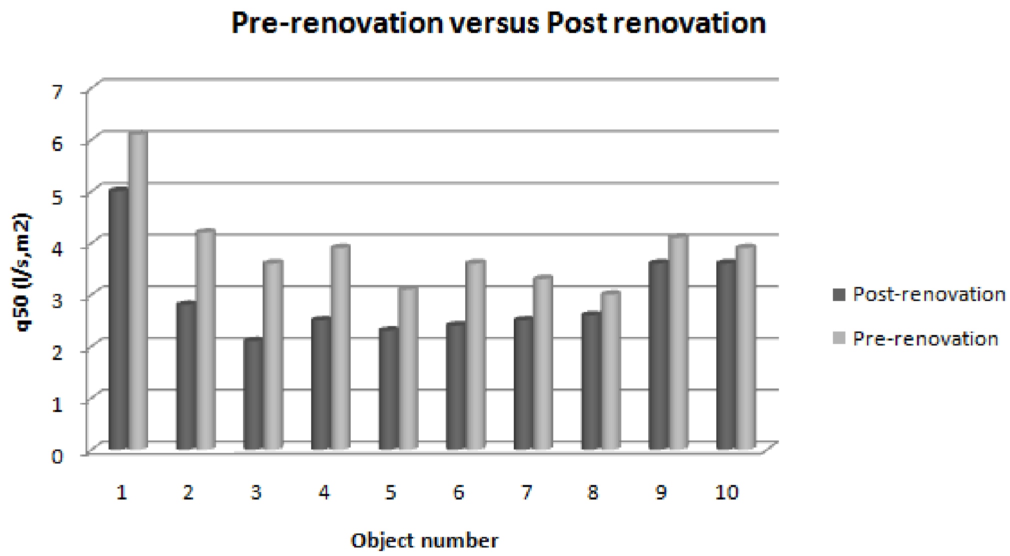


Figure 5.32 The influence of renovation

5.3 Statistical analysis and Prediction

In previous chapter, the relationship between the airtightness and its related factors has been discussed. Based on these discussions, the reader would get more explicit perspectives on how the building airtightness varies with respect to these factors. However, the project also has an attempt to predict the airtightness of a Swedish single family house. Therefore, a statistical analysis needs to be performed in order to provide a basis for prediction.

5.3.1 Statistical method

The statistical analysis will be performed through two steps. First, the F-test of equality of variance will be conducted in order to test whether two populations have the same variance or not. Afterwards, the Student’s T-test will be used to test whether the means of two groups are statistically significant or not. However, there are two options for the Student’s T-test in this study, which consists of two-sample T-test with equal variance and two-sample T-test with unequal variance. Therefore, the F-test becomes a prerequisite for the Student’s T-test. The principle of these two statistical methods is described as follows.

5.3.1.1 Variance

In statistical analysis, the variance describes the average distance between each of a set of data points and their mean value. It is one of several descriptors of a distribution. It is equal to the sum of the squares of the deviation from the mean value (Investorwords). It can be calculated by using Equation 5.5 and Equation 5.6.

$$S^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2 \qquad (5.5)$$

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (5.6)$$

Where

S^2 - Variance

n - Sample size

μ - Sample mean

5.3.1.2 P-value

In statistical null hypothesis testing, the P-value is a probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true. The lower the P-value, the less likely the result is if the null hypothesis is true, and consequently the more ‘significant’ the result is, in the sense of statistical significance. One often accepts the alternative hypothesis, (i.e. rejects a null hypothesis) if the p-value is less than 0.05 or 0.01, corresponding to a 5% or 1% chance respectively of rejecting the null hypothesis (Wikipedia).

5.3.1.3 F-test of equality of variance

In statistics, the F-test for the null hypothesis is that two normal populations have the same variance is often used. If we consider there are two groups of data. The hypothesis to be tested is that the variances of these two groups are equal (Wikipedia). Let,

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \quad , \quad \bar{Y} = \frac{1}{m}\sum_{i=1}^{m} Y_i \qquad (5.7)$$

to be the sample means, let,

$$S_X^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2 , \; S_Y^2 = \frac{1}{m-1}\sum_{i=1}^{m}\left(Y_i - \bar{Y}\right)^2 \qquad (5.8)$$

to be the sample variance, then the test statistic

$$F = \frac{S_X^2}{S_Y^2} \qquad (5.9)$$

has an F-distribution with n –1 or m – 1 degrees of freedom if the null hypothesis of equality of variance is true. Otherwise, if $F \geq F_{\alpha/2}$ (n –1, m – 1), in other words, F-value falls into the shadowy area (Figure 5.33), the null hypothesis is rejected, then these two groups have unequal variance (Wikipedia).

For example, the houses built before 1980s with two different ventilation types were compared and the results are shown in Table 5.6.

House with balanced ventilation type (denoted by X) and the corresponding q_{50} values:

X= {1.1, 1.1, 1.7, 1.4, 0.6, 0.4, 1.8, 0.9, 0.6, 0.6}

House with natural ventilation type (denoted by Y) and the corresponding q_{50} values:

Y= {1.3, 2.3, 0.8, 0.8, 1.7, 0.9, 1.5, 0.4, 1.3, 1.7, 2.5, 3.3, 1, 1.3, 1.1}

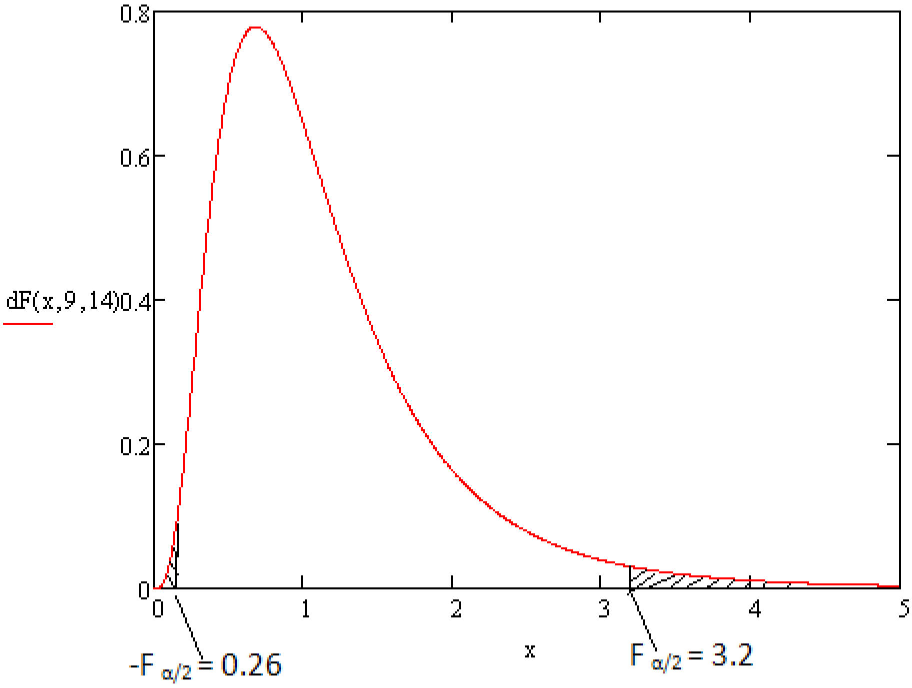


Figure 5.33 F-distribution with degrees of freedom 9 and 14

Table 5.6 Results from the F-test

Sample mean $\bar{X}$	Sample mean $\bar{Y}$	Sample variance of X	Sample variance of Y	α /2-value	F-value	F-critical value(lower limit) ($F_{\alpha/2}$)	F-critical value (upper limit) ($F_{\alpha/2}$)	P-value
1.02	1.46	0.24	0.58	0.025	0.42	0.263	3.209	0.09

As it can be seen from Table 5.6, the F-value (0.42) falls within the range between 0.263 (lower limit) and 3.209 (upper limit). On the other hand, the P-value (0.09) is larger than 0.05. Therefore, the null hypothesis is accepted according to the F-test. In other words, these two groups have equal variance.

5.3.1.4 Student's T-test

The student's T-test is a statistical hypothesis test in which the test statistic follows a student's t distribution if the null hypothesis is accepted(Wikipedia). Normally, the student's T-test has two different types including independent one-sample T-test and independent two-sample T-test. In subdivision of independent two-sample T-test, it includes equal sample sizes with equal variance, unequal sample sizes with equal variance and unequal sample sizes with unequal variance. Since all the categories from the database have different sample sizes, the latter types of independent two-sample T-test are widely applied in this study. The principles of these two tests are described as follows:

Unequal sample sizes, equal variance

This test is used only when it can be assumed that the two distributions have the same variance. The t-statistic is to test whether the means of two groups are significantly different and it can be calculated as follows:

$$t = \frac{\bar{X} - \bar{Y}}{S_{XY} \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \qquad (5.10)$$

Where

$$S_{XY} = \sqrt{\frac{(n_1 - 1)S_X^2 + (n_2 - 1)S_Y^2}{n_1 + n_2 - 2}} \qquad (5.11)$$

S_{XY} is an estimator of the common standard deviation of the two samples: it is defined in this way so that its square is an unbiased estimator of the common variance whether or not the population means are the same. In these formulae, n = number of participants, 1 = group one, 2 = group two. n − 1 is the number of degrees of freedom for either group, and the total sample size minus two (that is, $n_1 + n_2 - 2$) is the total number of degrees of freedom, which is used in significance testing (Wikipedia).

Unequal sample sizes, unequal variance:

This test is used only when the two population variances are assumed to be different and hence must be estimated separately. The t statistic is to test whether the two population means are significantly different and it can be calculated as follows:

$$t = \frac{\bar{X} - \bar{Y}}{S_{\bar{X} - \bar{Y}}} \qquad (5.12)$$

Where

$$S_{\bar{X} - \bar{Y}} = \sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}} \qquad (5.13)$$

Where S is the unbiased estimator of the variance of the two samples, n = number of participants, 1 = group one, 2 = group two. Note that in this case, $S_{\bar{X} - \bar{Y}}$ is not a pooled variance. For use in significance testing, the distribution of the test statistic is approximated as being an ordinary Student's t distribution with the degrees of freedom calculated using

$$d.f. = \frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\frac{\left(\frac{S_1^2}{n_1}\right)^2}{(n_1 - 1)} + \frac{\left(\frac{S_2^2}{n_2}\right)^2}{(n_2 - 1)}} \qquad (5.14)$$

This is called the Welch-Satterthwaite equation (Wikipedia).

According to the results from the F-test before, the buildings with two ventilation types have equal variance. Therefore, the unequal sample size with equal variance is chosen for the student's T-test. In addition, In addition, the null hypothesis to be tested is that the airtightness of balanced ventilation houses is the same as the natural ventilation ones. The test results are shown in Table 5.7.

H_0: $\bar{X} = \bar{Y}$

H_1: $\bar{X} \neq \bar{Y}$

H_0 = null hypothesis

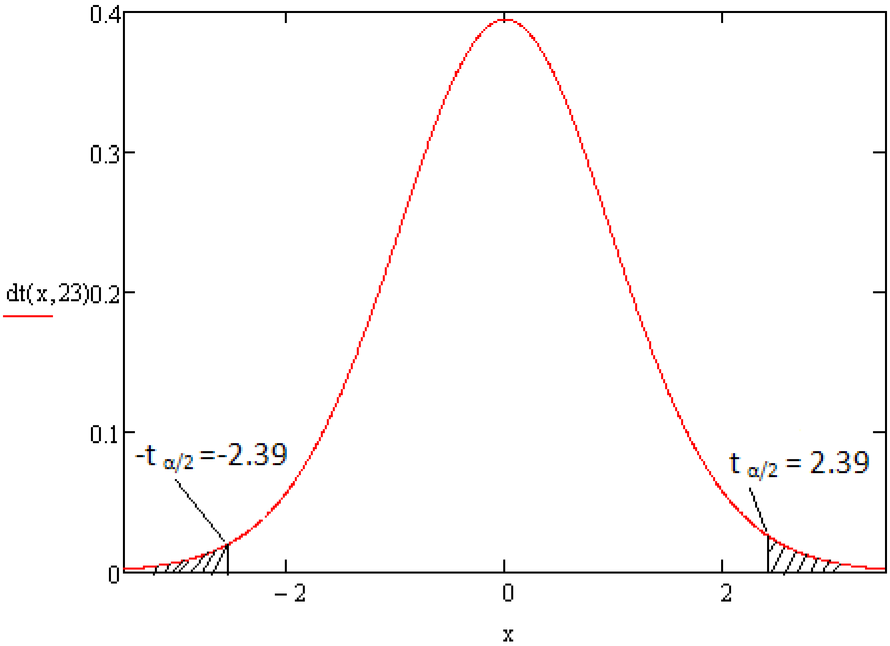


Figure 5.34 t- density distribution diagram

According to the principle of student's T-test, the null hypothesis is rejected (H_1: $\bar{X} \neq \bar{Y}$) if the calculated t-value falls into the shadowy area, where $t \leq -t_{critical}$ or $t \geq t_{critical}$, $P \leq 0.05$. Otherwise, the null hypothesis is accepted (H_0: $\bar{X} = \bar{Y}$). This is illustrated in Figure 5.34.

Table 5.7 Results from the T-test

$\bar{X}$	$\bar{Y}$	Sample variance of X	Sample variance of Y	Degree of freedom	α /2-value	t-value	t-critical value $t_{\alpha/2}$	P-value
1.02	1.46	0.24	0.58	23	0.025	-1.62	-2.39	0.11

As it can be seen from Table 5.7, the P-value yielded from the student's T-test is larger than 0.05, while the t-value (-1.62) is larger than the t-critical value (-2.39). As a consequence, we believe that the null hypothesis is accepted. Therefore, it is reasonable to say that the mean of these two groups are not statistically significant.

5.3.1 Statistical results

In this section, the airtightness related factors will be discussed in a statistical way, from which the classifications are discussed in a quantitative way.

Ventilation type (pre-1980)

Table 5.8 Classifications with respect to ventilation types before 1980

		Air permeability at 50 Pa ($l/s,m^2$)		
Ventilation type	Number of house	Average value	Median value	Standard deviation
Balanced ventilation	10	1	1	0.49
Mechanical exhaust	36	1.3	1.2	0.73
Natural ventilation	15	1.5	1.3	0.76

Table 5.9 The student's T-test results of ventilation type before 1980

	Balanced ventilation	Mechanical exhaust ventilation	Natural ventilation
Balanced ventilation	-	0.19	0.12
Mechanical exhaust ventilation	-	-	0.61

If P <0.05, then those two groups are statistically significant

Ventilation type (post-2000)

Table 5.10 Classifications with respect to ventilation types after 2000 and the student's T-test results

		Air permeability at 50 Pa (l/s,m^2)			Result from student's T-test
Ventilation type	Number of house	Average value	Median value	Standard deviation	P-value
Balanced ventilation	5	0.13	0.07	0.09	9.54*10e-6
Mechanical exhaust	31	0.63	0.52	0.47	

If P <0.05, then those two groups are statistically significant

Foundation type (pre-1980)

Table 5.11 Classifications with respect to foundation types before 1980

		Air permeability at 50 Pa (l/s,m^2)		
Foundation type	Number of house	Average value	Median value	Standard deviation
Crawl space	12	1.2	1.3	0.61
Basement	18	1.5	1.2	0.87
Slab on ground	44	1.24s	1.15	0.62

Table 5.12 The student's T-test of foundation type before 1980

	Crawl space	Basement	Slab on ground
Crawl space	-	0.29	0.68
Basement	-	-	0.32

If P <0.05, then those two groups are statistically significant

Foundation type (Post-2000)

Table 5.13 Classifications with respect to foundation types after2000

		Air permeability at 50 Pa (l/s,m^2)			Result from student's T-test
Foundation type	Number of house	Average value	Median Value	Standard deviation	P- value
Crawl space	12	0.59	0.53	0.15	0.45
Slab on ground	30	0.51	0.48	0.52	
Basement	1	0.53	0.53	0	-

Predominant Wall materials (pre-1980)

Table 5.14 Classifications with respect to predominant wall materials before 1980

		Air permeability at 50 Pa (l/s,m^2)		
Wall material	Number of house	Average value	Median Value	Standard deviation
Light-weight concrete	19	1	1	0.66
Concrete	5	0.8	0.8	0.5
Timber-framed	46	1.4	1.2	0.71

Table 5.15 The student's T-test of predominant wall materials before 1980

	Light-weight concrete	Concrete	Timber-framed
Light-weight concrete	-	0.44	0.07
Concrete	-	-	0.07

If P <0.05, then those two groups are statistically significant

Predominant Wall material (post-2000)

Table 5.16 Classifications with respect to predominant wall materials after 2000 and the student's T-test results

		Air permeability at 50 Pa (l/s,m^2)			Result from student's T-test
Wall material	Number of house	Average value	Median value	Standard deviation	P-value
Light-weight concrete	2	0.27	-	0.66	-
Concrete	1	0.2	-	0.5	-
Masonry block	11	0.72	0.72	0.32	0.25
Timber-framed	40	0.55	0.51	0.45	

If P <0.05, then those two groups are statistically significant

Construction method (pre-1980)

Table 5.17 Classifications with respect to construction method before 1980 and the student's T-test results

		Air permeability at 50 Pa (l/s,m^2)			Result from student's T-test
Construction method	Number of house	Average value	Median value	Standard deviation	P-value
site-built	25	1.1	1.1	0.55	0.24
prefabricated	46	1.6	1.2	0.76	

If P <0.05, then those two groups are statistically significant

Construction method (post-2000)

Table 5.18 Classifications with respect to construction method after 2000 and the student's T-test results

		Air permeability at 50 Pa (l/s,m^2)			Result from student's T-test
Construction method	Number of house	Average value	Median value	Standard deviation	P-value
site-built	10	0.22	0.25	0.15	0.0009
prefabricated	10	0.53	0.52	0.15	

If P <0.05, then those two groups are statistically significant

Number of storey (pre-1980)

Table 5.19 Classifications with respect to number of storey before 1980

		Air permeability at 50 Pa (l/s,m^2)		
Number of storey	Number of house	Average value	Median value	Standard deviation
One storey	20	1.3	1.1	0.75
One and half storey	36	1.5	1.4	0.69
Two storey	18	0.9	0.9	0.43

Table 5.20 The student's T-test results of number of storey before 1980

	One storey	One and half storey	Two storey
One storey	-	0.37	0.05
One and half storey	-	-	0.0005

If P <0.05, then those two groups are statistically significant

Number of storey (post-2000)

Table 5.21 Classifications with respect to number of storey after 2000

		Air permeability at 50 Pa ($l/s,m^2$)		
Number of storey	Number of house	Average value	Median value	Standard deviation
One storey	26	0.43	0.44	0.23
One and half storey	16	0.81	0.61	0.67
Two storey	21	0.46	0.47	0.13

Table 5.22 The student's T-test results of number of storey after 2000

	One storey	One and half storey	Two storey
One storey	-	0.02	0.56
One and half storey	-	-	0.03

If P <0.05, then those two groups are statistically significant

Year of construction

Table 5.23 Classifications with respect to year of construction

		Air permeability at 50 Pa ($l/s,m^2$)		
	Number of house	Average value	Median value	Standard deviation
Before 1970	8	1.8	1.5	0.79
1970s	68	1.2	1.1	0.64
Post 2000	65	0.54	0.51	0.40

Table 5.24 The student's T-test results of year of construction

	Before 1970	1970s	Post 2000
Before 1970	-	0.005	0.002
1970s	-	-	3.37*10e-11

If P <0.05, then those two groups are statistically significant

Energy efficient focus

Table 5.25 Classifications with respect to energy efficient program and the student's T-test results

		Air permeability at 50 Pa (l/s,m^2)			Result from student's T-test
	Number of house	Average value	Median value	Standard deviation	P- value
Energy efficient house	6	0.15	0.14	0.09	2.3*10e-6
Non-energy efficient house	38	0.61	0.52	0.46	

If P <0.05, then those two groups are statistically significant

Installation layer

Table 5.26 Classifications with respect to installation layer and the student's T-test results

		Air permeability at 50 Pa (l/s,m^2)			Result from student's T-test
	Number of house	Average value	Median value	Standard deviation	P- value
House built without installation layer	6	0.73	0.73	0.25	0.0003
House built with installation layer	9	0.27	0.24	0.4	

5.3.2 Prediction

5.3.2.1 Weighting

Before processing the prediction of airtightness, weightings have to be allocated to each airtightness related factor. Initially, it was considered to solve this problem by using the ranking from question two in the questionnaire (see Appendix A), however, there were large discrepancies between the participants, which can be seen in Table 5.27 below. In addition, some test engineers only have five years working experiences on the airtightness. Therefore, when attempting to ask them to provide the rankings, it is hard to get satisfactory answers. For instance, one engineer suggested that the workmanship could have the largest impact on the airtightness, while he was not certain about other factors. As a consequence, many other factors were not assessed.

Table 5.27 Rankings of different airtightness related factors from test engineers

Variance	**Ranking 1**	**Ranking 2**	**Ranking 3**	**Ranking 4**
Year of construction	4	Uncertain	2	6
Quality of workmanship	3	1	3	1
Type of ventilation	5	Uncertain	6	4
Number of storey	6	Uncertain	5	5
Predominant wall materials	1	Uncertain	4	3
Construction type	2	Uncertain	1	2

Note: ranking 1- strongest influence, ranking 6 – weakest influence

Alternatively, the P-values yielded from the student's T-test are intended to be used to allocate the weightings. Coincidentally, the same study has been conducted by Kalamees (2007). As it can be seen from Table 2.2, four levels of statistical significance are calculated by using the student's T-test, which includes not significant ($P>0.05$), significant ($P<0.05$), highly significant ($P<0.01$), extremely significant ($P<0.001$).

In order to have a more reliable weighting system, five levels of weightings are used in this study. As it can be seen from Table 5.28, the foundation type before 1980 only gains one. This is mainly owing to its P-values (0.29, 0.68, 0.32) which are overwhelmingly larger than 0.05, which means the differences between three foundation types are not statistically significant. In contrast, the ventilation type after 2000 gets five, since its P-value (9.54*10e-6) is extremely smaller than 0.05. In principle, the higher P-value yielded from the Student's T-test, the smaller impact on the airtightness. In addition, it is worth mentioning that the weighting for the year of construction is entirely relied on its smallest P-value (3.37*10e-11) rather than other two P-values. In this way, it avoids underestimating its influence on the airtigtness, since the average values of the different age groups in Table 5.23 are quite noticeable.

This is also the case for the number of storey before 1980. Furthermore, the study of workmanship is excluded here. This is mainly because of that the workmanship is evaluated completely based on the energy efficient focus. They can be regarded as a same concept in this study. Since the prediction only focuses on the Swedish single family houses, the influence of building type is also omitted.

Table 5.28 Weightings of different airtightness related factors according to P-value

Variable	Calculated P – value	Criterion	Weighting
Ventilation type post-2000	P = 9.54*10e-6	P<0.00005	5
Energy efficient focus (only for post-2000 group)	P = 2.3*10e-6	P<0.00005	5
Year of construction	P = 3.37*10e-11, P = 0.005, P = 0.002	P<0.00005	5
Installation layer (only for post-2000 group)	P = 0.0003	P<0.0005	4
Construction method post-2000	P = 0.0009	P<0.005	3
Number of storey pre-1980	P = 0.0005, P = 0.05, P = 0.37	P<0.005	3
Number of storey post-2000	P = 0.02, P = 0.03 P = 0.56	P<0.05	2
Ventilation type pre-1980	P = 0.19, P = 0.12 P = 0.61	P>0.05	1
Foundation type pre-1980	P = 0.29, P = 0.68 P = 0.32	P>0.05	1
Foundation type post-2000	P = 0.29, P = 0.68 P = 0.32	P>0.05	**1**
Predominant wall material pre-1980	P = 0.44, P = 0.07, P = 0.07	P>0.05	1
Predominant wall material post-2000	P = 0.25	P>0.05	1
Construction method pre-1980	P = 0.24	P>0.05	1

5.3.2.2 Prediction

After establishing the weighting system, predictions of the Swedish single family house were performed. Three examples were chosen for prediction as it can be seen in Table 5.29, Table 5.30 and Table 5.31 respectively. The differences between the predictions and real measurement data were also compared.

Example one:

Table 5.29 Prediction of the Swedish single family house built in 1975

House description	**Year of construction**	**Predominant wall material**	**Number of storey**	**Ventilation type**	**Construction method**	**Foundation type**
Detail	1977	Timber frame	1.5	Mechanical exhaust	Site built	Slab on ground
Average q_{50} (l/s,m^2)	1.2	1.4	1.5	1	1.1	1.24
Weighting	5	1	3	1	1	1

$$q_{50predicted} = \frac{\sum averageq_{50} \cdot weighting}{\sum weighting} = \frac{1.2\cdot 5+1.4\cdot 1+1.5\cdot 3+1\cdot 1+1.1\cdot 1+1.24\cdot 1}{5+1+3+1+1+1}$$

$= 1.27$ l/s, m^2

Coincidently, there are nine houses from the database that match the description of predicted example and the difference between the real measurement data and the prediction are shown in Figure 5.35 below.

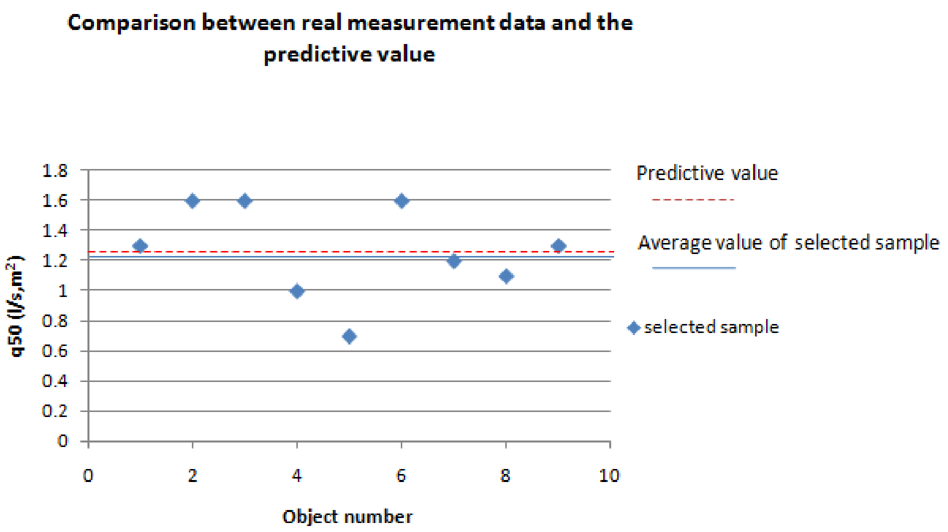


Figure 5.35 Difference between the prediction and the real measurement data

Example two:

Table 5.30 Prediction of the Swedish single family house built in 2007

House description	**Year of construction**	**Predominant wall material**	**Number of storey**	**Ventilation type**	**Energy efficient focus**
Detail	2007	Timber frame	1	Mechanical exhaust	NO
Average q_{50} (l/s,m^2)	0.54	0.55	0.43	0.63	0.63
Weighting	5	1	2	5	5

$$q_{50predicted} = \frac{\sum averageq_{50} \cdot weighting}{\sum weighting} = \frac{0.54 \cdot 5 + 0.55 \cdot 1 + 0.43 \cdot 2 + 0.63 \cdot 5 + 0.63 \cdot 5}{5 + 1 + 2 + 5 + 5}$$

$$= 0.58 \text{ l/s, m}^2$$

According to the prediction, there are fifteen houses that match the description of predicted sample and the difference between the real measurement data and prediction are shown in Figure 5.36.

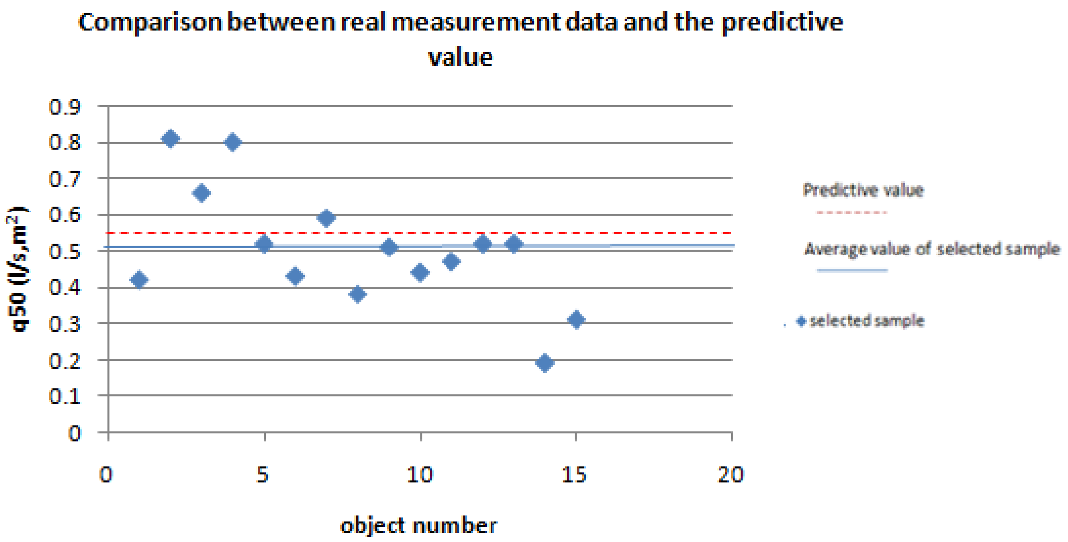


Figure 5.36 Difference between the prediction and the real measurement data

As it can be seen from Figure 5.35 and Figure 5.36 respectively, the differences between the predicted value and average value of real measurement data are quite small. The difference in percentage is 0.7% and 16% for example one and example two separately. Therefore, the database has good accuracy of predicting the q_{50} value. It avoid avoids underestimating or overestimating the building's airtighness substantially by simply using the former BBR code or referring the q_{50} value from other countries.

Example three:

Table 5.31 Prediction of the Swedish single family house built in 1977

House description	**Year of construction**	**Predominant wall material**	**Number of storey**	**Ventilation type**
Detail	1977	Timber frame	1	Mechanical exhaust
Average q_{50} (l/s,m^2)	1.2	1.4	1.3	1
Weighting	5	1	3	1

$$q_{50predicted} = \frac{\sum averageq_{50} \cdot weighting}{\sum weighting} = \frac{1.2 \cdot 5 + 1.4 \cdot 1 + 1.3 \cdot 3 + 1 \cdot 1}{5+1+3+1}$$

$$= 1.23 \text{ l/s,m}^2$$

According to the prediction, there are four houses that match the description of predicted sample. The difference between the real measurement data and prediction are shown in Figure 5.37.

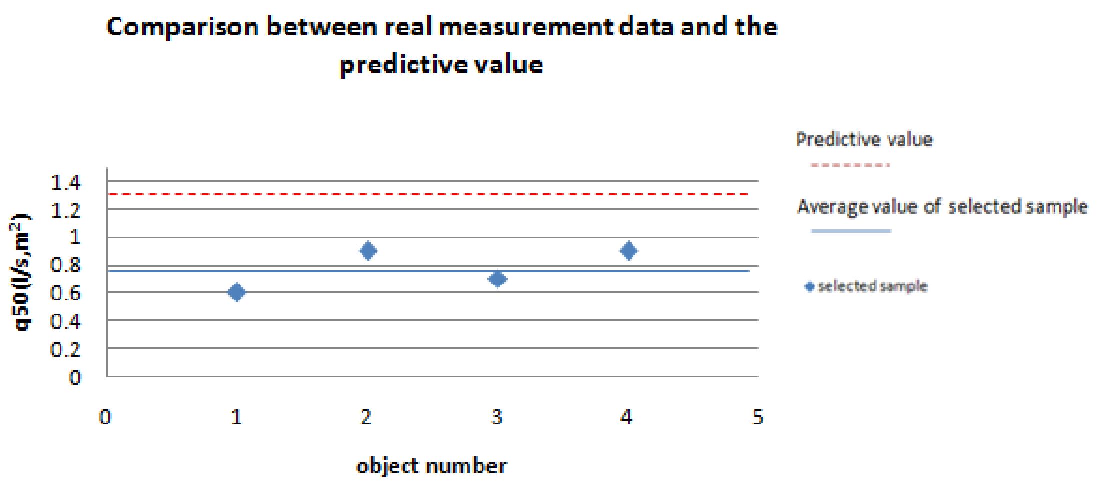


Figure 5.37 Difference between the prediction and the real measurement data

Due to the lack of information on some key airtightness related factors, such as, installation layer and energy efficient focus etc, it is inescapable to have some bad predicted outcomes. As it can be seen from Figure 5.37, the predicted value (1.23 $l/s,m^2$) is dramatically larger than average value of selected samples from the database (0.78 $l/s,m^2$). In addition, all the q_{50} values of the selected samples are smaller than the predicted value. Unfortunately, no clues can be traced from Kronvall J. (1980) since this is the only source that we can obtain the information on these houses. Therefore, we can only presume that these houses were not randomly selected before the blower door test. It is likely that these houses had a strong awareness on the airtightness. Meanwhile, the installation layer probably had been used during the construction phase. According to Table 5.25 and Table 5.26, the energy efficient houses (0.15 $l/s,m^2$) are four times more airtight than the non-energy efficient houses (0.61 $l/s,m^2$). In addition, the houses built with installation layer (0.27 $l/s,m^2$) are nearly three times more airtight than the ones without installation layer (0.73 $l/s,m^2$). On the other hand, one test engineer had confirmed that use of an installation layer was first introduced in Sweden's building industry in the late of 1970s. Based on these quantitative comparisons and presumptions, it is reasonable that these four houses' q_{50} values are smaller than the predicted one. Therefore, if there are some other buildings in the database that match the studied case also have been built with installation layer or focus on the airtightness, then their q_{50} values will be smaller than the predicted value as well.

6 Conclusions

In this study, a total amount of 374 measurement data from different publications and SP airtightness tests were assessed regarding to various airtightness related factors, such as, year of construction, number of storey and foundation type etc. These factors were identified through three steps consisting of literature reviewing, questionnaires and interviews. The data were put into several groups for classification, such as, year of construction, number of storey and energy efficient focus etc. The classification results showed that most of classifications were reasonable and meaningful. The differences between each variable within each group were clear to be observed. There was a clear correlation between the building airtightness and the airtightness related factors. For instance, the buildings with slab on ground were more airtight than the ones with basement or crawl space; energy efficient buildings were more airtight than conventional ones; one-storey houses were the best case on the airtightness; the buildings with balanced ventilation system were more airtight than the buildings with mechanical exhausted ventilation or natural ventilation. Furthermore, when considering the cross dependency effect of different factors, such as, construction method, project goal and predominant wall materials, the latter two factors appear to be more dominant on the airtightness. This can be proved by Figure 5.8 and Figure 5.10. It is also worth mentioning that strong awareness, well educated builder on airtightness and early search of leakage area is of great importance to construct an airtight building (Chapter 4).

However, some classifications were inconsistent with former research and feedback from interviews. It is mainly owing to the limited amount of measurement data. For instance, the average n_{50} value of the 1980s group was smaller than that in the post-2000 group. By contrast, all test engineers had agreements that the buildings' airtightness was improved dramatically with increasing year. In addition, the buildings built with basement had the same airtightness level as the ones built with crawl space in the post-2000 group from the database. By contrast, the buildings with crawl space were the worst case on the airtightness from test engineers' viewpoints. Furthermore, multi-storey buildings before 1980 were less airtight than single family houses, which were contradict with former research by Korpi et al. (2006). The classification also showed that prefabricated construction method resulted in leakier buildings than site-built ones. By contrast, former research by Korpi et al. (2006) and Kalamees (2007) stated that the site-built buildings were not as airtight as prefabricated ones. Unfortunately, no detailed information was provided by them. Otherwise, it is interesting to investigate the relationship between the airtightness and construction method in Finland to a deeper level, in order to compare it with Swedish case. In addition, some test engineers have suggested that both prefabricated method and site-built method can build an equal airtight house according to the responses from the questionnaire. The prefabricated elements are usually airtight controlled in the factory. However, they are assembled together in an un-tight manner on site. Therefore, we can conclude that the construction method does not affect the airtightness a lot. If more attention has been paid on the airtightness, then an airtight building can be built no matter what kind of the construction method we have used.

In addition, in order to provide statistical analysis of measurement data and to predict the q_{50} value of a Swedish single family detached house, a statistical model was established using the F-test and the Student's T-test method. Based on the test results, energy efficient focus, use of an installation layer, year of construction, number of storey, ventilation type (post-2000), and construction method (post-2000) was found to be the significantly influential factors on the airtightness. All of their P-values were smaller than 0.05 (indicator of the statistical significance and insignificance). In contrast, construction method (pre-1980), predominant wall materials, foundation type and ventilation type (pre-1980) only had minor impact, which was not statistical determined ($P > 0.05$). Furthermore, three predictions of q_{50} value on Swedish single family houses were made. According to the prediction, the first two examples showed good agreements with the mean of real measurement data. The difference in percentage was 0.7% and 16% respectively. However, due to the lack of information on the key airtightness related factors, such as, energy efficient focus and use of an installation layer, a remarkable deviation occurred between the prediction and the mean value of real measurement data in example three. The difference between them in percentage was 57%.

As mentioned above, there are some discrepancies between classifications and airtightness test engineers' experiences and former studies. Hence, further study could be conducted through following steps. Firstly, more measurement data need to be fed into the database in order not only to trace the reasons that lie behind each discrepancy, but also to improve the accuracy of prediction. Secondly, more airtightness related factors could be incorporated into the database, for instance, the length of window and door frame, advanced ranking of workmanship quality. The list of construction materials could be developed into a deeper level by investigating the materials used for wall, roof and ceilings separately. In general, the more building characteristics integrated into the database, the more intelligent it becomes. Thirdly, a multi-regression statistical model could be used when the database has sufficient measurement data. By using this model, we could learn more about the relationship between different airtightness related factors, which make it possible to refine the prediction.

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Paroc (2010): *Pitched roof*. Downloaded from: http://www.paroc.com/channels/com/building+insulation/solutions/external+walls/stud+walls+ii.asp (2010/04/05)

Wikipedia: *P-value*. Downloaded from: Http://en.wikipedia.org/wiki/P-value (2010/07/02)

Wikipedia: *F-test of equality of variances*. Downloaded from: Http://en.wikipedia.org/wiki/F-test_of_equality_of_variances (2010/07/02)

Wikipedia: *Student's T-test*. Downloaded from: Http://en.wikipedia.org/wiki/Student's_t-test (2010/07/02)

InvestorWords: *Variance*. Downloaded from: http://www.investorwords.com/5227/variance.html (2010/09/26)

Appendix A: Questionnaire

1. What is the common air leakage paths in Sweden based on your expertise? If there are some more critical leakage paths, please add them just below the options.
   A. Gaps around windows and doors
   B. Service penetration through openings
   C. Gaps around floor to wall joints
   D. Gaps around wall to ceiling joints
   E. Opening of loft ladder

2. Which parameters do you think will have the dramatic impact on the air tightness level of building in Sweden? Why?
   A. Year of construction
   B. Construction type
   C. The workmanship
   D. The type of ventilation system
   E. Number of storey
   F. Wall materials
   Your comments:

3. Do you think the building type will have impact on air tightness level of building?
   A. Yes
   B. No

4. If all buildings that listed below are made of same materials for walls, insulation and air barrier. Generally, which one do you think will be the leakiest one? Why?
   A. Single detached house
   B. Row house
   C. Multi-storey apartment and commercial building
   Your comments:

5. Do you think number of storey will have impact on air tightness level of building?
   A. Yes
   B. No

6. Generally, which one do you think will be tightest? Why?
   A. Single storey
   B. One and half storey
   C. Two storey
   D. Even more
   Your comments:

7. Do you think the building materials will have impact on the air tightness level of building?
   A. Yes
   B. No

8. If the building is made of materials listed below separately with. Generally, which one will be tighter than others, why? If it is possible, please give the order.

   A. Timber-frame
   B. Lightweight concrete
   C. concrete
   D. Brick

   Your comments:

9. Do you think the workmanship will have impact on the air tightness level of building?
   A. Yes
   B. No

10. Do you think the foundation type will have impact on air tightness level of building?
    A. Yes
    B. No

11. Generally, which foundation do you think will lead good air tightness (assume basement and crawl space both are unconditioned)? Why is it air tight? If it is possible, please give the order.
    A. Basement
    B. Crawl space
    C. Floor slab on the ground

    Your comments:

12. Do you think the construction method will have impact on air tightness level of building?
    A. Yes
    B. No

13. Which construction method do you think will build an air tight building? Why?
    A. Prefabricated
    B. Built on site

    Your comments:

14. In Sweden, do you think there is leakage trend correlating to the age of the construction?
    A. yes
    B. no

15. If there is a correlation, how about the average air tightness level according to year of construction list below? Why the houses are tighter in a specific period than other one?
    A. Before 1970s
    B. 1970 – 1979
    C. 1980 – 1989
    D. 1990-1999
    E. 2000-present

    Your comments:

16. Do you think the type of ventilation system will have impact on the air tightness level of building?
    A. Yes
    B. No

17. If the house is installed with different ventilation system listed below, which one do you think is leakiest? Why?
    A. Natural ventilation
    B. Mechanical exhaust
    C. Balance ventilation and heat exchanger

    Your comments:

Appendix B: Database structure

House number	House location	Year of construction	construction type	legnth (m)	width (m)	height (m)
1	Sweden	1977	single family detached house	NA	NA	NA
3	Sweden	1977	single family detached house	NA	NA	NA
4	Sweden	1977	single family detached house	NA	NA	NA
5	Sweden	1977	single family detached house	NA	NA	NA
6	Sweden	1977	single family detached house	NA	NA	NA
7	Sweden	1978	single family detached house	NA	NA	NA
8	Sweden	1976	row house	NA	NA	NA
9	Sweden	1976	single family detached house	NA	NA	NA
10	Sweden	1976	single family detached house	NA	NA	NA
11	Sweden	1976	single family detached house	NA	NA	NA
12	Sweden	1976	single family detached house	NA	NA	NA
13	Sweden	1976	single family detached house	NA	NA	NA
14	Sweden	1975	single family detached house	NA	NA	NA
15	Sweden	1969	single family detached house	NA	NA	NA
16	Sweden	1969	row house	NA	NA	NA
17	Sweden	1976	single family detached house	NA	NA	NA
18	Sweden	1965	single family detached house	NA	NA	NA
19	Sweden	1976	single family detached house	NA	NA	NA
20	Sweden	1976	single family detached house	NA	NA	NA
21	Sweden	1974	single family detached house	NA	NA	NA
22	Sweden	1977	single family detached house	NA	NA	NA
23	Sweden	1977	single family detached house	NA	NA	NA
24	Sweden	1976	single family detached house	NA	NA	NA
25	Sweden	1977	single family detached house	NA	NA	NA
26	Sweden	1977	single family detached house	NA	NA	NA
27	Sweden	1976	single family detached house	NA	NA	NA
28	Sweden	1977	single family detached house	NA	NA	NA
29	Sweden	1977	single family detached house	NA	NA	NA
30	Sweden	1977	single family detached house	NA	NA	NA
31	Sweden	1977	single family detached house	NA	NA	NA
32	Sweden	1977	single family detached house	NA	NA	NA
33	Sweden	1977	row house	NA	NA	NA
34	Sweden	1977	single family detached house	NA	NA	NA
35	Sweden	1975	single family detached house	NA	NA	NA

Note: NA=Not available

Ventilation type	Foundation type	Energy efficinent	Constrcution method	q50 (l/s, m2)	Installation layer
Mech. Exhuast	crawl space	NA	Prefabricated	1.6	NA
Mech. Exhuast	floor on ground	NA	Prefabricated	1.7	NA
Balanced system+heat recovery	floor on ground	NA	Prefabricated	1.1	NA
Balanced system+heat recovery	basement	NA	Prefabricated	1.1	NA
Mech. Exhuast	floor on ground	NA	Prefabricated	3.3	NA
Mech. Exhuast	floor on ground	NA	Prefabricated	0.3	NA
NA	floor on ground	NA	Prefabricated	0.3	NA
NA	floor on ground	NA	Prefabricated	0.3	NA
NA	floor on ground	NA	Prefabricated	0.8	NA
NA	floor on ground	NA	Site-built	1.9	NA
NA	floor on ground	NA	Site-built	1.1	NA
Balanced system+heat recovery	crawl space	NA	Prefabricated	1.7	NA
Balanced system+heat recovery	crawl space	NA	Prefabricated	1.4	NA
Natural ventilation	crawl space	NA	Prefabricated	1.3	NA
Mech. Exhuast	floor on ground	NA	Prefabricated	1.8	NA
Mech. Exhuast	floor on ground	NA	Prefabricated	1.1	NA
Natural ventilation	crawl space	NA	Site-built	2.3	NA
Balanced system+heat recovery	floor on ground	NA	Prefabricated	0.6	NA
Balanced system+heat recovery	crawl space	NA	Site-built	0.4	NA
Mech. Exhuast	basement	NA	Site-built	1.0	NA
Natural ventilation	floor on ground	NA	Prefabricated	0.8	NA
Natural ventilation	floor on ground	NA	Prefabricated	0.8	NA
Balanced system+heat recovery	floor on ground	NA	Prefabricated	1.8	NA
Mech. Exhuast	floor on ground	NA	Site-built	1.3	NA
Mech. Exhuast	floor on ground	NA	Site-built	1.6	NA
Mech. Exhuast	crawl space	NA	Prefabricated	0.6	NA
Mech. Exhuast	floor on ground	NA	Site-built	0.9	NA
Mech. Exhuast	floor on ground	NA	Prefabricated	2.7	NA
Mech. Exhuast	floor on ground	NA	Site-built	1.6	NA
Mech. Exhuast	floor on ground	NA	Prefabricated	1.6	NA
Mech. Exhuast	floor on ground	NA	Site-built	1.0	NA
Mech. Exhuast	crawl space	NA	Prefabricated	2.1	NA
Mech. Exhuast	floor on ground	NA	Site-built	0.7	NA
Natural ventilation	floor on ground	NA	Prefabricated	1.7	NA

Note: NA=Not available

workmanship	n50 (1/h)	Degradation n50 (1/h)
NA	4.8	NA
NA	4.5	NA
NA	3.2	NA
NA	2.6	NA
NA	7.9	NA
NA	1.0	NA
NA	NA	NA
NA	NA	NA
NA	NA	NA
NA	NA	NA
NA	NA	NA
NA	5.2	NA
NA	6.0	NA
NA	4.2	NA
NA	6.6	NA
NA	3.4	NA
NA	10.6	NA
NA	2.8	NA
NA	1.2	NA
NA	1.6	NA
NA	4.7	NA
NA	2.4	NA
NA	4.8	NA
NA	2.9	NA
NA	3.9	NA
NA	2.7	NA
NA	2.7	NA
NA	6.9	NA
NA	4.2	NA
NA	4.2	NA
NA	2.7	NA
NA	7.4	NA
NA	2.0	NA
NA	4.3	NA

Note: NA=Not available

Appendix C: List of reports and publication for data collection

Source of airtightness measurement data	Involved airtightness related factors
Airtightness- measurements and measurement methods Johnny Kronvall (1980)	Year of construction, Predominant wall materials, Construction method, Number of storey, Basement type, Ventilation type, Construction type
Airtightness measurements by SP	Project goal and workmanship quality, Year of construction, Predominant wall materials, Construction method, Construction type, Number of storey, Basement type, Ventilation type, Installation layer, Joint length/Envelope area
Airtightness of 12 non-residential large buildings results fromfield measurement study Andres Litvak (2001)	Construction type
Air Permeability of some Australian Houses K. L. Biggs (1986)	Number of vents
Airtightness requirements for high performance building envelopes Klutting et al. (2009)	Deterioration
Att uppnå god lufttäthet-En studie av faktorer som påverkar byggnadens lufttäthet Emma Eliasson (2010)	Number of storey Installation layer
Improving the airtightness of existing plaster board-lined load-bearing masonry dwellings D. Johnston (2006)	Renovation
Luftkvalitet och ventilation i täta småhus En uppföljning av 44 Hjältevadshus byggda under åren 1982-89 Ingemar Nilsson (1993)	Deterioration