INDOOR AIR QUALITY AND HEALTH

An Analysis of the Indoor Air Quality and Health in New Zealand's Homes

Holger de Groot

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“Understanding the environmental performance of a building should be as easy as understanding the performance of your vehicle via its Warrant of Fitness. Why do we not ask how energy efficient our buildings are, how much water they use, how warm they are or what the air quality is like? Do we have faith that our Building Code can deliver a home that performs well in all these areas?"

Jane Henley, Chief Executive, New Zealand Green Building Council [1]

[1] New Zealand Business Council for Sustainable Development (NZBCSD). *Better Performing Homes for New Zealanders: Making it Happen*. New Zealand: NZBCSD, A-2008, p.23.

ABSTRACT

Allergies have become a serious health problem with considerable social and economic impact. Especially the indoor environment of New Zealand's residential buildings plays a major role in the increasing numbers of allergies, airways infections and cases of Sick Building Syndrome (SBS). This master thesis examines the indoor air pollution in relation to construction details, insulation levels, ventilation and humidity. Dampness problems such as condensation on windows and mould growth are related to the indoor humidity caused by wrong ventilation (or a lack thereof), heating habits, rising damp and building envelope. This thesis addresses these issues by studying moisture damage caused by damp housing in buildings with poor ventilation and insulation between the 1950's and the 1980's. The thesis argues that existing homes have to be retrofitted to meet new sustainable standards in order to provide a healthier indoor air quality (IAQ) and to reduce the risk of allergies and asthma.

The first part of this thesis examines general health effects which are related to IAQ and identifies common exposure sources in homes. The second part illustrates the problem of damp housing which currently presents the most common cause of allergies in New Zealand homes. Therefore, the thesis identifies their specific influence on health in general and possible risks of developing allergies in particular. Regarding this, it is proved that adequate ventilation in homes prevents adverse health effects, such as coughing, wheezing, airway infections and asthma and can also reduce and ideally eliminate existing mould in homes. [1] Part three gives a review of recent international and national research studies on this topic. Additionally, the thesis evaluates data of the University of Otago to determine the association between damp housing and allergies. Part four introduces the existing housing stock of New Zealand and its different building typologies in order to give examples of interventions to keep current mould and dampness problems under control.

Overall, this thesis addresses the lack of information about IAQ in New Zealand homes and illustrates the interrelation between ventilation, heating, building materials and dampness. Simulation software is also introduced to verify possible "changes" in terms of building physics after retrofit solutions have been applied. In this context, the thesis presents preventative actions, advises how dampness problems can be proactively avoided and provides practical recommendation for refurbishments of specific building typologies, built between the 1950's and the 1980's.

[1] Yuanhui Zhang. *Indoor air quality engineering*. Boca Raton, Florida, USA: CRC Press, 2005, pp.4-5.

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ABBREVIATIONS

AAFA	Asthma and Allergy Foundation of America
AC	Air Conditioner
ACC	Auckland City Council
ACH	Air Changes per Hour
AGD	Additional Geographical Data
AMSL	Above the Mean Sea Level
AQC	Air Quality Control
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BBE	Building Biology and Ecology institute
BRI	Building Related Illness
BRANZ	Building Research Association of New Zealand
CH_2O	Formaldehyde
COPD	Chronic Obstructive Pulmonary Disease
CO_2	Carbon Dioxide
DBH	Dampness in Buildings and Health
DHC	Department of Housing Construction
DWD	German National Weather Service (Acronym of the German name: Deutscher Wetter Dienst)
ECHRS	European Community Respiratory Health Survey
EBANZ	Earth Building Association of New Zealand
EECA	Energy Efficiency and Conservation Authority
EPFL	Swiss Federal Institute of Technology
EPS	Expanded Polystyrene
ERV	Energy Recovery Ventilator
ETS	Environmental Tobacco Smoke
EUROPART	European Research Programme for the Partitioning of Minor Actinides
HDM	House Dust Mites
HEEP	Household Energy End-use Project
HERS	Home Energy Rating System
HHI	Healthy Housing Index
HNZC	Housing New Zealand Corporation
HRV	Heat Recovery Ventilator
HSS	High Standard of Sustainability
HVAC	Heating, Ventilation and Air Conditioning

ISAAC	International Study of Asthma and Allergies in Childhood
IBP	Fraunhofer Institute for Building Physics
IEA	International Energy Agency
IEQ	Indoor Environment Quality
JAS	Japanese Agricultural Standard
Long.	Longitude
Lat.	Latitude
Low-e	Low Emissivity
MCS	Multiple Chemical Sensitive
NIWA	New Zealand National Institute of Water & Atmospheric Research
NZBC	New Zealand Building Code
NZBCSD	New Zealand Business Council for Sustainable Development
NZGBC	New Zealand Green Building Council
NZPA	New Zealand Press Association
NZS	New Zealand Standard
OECD	Organisation for Economic Cooperation and Development
PEL	Permissible Exposure Limit
PF	Phenol-Formaldehyde
PHAC	Public Health Advisory Committee
PM	Particulate Matter
R.C. Slab	Reinforced Concrete Slab
RH	Relative Humidity
Rn	Radon
R-value	Thermal Resistance
SBS	Sick Building Syndrome
SEA	Safety and Environmental Associates
TRY	Test Reference Years
TVOCs	Total Content of Volatile Organic Compounds
UF	Urea-Formaldehyde
ULPA-Filter	Ultra Low Penetration Air Filter
UN	United Nations
uPVC	Un-plasticised Poly Vinyl Chloride
UTC	Universal Time, Coordinated
UV	Ultraviolet Sunlight

VOCs	Volatile Organic Compounds
WELS	Water Efficiency Labelling Scheme
WHO	World Health Organization
WTU	International Association for Science and Technology of Building Maintenance and Monuments Preservation (Acronym of the German name: Wissenschaftlich-Technische Arbeitsgemeinschaft für Bauwerkserhaltung und Denkmalpflege)
WUFI	Transient Heat and Moisture (Acronym of the German name: Wärme und Feuchte instationär)

INTRODUCTION

A particular interest of the author in sustainable design and health in relation to the built environment has inspired the research of this master thesis. Regarding this, the subject is focused on aspects of dampness and mould growth in housing and its relation to the indoor air quality (IAQ) which are particularly relevant issues for homeowners. Generally, sustainable design consists of the principles and practices of architecture that reduce environmental impacts to protect environmental quality and human health. These can also improve the life-cycle economics of the investments in the built environment. [1] Compared to these arguments to introduce sustainable principles and practices in New Zealand's architecture, IAQ and the related aspect of health seem to be poorly considered as further positive contributions so far. However, considering that approximately 15% of the adult population and 20% of children under the age of 15 are affected by asthma in New Zealand, it is necessary to review common practice and to gather more information on health effects in New Zealand homes. [2]

According to Robert Vale, who was asked why IAQ and health might not be an important argument to move forward the sustainable development in New Zealand and why the public is not accessible for such an argument, people rather like to spend their money on things which are killing them instead of keeping them alive. [3] In fact, in New Zealand consumers do not associate more sustainable homes, which provide savings in electricity, water and health costs for occupants, with a greater value of buildings when buying and selling. Therefore, this thesis argues that there is a lack of information about IAQ and health in New Zealand buildings. It illustrates that consumers are not able to measure the value of a differentiation between standard homes and sustainable homes which provide a vastly different performance. [4] Furthermore, a definition of "clean indoor air" by the New Zealand Building Code (NZBC) is missing and has to be established in order to define IAQ in New Zealand homes. It is proven that badly constructed houses are difficult and expensive to heat and that a consequent inadequate thermal comfort in a home can lead to mould growths. Cold and damp houses can lead to negative health consequences such as respiratory symptoms for

[1] California Polytechnic State University. *Sustainable Environmental Design Education (SEDE): Definition of Sustainable Design*. CalPoly, USA, Retrieved October 23, 2008 from the World Wide Web: http://www.calpoly.edu/~sede/home.html.
[2] National Institute of Public Health. *Indoor Environment and Health: A book for everyone who cares about a healthy indoor environment*. Trelleborg., Sweden: Berlings Skogs, 1999, pp.22-23.
[3] Robert Vale. Personal comment. Friday Forum #12: The Sustainable Housing Debate - Green versus autonomous versus sustainable, Auckland, New Zealand, 2008.
[4] New Zealand Business Council for Sustainable Development (NZBCSD). *Better Performing Homes for New Zealanders: Making it Happen*. New Zealand: NZBCSD, A-2008, p.9.

the occupants. [5] Therefore, it is necessary to explore the relation between inadequate heating, dampness problems, cold and mouldy houses and health problems that have been highlighted in several national and international research studies.

The scope of this research paper is to explore the effects of environmental exposures in terms of temperature, ventilation, dampness and on health problems, such as allergies, airways infection and asthma. In this context, the research considers recent international and national studies on this topic, proving that these health problems are becoming increasingly significant in New Zealand's context. Following this, the thesis provides practical recommendations for the refurbishment of particular building typologies that were built between the 1950's and the 1980's. Finally, simulation software is introduced to assess possible "changes" in terms of building physics and to achieve the best possible comfort conditions.

Research for this thesis was primarily literary, using recent research publications, books and journal articles. Secondarily, the research was based on collaboration with researchers, physicists and engineers of the Building Research Association of New Zealand (BRANZ), with sustainable designers and engineers of the Building Biology and Ecology institute (BBE) in Wellington and Auckland, and medical researchers and scientists of the Otago University in Wellington. Personal discussions with architects throughout New Zealand have also been successful as have online media sources to provide background information concerning new products and materials.

The study itself is structured into five parts. Part one comprises health effects related to the built environment and explores different sources of indoor air pollutants. Part two explores the problem of damp housing and mould and examines the association between insulation and the need of ventilation. Part three gives a review of recent international and national studies on this topic to examine their outcomes in order to find solutions that are suitable for New Zealand. Part four illustrates the existing housing stock of New Zealand that suffers under mould and dampness problems. It also explores benefits of the introduction of simulation software in combination with practical recommendations for the refurbishment of particular building typologies. Finally, part five presents the results and outcomes of this research and gives an overall conclusion.

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[5] Brenda Boardman. *Fuel poverty: from cold homes to affordable warmth*. London, UK: Belhaven Press, 1991.

1. HEALTH EFFECTS RELATED TO INDOOR AIR QUALITY

1.1. A LARGE BURDEN TO NEW ZEALAND'S SOCIETY

Looking back 30 years ago, allergies were a relatively uncommon disease. Today, allergies affect a large part of the population in industrialised countries and represent a large burden to society worldwide. The question is what has changed in the environment that is driving this increase of allergies, as the time period has been too short for important genetic changes. The International Study of Asthma and Allergies in Childhood (ISAAC) [1] and the European Community Respiratory Health Survey (ECHRS) [2] have mapped variations in the prevalence of asthma symptoms worldwide and indicated causative environmental factors (refer to figure 1.1). As ISAAC and ECHRS also reported a 15-fold difference between countries, their results prove that the increase of allergies has to be associated with changes in our environment. For example, Western EU countries have a prevalence that is up to ten times higher than the prevalence in Eastern EU countries. [3]

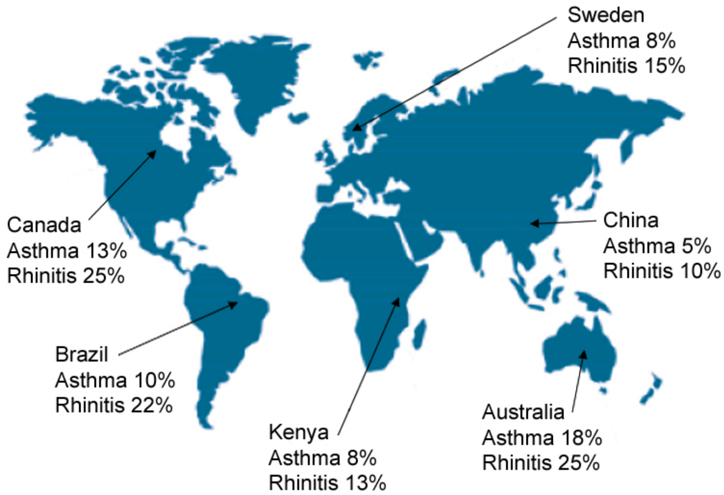

Figure 1.1
Allergic Rhinitis and Asthma
The worldwide prevalence of allergic rhinitis and asthma according to the International Study of Asthma and Allergies in Childhood (ISAAC) Data.

Compared to Europe, New Zealand has the second highest rate of asthma in the world. Data of hospital admissions in New Zealand show that asthma is the most common cause of admission for children to a hospital and its number has doubled during the last 30 years. Furthermore, Maori and Pacific people are disproportionately affected by asthma as well as people from lower socio-economic groups, according to the Public Health Advisory

[1] M.I. Asher. "Worldwide variations in the prevalence of asthma symptoms: the International Study of Asthma and Allergies in Childhood (ISAAC)", *European Respiratory Journal*, Volume 12, 1998, pp.315-335.

[2] P. Burney. "Variations in the prevalence of respiratory symptoms, self-reported asthma attacks and use of asthma medication in the European Respiratory Health Survey (ECHRS)", *European Respiratory Journal*, Volume 9, 1996, pp.687-695.

[3] C.G. Bornehag, S. Bonini, A. Custovic, Custovic, P. Custovic, P. Matricardi, T. Sigsgaard, S. Skerfving, A. Verhoeff and J. Sundell. "Allergies, pets and dampness, EUROEXPO", *Indoor Air*, Volume 14, 2004, pp.243-257.

Committee's (PHAC) first report to government, called "The Health of People and Communities".[4] This fact is the subject of a wide debate and speculations about the cause but the most concern and association is given between damp housing and allergies.

In order to fill this gap of information, researchers of the University of Otago have explored houses that are occupied by low income earners. The outcome of this study clearly demonstrates that New Zealand homes with proper insulation provide significant health gains to the occupants.[5] In fact, 1.04 million homes in New Zealand (which equals 65% of the current housing stock) were built before insulation was required by the New Zealand Building Code (NZBC). Many of these buildings are now upgraded but many of them still do not provide a sufficient insulation level. Furthermore, many homes which were built after insulation was required do not provide proper insulation in order to meet current insulation requirements either. Research has proven that about 375,000 New Zealand homes have inadequate ceiling insulation and over one million provide an inadequate underfloor insulation (refer to figure 1.2).[6]

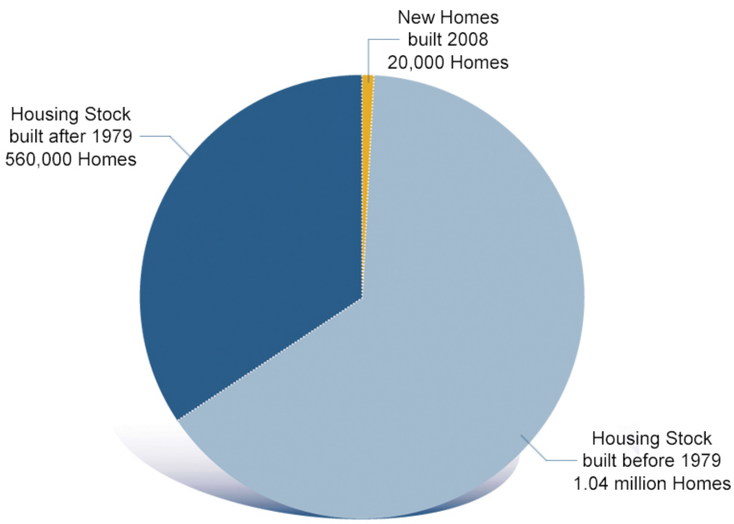

Figure 1.2
Age of NZ Housing Stock
Nearly 1.04 million of New Zealand homes, which is 65% of the current housing stock were built before insulation was required by the New Zealand Building Code (NZBC).

A national survey of 3526 New Zealanders that was conducted in October and November 2008 by ShapeNZ for the New Zealand Business Council for Sustainable Development (NZBCSD) shows that 10% of the sample actually feels warmer at work or educational buildings where they study than at home. Another 5% of these 3526 people are neither not warm, nor comfortable at work or where they study either. Only 29% rank their houses as

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[4] New Zealand Business Council for Sustainable Development (NZBCSD). *Mainstreaming Sustainability in Building: Prepared for the New Zealand Business Council for Sustainable Development*. Auckland, New Zealand: NZBCSD, B-2008, p.29.
[5] Philippa Howden-Chapman, "New Zealand research shows insulating houses results in better health", *New Zealand Herald*, 5th March, 2007.
[6] New Zealand Business Council for Sustainable Development (NZBCSD). *Better Performing Homes for New Zealanders: Making it Happen*. Auckland, New Zealand: NZBCSD, A-2008, p.10.

very warm and comfortable, while 60% report that their houses could be warmer and more comfortable. Some of them even say that they live in the living room to avoid mouldy and damp bedrooms during winter time.[7] The results are major ill health and economic costs that represent a large burden to New Zealand's society.[8] Philippa Howden-Chapman, social scientist and deputy head in the Department of Public Health at the Wellington School of Medicine and Health Sciences stated in relation to research outcomes:

> "The results are clear and our research is very robust because of the size of the sample and the randomised methodology. This is the first time, that there has been such a clear and demonstrable link between housing and health and it gives a strong evidence-base on the best way to retro-fit our old, cold and unhealthy housing."[9]

Of course, the relationship between damp housing and health is very complex and contains different factors that have an affect on the indoor air quality.[10] Generally, housing is a fundamental component of the quality of people's lives and so occupants want their home to be as comfortable as possible. However, the general New Zealand public currently sees a comfortable home as one that is warm and dry but also uses a large amount of energy. This might be true for ordinary homes, but homes designed according to sustainable standards provide much more comfort and a healthier environment while using less energy and water. The fact that existing homes can use less energy and water on one site, and be much more comfortable than now on the other seems to be a paradox for most New Zealanders.[11] Currently, there are about 1.6 million homes in New Zealand. A major report, which was published by the NZBCSD and presents the outcomes of a two year research project, indicates that one million houses of the existing housing stock are performing poorly in terms of insulation. Furthermore, 45% of them are reported as mouldy which can explain why 26% of existing homes - or in other words 410.000 homes - are indicated as houses that can make their occupants ill.[12] Of course, there have been some refurbishments to improve

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[7] New Zealand Business Council for Sustainable Development (NZBCSD). *Media Release: Major new survey reveals New Zealanders' views on the state of their homes and policy solutions*. Auckland, New Zealand: NZBCSD, D-2008.

[8] New Zealand Business Council for Sustainable Development (NZBCSD). *Media Release: Plan unveiled to upgrade New Zealand's million unhealthy, inefficient homes*. Auckland, New Zealand: NZBCSD, C-2008.

[9] Philippa Howden-Chapman, 2007.

[10] Cliff Taylor, *Toxic houses ruining occupants' health*. New Zealand Herald, New Zealand, Retrieved November 30, 2008 from the World Wide Web: http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=10545734.

[11] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.2.

[12] New Zealand Business Council for Sustainable Development (NZBCSD). *Media Release: $20 billion cost of fixing country's homes less than 4% of their value*. Auckland, New Zealand: NZBCSD, E-2008.

insulation levels in the existing housing stock and only 6% of them are completely uninsulated. However, 64% do not provide any kind of underfloor insulation, 29% do not provide insulation in ceilings and 71% do not have completely insulated external walls. [13]

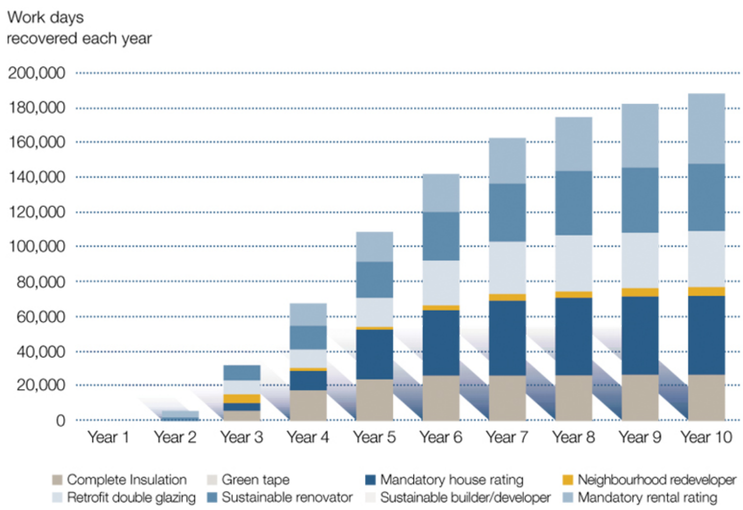

Figure 1.3
Fewer Day off Work
Healthier homes can improve overall productivity, as 780 people in New Zealand do not turn up to work each day because of cold and damp houses which contribute to their illness.

According to the NZBCSD, a quarter of a million homes in New Zealand are currently too cold and damp, as well as poorly built which means that they can cause serious health problems as they do not meet the insulation requirements of the new NZBC. Cliff Taylor, reporter at NZ Herald, mentioned in an article that it would cost more than NZD 20 billion over the next decade to solve this problem. He pointed out that these houses are poorly insulated, contain mould such as black mould, and provide a low indoor air quality. The results are occupants who are suffered from a wide range of illnesses, including mould allergies and asthma. People who responded to another survey that has been done on this issue said that mould and damp in their house had caused their children to be repeatedly admitted to a hospital with respiratory and other health problems. [14] In fact, healthier homes improve the quality of life and, therefore, fewer days off work. In 2008, a report by the NZBCSD stated that 780 people in New Zealand do not turn up to work each day because of cold and damp houses which contribute to their illness. If these houses would be e.g. retrofitted with insulation and double glazing it can save 180,000 work days which equates to at least NZD 17 million a year in lost production that is based on a minimum wage of NZD 12.00 per hour. Therefore, a retrofitting can result in healthier homes and could improve the productivity of New Zealand (refer to figure 1.3). [15] However, damp housing it is not just a problem that can be viewed in older homes. Also many new and renovated homes have been designed and built with low level of insulation and heating system, as well as a lack of

[13] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.12.
[14] Cliff Taylor, 2008 from the World Wide Web: http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=10545734.
[15] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.30.

adequate ventilation or double glazing. New Zealand is suffering from this massive housing problem that has to be faced and solved. Business Council chief executive Peter Neilson concluded, that anyone who travels to New Zealand would come to the conclusion that they have never been colder in homes. [16]

Type of Room	Mean Indoor Air Temperature (°C)				
	Morning 7am - 9am	Day 9am - 5 pm	Evening 5pm - 11pm	Night 12am - 7am	Average over entire day *
Livingroom	13,5	15,8	17,8	14,8	15,8
Bedroom	12,6	14,2	15,0	13,6	14,1
Ambient	7,8	12,0	9,4	7,6	

* The hour from 11pm to 12pm is not included due to software limitations

Table 1.1

Average Indoor Air Temperature

Compared to the overnight which is the coldest time outside, the mornings are the coldest time inside an average New Zealand home. Furthermore, the evenings are the warmest as it is the most common heating time inside New Zealand homes. In this context, the bedrooms on average are usually 3.8°C colder than the living room which is usually caused by heating in the living room and typically no heating in the bedrooms.

In this regard, the World Health Organization (WHO), an indoor temperature that should not be lower than 18°C for living areas and 16°C for bedrooms, as there is a dramatic improvement in health at this level. [17] Research studies have also shown that the mortality rate in New Zealand is lower on days in which the average ambient temperature ranges between 15 to 25°C, compared to on days when the average ambient temperature becomes hotter or colder than this. Especially for very old and very young people the indoor air temperature should be about 20°C. The WHO also has proven that an indoor air temperature that is below 15°C can be a risk factor in increasing asthma severity and chronic obstructive pulmonary disease (COPD). [18] However, in winter time many New Zealand households are frequently an average 6°C below the recommended indoor air temperature of 20°C (refer to table 1.1). Furthermore, nearly 30% do not even meet the recommended minimum indoor air temperature of 16°C. [19] This problem will be intensified in New Zealand households by 2030 because 24% of the New Zealand population will be over the age of 60 by then. It must also be considered that the number of people aged over 80 is due to increase within the next

[16] Cliff Taylor, 2008 from the World Wide Web: http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=10545734.

[17] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.16.

[18] Philippa Howden-Chapman, “Housing standards: a glossary of housing and health”, *J. Epidemiol Community Health*, Issue 58, 2004, p. 163.

[19] New Zealand Business Council for Sustainable Development (NZBCSD), B-2008, p.24.

years and, therefore, the indoor air temperature and quality is an ever more important determinant of health for a growing percentage of the population. [20]

1.2. SICK BUILDING SYNDROME

Generally, it is a fact that the human health is affected by many different factors, such as heredity, environment, life style and age, and depends on the interaction between several of these factors, directly and indirectly. The health of occupants is directly affected by a number of aspects of housing, such as the building structure, internal conditions which include e.g. dampness, temperatures and indoor contaminants, as well as the behaviour of the occupants. But also affluence and the effects of the neighbourhood are widely seen as increasingly important factors that can have an indirect impact on our health. Philippa Howden-Chapman stated in this context that housing in New Zealand is a neglected site for public health action. This has been identified in a number of recent national research reports that show how the conditions of a building, including the material and social aspects, as well as the local neighbourhood can have an effect on our health. [21] Over the past decades, the exposure to indoor air pollutants has increased, as well as the spread of allergic diseases. This development is in relation to the change of our life style and the achievement of good social and economic conditions which include e.g. the change of ventilation rates, the introduction of synthetic building materials and the increase of chemicals in personal care products and household cleaners. [22] It is not proved that there is a connection between the disappearance of protective factors and the emergence of damaging factors but the cause of the increase has to be found among the trigger symptoms. [23]

Traditionally, people have spent more time outdoors than indoors, but with countries becoming more developed people spend 90% of their time indoors now. The elderly and young children spend even more time indoors. Therefore, the quality of the indoor environment as a cardinal exposure factor for humans and should be as high as possible, as it has a strong affect on health (refer to figure 1.4). [24] Allergies, airways infections and other health conditions are related to indoor exposures and are as a serious health problem with a considerable social and economic impact on our society. With this in mind we can direct our attention to indoor air quality, which has, in turn, moved foreword the awareness of poor health relating to poor indoor environment. Two types of illnesses that have been identified as being correlated to poor indoor air quality are Sick Building Syndrome (SBS) and Building-

[20] New Zealand Business Council for Sustainable Development (NZBCSD), November 2008, p.11.
[21] Philippa Howden-Chapman, 2004, p. 162.
[22] Yuanhui Zhang, *Indoor air quality engineering*. Boca Raton, Florida, USA: CRC Press, 2005., p.4.
[23] National Institute of Public Health. *Indoor Environment and Health: A book for everyone who cares about a healthy indoor environment*. Trelleborg., Sweden: Berlings Skogs, 1999, p.20.
[24] Yuanhui Zhang, 2005., p.4.

Related Illness (BRI). The definition of SBS varies slightly in the literature and it is not clear if there is one syndrome, many different syndromes or just single unrelated symptoms. Generally, SBS is a broad term that is used to describe the reaction of humans to environmental hazards that are restricted to industrial, commercial or residential buildings. The list of symptoms includes irritation of sensory organs (eyes, nose, throat, ears and skin), fatigue, headache, respiratory disorder, difficulty in concentration and nausea. [25]

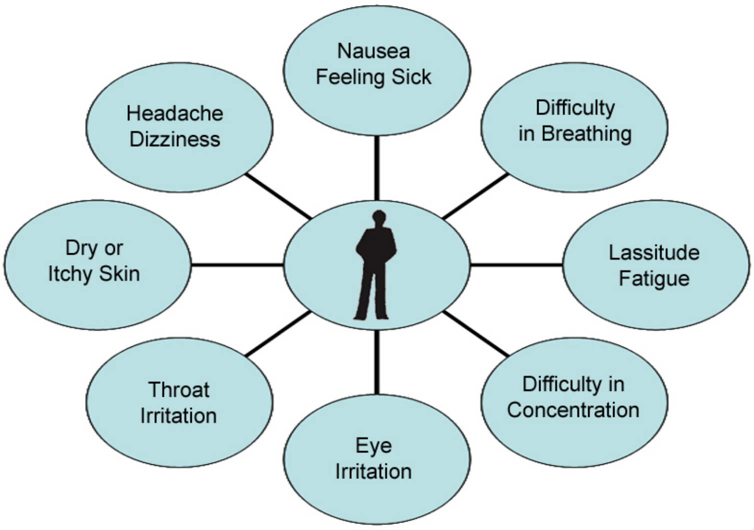

Figure 1.4
Sick Building Syndrome (SBS)
Buildings that have environmental hazards can lead to Building-Related Illness (BRI).

When several people or occupants report health problems e.g. in the respiratory passages, in the digestive tract or with their skin, and these are associated with time spent in a certain building, such buildings are often referred to as sick buildings. The symptoms typically occur after the occupant has spent a short time in the building and increase during the stay. Prevalence of these symptoms differs greatly between each sick building. But once the person has left the particular building, many of these symptoms disappear. [26] Compared to SBS, BRI is defined as a specific, recognised disease entity that is caused by agents. Once the cause of a SBS symptom is diagnosed and the agent is clinically identified it becomes a BRI. But the general public mostly does not distinguish between SBS and BRI and, therefore, SBS usually refers to all illnesses that are related to poor indoor environments. [27]

1.3. AIRWAYS INFECTION AND ASTHMA

SBS symptoms include hypersensitivity pneumonities, humidifier fever, asthma and legionella that are normally an over-reaction of the human immune system. This over-reaction is called an allergy and allergic people (immunologically hypersensitive) react to very small quantities of substances, called allergens. Today, asthma is one of the most

[25] Yuanhui Zhang, 2005., pp.4-5.
[26] National Institute of Public Health, 1999, p.21.
[27] Yuanhui Zhang, 2005., p.5.

common allergic diseases, as well as allergic rhinitis and atopic eczema that are caused by an interaction between hereditary factors and the environment. The environment can be seen as the key factor as it gets our immune system to react unfavourably to allergens. This is known as sensitisation. The environment also triggers symptoms in those people who are already sensitised. The fact is that allergies are increasing in New Zealand, as well as worldwide and it might be that there are also unidentified factors in the indoor environment which contribute to the increase in allergies. [28]

Airways infection such as the common cold, sinusitis, ear and throat infections and influenza are common among adults (1-2 infections per year) and children (3-6 infections per year). The most important route for the spread on infections is assumed to be direct contact between people, or contact via objects. Studies on the significance of the indoor environment for the spread of reparatory infections have shown that children who live in damp housing have considerably more infections in the airways than children who live in buildings without such problems. Especially elderly people and people who have a compromised immune response system are affected by respiratory diseases. The mechanism behind this association is not yet known and is presently subject to on-going controversy. However, research studies have proven that the indoor environment has an important influence on airborne infections. [29] Never the less, more research is needed to find out how mould and spores can affect people and, especially, how damp housing can support the development of asthma and causes shortness of breath and respiratory illnesses. [30]

[28] National Institute of Public Health, 1999, pp.19-20.
[29] National Institute of Public Health, 1999, pp.22-23.
[30] Reuters. “Respiratory problems linked to damp and mould”, *The New Zealand Herald*, 31st Mai, 2004.

2. SOURCES OF CONTAMINANTS IN RESIDENTIAL BUILDINGS

2.1. POLLUTANTS IN THE INDOOR AIR

Generally, the term “air quality” refers to the degree of pollution of “clean air” which is defined as dry atmospheric air. Such air can usually be found in rural areas or over the ocean far away from air pollution sources. The chemical composition of such dry atmospheric air contains approximately 78.1% Nitrogen (N), 20.9% Oxygen (O), 0.9% Argon (Ar) and 0.03% Carbon Dioxide (CO_2), as well as smaller quantities of other substances (refer to figure 2.1). Regarding this, a lower concentration of airborne pollutants in the indoor environment leads to a higher indoor air quality (IAQ). In this context, airborne pollutants are defined as substances which can e.g. affect human health and comfort, as well as reduce the performance and production of plants. They can normally be found in form of solid, liquid and gaseous substances, such as particulate matter, known as PM or mists. For example, a high level of CO_2 emissions can cause serious air quality problems as CO_2 is proved to be partly responsible for the greenhouse effect and global warming. [1]

Substance	Content (%[a])	Concentration (ppm[a])
Nitrogen	78.084 ± 0.004	780,840
Oxygen	20.946 ± 0.002	209,460
Argon	0.934 ± 0.001	9,340
Carbon dioxide	0.033 ± 0.001	330
Neon		18
Helium		5.2
Methane		1.2
Krypton		0.5
Hydrogen		0.5
Xenon		0.08
Nitrogen dioxide		0.02
Ozone		0.01–0.04

[a] In volume.

Figure 2.1
Typical Dry Atmospheric Air
The chemical composition and volumetric content of typical dry atmospheric air, commonly known as clean air.

The concentration of airborne pollutants can be measured and expressed in terms of the mass, volume, or particle number per unit volume of air. The mass of specific particles per unit volume of air is known as C_{pm} and usually measured in mg/m³ (milligram of particles per cubic meter of air). Compared to C_{pm}, the number of particles per unit volume of air in which the particles are airborne is called C_{pn} and can be measured in particles/m³. In practice it is mostly in particles/ml (number of particles per millilitre) as the C_{pn} usually exceeds 10^4 in particles/m³. The concentration of the particle mass or particle number can be converted

[1] Yuanhui Zhang, *Indoor air quality engineering*. Boca Raton, Florida, USA: CRC Press, 2005, p.1.

back and forth when the density and size of the specific particle or its size distribution is known. [2]

The Institute of Medicine at the National Academy of Sciences in the USA, has recently reviewed the role of pollutants in the indoor air for incidence and prevalence of asthma. Researchers conclude that they still do not know whether, or to what extent, the reported increases in asthma can be attributed to indoor exposures. Furthermore, they criticise that there has been little connection between the scientific literature regarding asthma and the scientific literature regarding the characteristics of healthy indoor environments to date. The Institute of Medicine comes to the conclusion that research on asthma has to become interdisciplinary. It needs to include not only clinicians, immunologists and researchers in related biological areas, but also engineers, architects, material manufacturers and others who are working on the design of indoor environments. [3] This outcome has been confirmed in interdisciplinary reviews of scientific literature which were conducted in Sweden, [4] as well as other Nordic countries [5] and the rest of Europe. [6]

At this point, the evidence for a true association between pollutants in indoor air, cough, wheezing and asthma, as well as airways infections and SBS is strong. With that in mind, modern buildings that have become more airtight in order to reduce the heating energy demand have to be discussed. This level of airtightness can lead to an increase of the concentration of airborne pollutants and different sorts of chemicals in the indoor environment which affects the health of occupants. [7] In order to implement an appropriate IAQ control strategy it is important to identify the sources of particulate contaminants in an indoor environment (refer to figure 2.2). Typical sources of contaminants in residential buildings are e.g. insulation and roofing materials, as well as textured paints that may release asbestos or chemical fumes. Furniture, household products or office machineries are usually known as sources of dust. Mites and their faeces are mostly found on carpets compared to allergens that can be found everywhere inside a house, such as pollen, mould spores and

[2] Yuanhui Zhang, 2005, p.21.

[3] Institute of Medicine. *Clearing the Air: Asthma and Indoor Air Exposures*. Washington, D.C., USA: National Academy Press, 2000.

[4] Xavier R. Bonnefoy, Matthias Braubach, Brigitte Moissonnier, Kubanychbek Monolbaev and Nathalie Röbbel, "Housing and Health in Europe: Preliminary Results of a Pan-European Study" *American Journal of Public Health*, Volume 93, September, 2003, pp.1559-1563.

[5] C.G. Bornehag, S. Bonini, A. Custovic, Custovic, P. Custovic, P. Matricardi, T. Sigsgaard, S. Skerfving, A. Verhoeff and J. Sundell. "Allergies, pets and dampness, EUROEXPO", *Indoor Air*, Volume 14, 2004, pp.243-257.

[6] M.I. Asher. "Worldwide variations in the prevalence of asthma symptoms: the International Study of Asthma and Allergies in Childhood (ISAAC)", *European Respiratory Journal*, Volume 12, 1998, pp.315-335.

[7] Russell Cooney. "Healthy Building Feature: Plants boost indoor air quality", *Build*, December, 1990, p.19.

Volatile Organic Compounds (VOCs) of household chemicals and cleaning agents, as well as animal hair. These sources of particulate contaminants are only a few examples and a complete list of all sources is useful but very difficult to complete as buildings normally differ in their function and structure. [8]

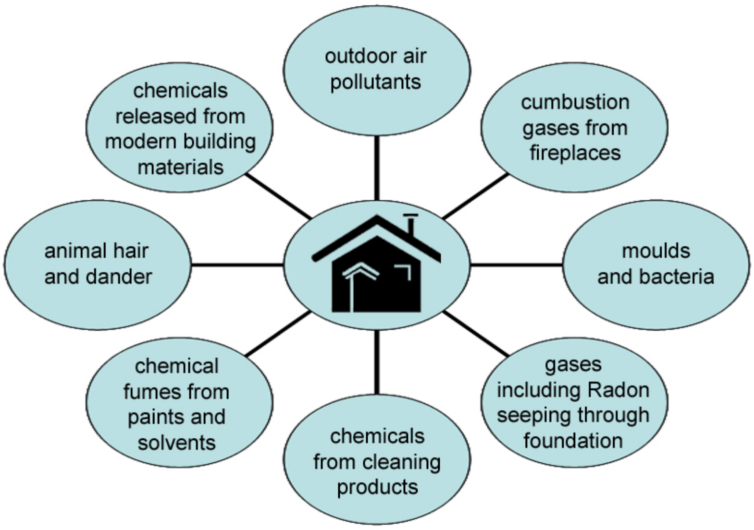

Figure 2.2
Sources of Indoor Pollutants
Exposure to these pollutants can irritate the lungs and sinuses, causing rashes and may contribute to chronic diseases.

2.2. DAMP HOUSING AND MOULD

As one of the main contaminants of the indoor environment, mould is a key trigger for allergic reactions that can be the eventual demise of the immune system. Generally, mould includes all species of microscopic fungi that grow in the form of multi-cellular filaments. There are thousands of types of moulds and all of them play an important part in the life cycle of decomposing organic materials. Some of them cause illnesses while others such as penicillin cure illnesses. Mould spores are the seeds or reproductive particles of mould which differ among species in their size, shape and colour. Each mould spore that germinates can give rise to new mould growth, which in turn can produce millions of mould spores. [9] Many airborne mould types are responsible for human respiratory allergies in indoor environments. Symptoms can be sneezing, itching, coughing and wheezing, as well as shortness of breath and chest pain. Research in this area can be difficult because the problem is to distinguish those effects that are caused by mould and those that are not. Another problem is that high levels of humidity in the indoor air leads to growth of mould but also increases the stickiness of the surfaces and reduces the dust levels in the indoor air. Therefore, research outcomes are often inconclusive [10] and any specific threshold limit values for moulds to prevent hypersensitivity, irritant or toxic responses have not been established. Generally, mould is measured in spores/m³ and a mould concentration below 500 spores/m³ is defined as low. A

[8] Yuanhui Zhang, 2005, p.25.
[9] Yuanhui Zhang, 2005, pp.28-29.
[10] William B. Rose. *Water in buildings: an architect's guide to moisture management and mould*. Hoboken, New Jersey, USA: John Wiley & Sons, c2005, p.244.

mould concentration of 500 to 1500 spores/m³ is known as moderate compared to a mould concentration above 1500 spores/m³ which is high. [11]

Today, about 60 varieties of mould types are known which can cause serious health problems. One of these is Stachybotrys, commonly called black mould (refer to figure 2.3). Stachybotrys chartarum is the most prevalent mould type and, additionally, the most aggressive disease trigger which is known. An odour of clamminess and mustiness are typical signs for Stachybotrys which produces spores when the temperatures in its environment are between 2°C and 40°C. Compared to other mould types which prefer warmer temperatures, black mould grows well at lower temperatures and is more common in colder and damper houses. Ideal culture mediums and conditions to produce and to release spores are building materials with high moisture, high cellulose and low nitrogen. [12] Stachybotrys chartarum can thrive at all times, especially when the relative humidity (RH) is above 70%. New Zealand's un-insulated houses provide ideal conditions for Stachybotrys as these buildings normally have a RH over 75%. When the RH is below 30% the Stachybotrys mould is primarily in the dormant stage. [13] In this context, it has to be known that most buildings in New Zealand provide an average RH of between 65% and 85% and provide a high risk of mould problems.

Figure 2.3
Colony of Stachybotrys
A widespread contamination of Stachybotrys covers virtually the entire wall as a result of a steam loss in a cold house.

2.3. HOUSE DUST MITES

Also related to the RH is another very important allergen source and significant asthma trigger in indoor environments: house dust mites (HDM). HDM are microscopic, spiderlike

[11] Yuanhui Zhang, 2005, p.29.
[12] Alexander Greig, "Indoor Air Quality and Health" in *A deeper shade of Green: Sustainable Urban Development, Building and Architecture in New Zealand*. Auckland, New Zealand: Balasoglou Books, 2008, pp.56-57.
[13] Yuanhui Zhang, 2005, p.29.

insects of the arachnid family which feed on dead skin that sloughs from the human body. A grown up dust mite is approximately about 200 µm long and usually invisible to the bare human eye (refer to figure 2.4). [14] An allergy to HDM is one of the most common allergic problems in the world and especially in New Zealand where one in six New Zealanders suffers from allergies. Dust mites (Dermatophagoides Farinae) require a humid indoor environment with humidity levels ranging between 55% and 75% RH as well as an ideal indoor temperature ranging between 20° to 25°C. The reason dust mites need relatively high humidity levels is that they cannot ingest water unlike other insects. They have to absorb the water they require from the air in order to survive and, therefore, they need a humid indoor environment. [15] The growth of dust mites is, therefore, related to the season and to the location of the room within the building, as humidity levels vary depending on these factors. Their growth also depends of the availability of food sources, the temperature levels and, as already mentioned before, the variations of the RH. The ideal home for a dust mite may, e.g., be a warm and humid bed. [16]

Figure 2.4
A microscopic dust mite image
An adult dust mite is approximately 200 µm long and is usually invisible to the bare eye.

HDM have a life expectancy of approximately 30 days and a female can produce one egg per day. However, during less than ideal conditions they go into a kind of dormancy and can revive when the conditions improve. When the indoor humidity rises above 50% and the conditions are warm, the HDM start to thrive and to produce waste pellets. In order to be fully rid of them they have to be exposed to temperatures of over 60°C for about one hour, or have to be exposed to temperatures below 20°C. A simple washing will just remove most of the waste matter but will not kill the HDM themselves. When HDM die, their bodies disintegrate into small fragments. When these fragments are present and stirred into the

[14] Yuanhui Zhang, 2005, pp.29-30.
[15] National Institute of Public Health, *Indoor Environment and Health: A book for everyone who cares about a healthy indoor environment*. Trelleborg., Sweden: Berlings Skogs, 1999, p.20.
[16] Alexander Greig, 2008, p.57.

indoor air, they can also be inhaled by sensitive people and be responsible for many sick building symptoms, such as difficulty breathing or even severe asthma attacks. [17] Generally speaking, an HDM allergy is an allergy to a microscopic organism that lives in the dust which is, again, present in all kind of buildings and workplaces. Usually it produces symptoms that are similar to those of a pollen allergy, such as frequent sneezing and irritated eyes. Some people also develop allergies to the faecal pellets of dust mites which contain high level of allergens. These allergens can cause e.g. itchy red bumps on the human skin. A limitation of dust mite infestation can be achieved through proper ventilation, opening windows and airing the bedding. HDM are perhaps the most common cause of perennial allergic rhinitis and occur mostly in buildings with moisture problems. [18]

2.4. BUILDING MATERIALS AND OFF-GASSING

Contaminant in the indoor environment can also be caused by other health stressors, like material off-gassing. Everything off-gases and this increases relative to the increased temperature of that building material. In this context, we have to notice that the number of people with allergic reactions to a wider range of chemical pollutants in the indoor environment has become acute in some cases. People which are affected are labelled as Multiple Chemical Sensitive (MCS). Suffering from MCS means that these people cannot handle the exposure limits which other people can. In New Zealand, it is estimated that 10% of the population is affected by heightened chemical sensitivity. In order to reduce material off-gassing that can be related to a number of different sources, it is necessary to take a look at the physical structure of housing. It encompasses building materials and design which is an important part of the built environment and can affect health of occupants. [19]

2.4.1 VOLATILE ORGANIC COMPOUNDS

The indoor environment can be contaminated by a large number of volatile gaseous organic compounds. Generally, these compounds contain carbon and hydrogen and can be generated e.g. by photocopiers, carpets and furnishings. Organic compounds that evaporate easily are known as Volatile Organic Compounds (VOCs). [20] A large amount of VOCs originates from humans, building materials, cleaning and hygiene products, as well as from combustible engines, industry and fuel spills. Research studies have shown that organic gases and vapours in low concentration can not be excluded as risk factors. Indoor exposure of VOCs can lead to chronic and acute health effects, such as dizziness, headache and

[17] Yuanhui Zhang, 2005, pp.29-30.
[18] National Institute of Public Health, 1999, p.20.
[19] Alexander Greig, 2008, p.56.
[20] Yuanhui Zhang, 2005, pp.31-32.

nausea in connection with the development of e.g. allergy, other hypersensitivity and SBS. [21] Long-term exposure to certain VOCs at high concentrations, e.g. benzene, has even been proven to cause cancer. Therefore, many VOCs have been classified as toxic and carcinogenic. [22] Baring these facts in mind, it has to be asked if the total content of VOCs (TVOCs) in the indoor air can be used as a measure of IAQ. From the standpoint of health, TVOCs is currently not considered to be a relevant value, either for the contents in indoor air, or the emissions from furnishing and building materials, as other pollutants affect human health as well. [23] Such indoor air hazards can be radon, mould and products with high volatile organic content, as well as formaldehyde (CH_2O), which can be found in hundreds of building components. [24]

2.4.2 FORMALDEHYDE

Generally, we can measure low levels of formaldehyde, which is a natural, colourless, pungent-smelling gas, in the indoor and outdoor environment. The natural levels are usually less than 0.03 ppm (parts-per-million parts of air) and most people do not have any reaction to formaldehyde levels below 0.1 ppm. People who suffer from MCS or are exposed at elevated levels above 0.1 ppm can be faced serious health problems, such as watery eyes, burning sensations in the eyes and throat, as well as nausea and difficulty breathing. A high concentration of formaldehyde can also trigger asthma attacks in people who already suffer from the illness. Furthermore, it has been proven that formaldehyde can cause cancer. [25] In this context, the public and governmental awareness has increased and building material manufacturers are forced to supply materials with lower concentrations of the chemical. Currently, the reduction of formaldehyde and other toxic ingredients in building materials is in process. However, the building industry uses formaldehyde as an important chemical to manufacture materials and numerous household products. As an example, formaldehyde resins and base materials, such as sawdust, wood chips and peeled wood are used by the industry to produce particle board, fibreboard, structural plywood, plywood reinforcement and plywood under flooring. Therefore, formaldehyde as a major allergy agent, is present in almost everything we manufacture and sources can be found inside all kinds of buildings and cars. [26]

The most significant sources of formaldehyde inside buildings are pressed wood products which contain urea-formaldehyde (UF) resins. Wood products that are produced for usage

[21] National Institute of Public Health, 1999, p.29-30.
[22] Yuanhui Zhang, 2005, pp.31-32.
[23] National Institute of Public Health, 1999, p.30.
[24] Yuanhui Zhang, 2005, pp.31-32.
[25] Yuanhui Zhang, 2005, pp.26-28.
[26] Alexander Greig, 2008, p.58.

inside the building are e.g. particleboard, that is used as subflooring and shelving, hardwood plywood panelling, that is used for decorative wall covering, as well as medium-density fibreboard. Especially medium-density fibreboard contains a higher resin-to-wood ratio than any other UF pressed wood product and is recognised as the material with the highest levels of formaldehyde emissions. Pressed wood products that are produced for the exterior construction usage are e.g. soft plywood and flake or oriented strand board. These products contain the dark or red/black phenol-formaldehyde (PF) resin. The difference between these two types of resins is the emission of formaldehyde to the environment. Pressed wood products which contain PF provide formaldehyde emissions at considerably lower rates than those products that are produced with UF resin. [27] Especially in summer, the amount of formaldehyde emission from building materials increases significantly due to the rise in temperatures throughout the whole building (Refer to figure 2.5).

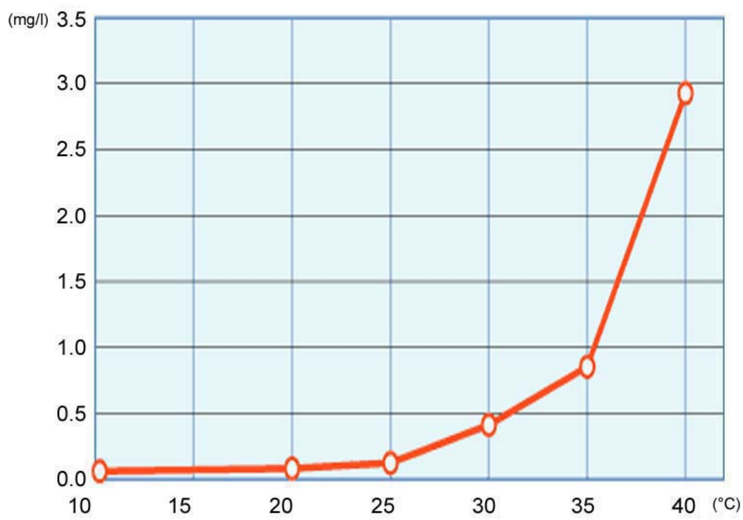

Figure 2.5
Emissions of Formaldehyde
Formaldehyde emissions (flooring) in relation to the indoor temperature; Desiccator Method, specified by Japanese Agricultural Standard (JAS) was used as measuring method

2.4.3 ASBESTOS

Another building material that is hazardous for the health of occupants is asbestos. Asbestos is a general term that describes a group of naturally occurring mineral silicates in various forms. The material was used widely for building products because of its high tensile strength, flexibility and resistance to high temperatures, acids and alkali (refer to figure 2.6). The asbestos fibres are characterised by their large aspect ratio and small diameter. Today, it is know that if people breathe in these fibres in a high quantity it can lead to an increased risk of Lung Cancer and Asbestosis, which means the lungs become scarred with fibrous tissue. Usually the symptoms of theses diseases do not appear until about 20 to 30 years

[27] Yuanhui Zhang, 2005, p.28.

after the first exposure to asbestos. Therefore, the permissible exposure limit (PEL) for asbestos fibres is 0.1 fibre/cm³ for the indoor environment. [28]

Asbestos used to be a common material that was extensively used till the mid 1970's as a building material for fire prevention, insulation, tiles and other products. The great asbestos alarm that followed at the beginning of the 1980's changed this situation completely. People started to decontaminate existing buildings from asbestos materials as one of the most usual measures. Today, asbestos decontamination is the last measure that is carried out after thorough considerations of other possibilities, as an improper removal can be more hazardous than leaving it in place. Furthermore, the mere presence of asbestos in a building structure may not necessarily mean indoor air pollution or hazards. [29] Leaving the material untouched means the escape of asbestos fibres is prevented. As long as the affected areas are not damaged over time, there are usually no serious problems, as the fibres are not released into the indoor air. As an example, studies have shown that the removal of asbestos can cause an increase of the indoor airborne asbestos fibre levels that can remain for a year or even longer (0.0002 to 0.004 fibre/cm³ 18 weeks after removal of asbestos). [30]

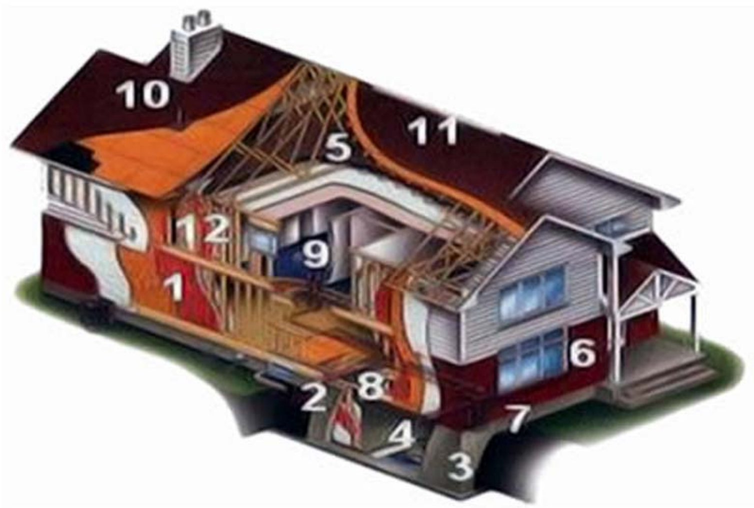

Figure 2.6
Where Asbestos can be found:
1) Cement boarding 2) Ground contamination 3) Insulation on pipes and debris 4) Cement ceiling panels 5) Loose fill insulation in voids 6) Wall covering 7) Under floor ducting pipework 8) Vinyl floor tiles 9) Cement panels 10) Chimney stack or riser 11) Felt covering 12) Miscellaneous products

2.4.4 RADON

Radon (Rn) is a natural product that can be found in high concentrations in many areas around the world. It is an extremely toxic, colourless and odourless naturally occurring, radioactive noble gas that is a result of the radioactive decay of radium. In relation to indoor

[28] Yuanhui Zhang, 2005, p.25.
[29] Yuanhui Zhang, 2005, p.26.
[30] National Institute of Public Health, 1999, pp.31-33.

environments, radon is a significant health hazard, as it can cause lung cancer. [31] Also, building materials which are stone based and contain radium can be a significant source of radon emissions to the indoor environment. Alum shale based aerated concrete, also known as blue concrete, has the highest radium content and can emit radon to the indoor air. [32] Released to the environment, the very heavy radon gas can accumulate at the floor level or an unventilated basement. The concentration of radon inside a building is measured in picocuries per litre of air (pCi/l) and only a simple test is needed to identify whether a building has high radon levels. Most buildings do not have high radon levels and, therefore, it is not common to do such tests, even though it is well known that the exposure to this gas is the second major cause of lung cancer worldwide. When a radon problem occurs, it is necessary to dilute the concentration in the indoor air. In this case the increase of the ventilation rate is the most effective method (refer to figure 2.7). [33]

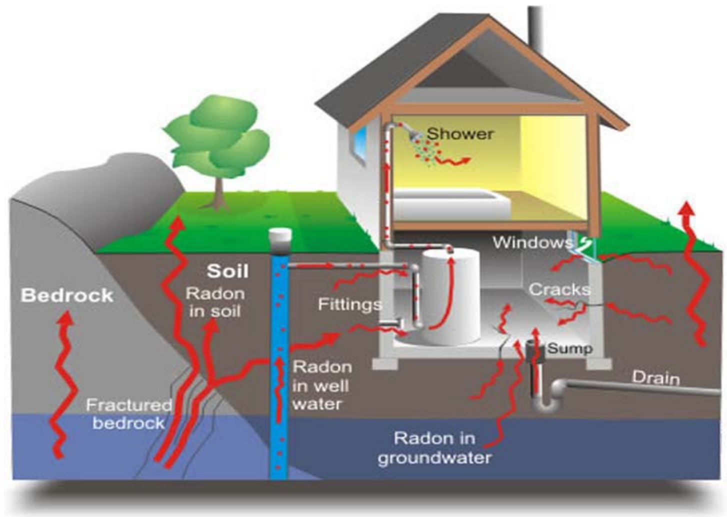

Figure 2.7
Radon Movement
Radon moves through porous areas in the soil and rock fractures near the surface of the earth. It enters the house as soil air often flows toward its foundation.

[31] Yuanhui Zhang, 2005, p.31.
[32] National Institute of Public Health, 1999, pp.33-34.
[33] Yuanhui Zhang, 2005, p.31.

3. UNDERSTANDING THE PROBLEM OF DAMP HOUSING

3.1. THE PROBLEM OF DAMP HOUSING

New Zealand is a country that is known for its high outdoor humidity. In this case, the New Zealand National Institute of Water and Atmospheric Research (NIWA) provides data which show that the average of the relative outdoor humidity can range between 80% in summer and 90% in winter time. [1] New Zealand is currently also noted for its high level of damp housing problems. Some authors mention that this fact probably reflects the problem of high indoor humidity levels, a relative poor housing stock and a high prevalence of inadequate insulation, as well as inadequate heating systems. The outcome of a national telephone survey underlines such arguments as it indicates that visible mould in rooms was reported in 35% of all houses in New Zealand. Of these 35%, 48% reported visible mould in bathrooms and 47% in their master bedrooms which can also be seen as a sign of poor building design and construction. [2]

Moisture in buildings is definitely a risk factor which can cause problems in a building structure, but most importantly it can also cause health problems. Therefore, it is very important for architects and engineers to understand the problem of damp housing as they create living spaces that should preserve the health of the occupants. In this context, the term “damp housing” goes often hand in hand with moisture problems, but it has to be noticed that there is a distinction between moisture in a building structure and the humidity of the indoor air. [3] For example, moisture in a building structure can affect building materials by microbial activities with emissions of smelly and irritant substances which then can cause serious health problems. Damp patches, visible mould or the smell of mould, blisters in plastics floor coverings and discoloration of oak parquet or cork backed linoleum are only a few examples in this case which can indicate a moisture problem. The indoor air humidity, commonly defined as the relative humidity (RH) describes the amount of water vapour that is contained in the indoor air. Generally, it is recommended maintaining a RH of 40 to 60% in order to provide an acceptable indoor air quality (IAQ). An RH level below 40% or above

[1] New Zealand National Institute of Water & Atmospheric Research (NIWA), *Overview of New Zealand Climate*, Auckland, New Zealand, Retrieved November 20, 2008 from the World Wide Web: http://www.niwa.cri.nz/edu/resources/climate.

[2] Department of Public Health: Housing and Health Research Programme. *Potential Health Impacts Associated with Mould in „Leaky Buildings“: A review commissioned by the Auckland City Council*. Wellington, New Zealand: University of Otago, 2007, p.26.

[3] National Institute of Public Health. Indoor Environment and Health: A book for everyone who cares about a healthy indoor environment. Trelleborg., Sweden: Berlings Skogs, 1999, pp.64-65.

60% can offer good conditions for breeding micro-organisms. [4] A high RH level can also cause condensation problems inside a house which can support active mould growth and effects on human health. Regarding this, it is important to understand the factors on which the RH depends, such as the indoor air temperature which plays the most important rule. [5]

3.1.1 THE RELATIVE INDOOR HUMIDITY

If moisture can affect a building structure, it is also possible that a building structure itself is the cause of a damp housing problem. For example, the insulating quality of the building envelope, consisting of roof, external walls and slab, plays a major rule in terms of the indoor air temperature which consequently affects the RH. [6] The fact is that a high indoor temperature reduces the amount of moisture that is available in building materials and, therefore, can lower the risk of mould growth. Commonly, a RH measured at the surface of the materials, varying between 70 to 80% is an unacceptable level and estimated as critical because it supports an active growth of mould and other decay microorganisms. With RH constantly at such critical level along with suitable nutrient medium, moisture, oxygen and temperature will provide the best conditions for spores to develop initial mould growth. [7] In this context, Jim North, a certified building biologist and an associate of the Building Biology and Ecology Institute of New Zealand (BBE), stated that the growth of mould can be minimised by controlling the level of the RH in a building. Generally, a RH should be maintained within the range of 40 to 60% RH. [8]

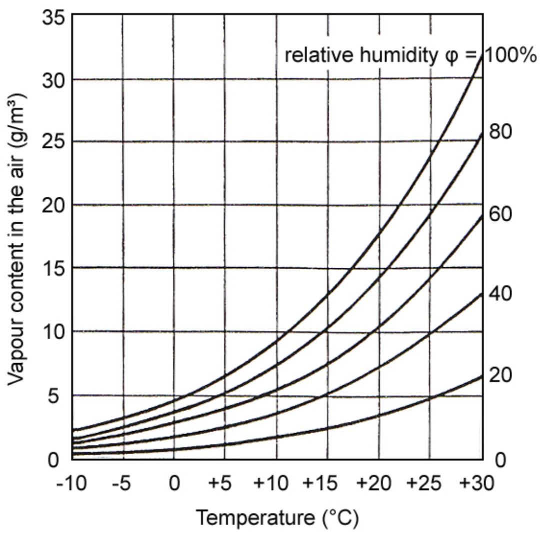

Figure 3.1
Psychrometric Chart
A psychrometric chart can be used to examine the relationship between temperatures, vapour content and relative humidity.

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[4] Clemens Richarz, Christina Schulz, Friedmann Zeitler, *Detail Practice: Energy-Efficiency Upgrades - Principles, Details and Examples*. Basel, Switzerland: Birkhäuser, 2007, p.14.
[5] National Institute of Public Health, 1999, pp.64-65.
[6] Reuters. "Respiratory problems linked to damp and mould", *The New Zealand Herald*, 31st Mai, 2004.
[7] Ralph Burkinshaw, Mike Parrett, *Diagnosing Damp*. Coventry, UK: RICS Business Services, c2003, p.19.
[8] Robyn Phipps, Jeremy Warnes, "Report TE220: Indoor Environment Quality". Auckland, New Zealand: Beacon Pathway Ltd, 2007, p.48.

Apart from the insulation factor, a high level of RH can also be caused e.g. by the location of the building or the life style of the occupants, such as not using extractor fans or opening windows during showering and cooking. [9] However, the value of a given RH has to be clearly understood to be able to recommend any actions to remedy dampness problems. [10] Generally, the RH is a dimensionless number which is expressed as a percentage. It describes simply the amount of water that is available in the indoor air which is related to indoor air temperature amongst other factors. In this case, a psychrometric chart can be used to examine the equilibrium of water vapour in the air at a specific temperature (refer to figure 3.1). The chart graphically expresses how the RH, air temperature and vapour content within the air are related to each other. For example, it shows that one cubic metre of air at minus 10°C has the ability to take up a maximum of 2 grams of water, compared to one cubic metre of air at a temperature of 20°C which is able to take up a maximum of 17 grams. The ratio between the possible maximum and the actually present amount of water vapour in the air is usually referred to as RH. That means that a 100% RH at minus 10°C describes an amount of water vapour of 2 grams compared to a 100% RH at 20°C that describes an amount of 17 grams (refer to figure 3.2). However, it has to be realised that the amount of water vapour in the air only very rarely reaches these maximum RH values under natural conditions. [11] For example, in the Auckland region the content of water vapour in the air is normally between 73% in January and 90% in July of the corresponding maximum value with an average air temperature of 15.1°C during the year. [12]

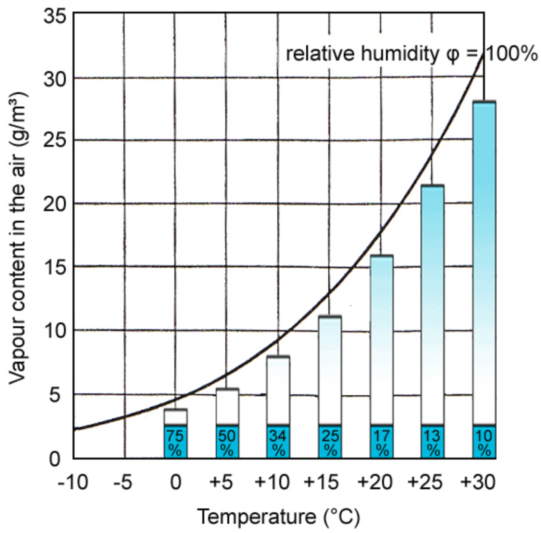

Figure 3.2
Water Content
3 grams of water in 1 m³ of air at a temperature of 25°C corresponds to a RH of 13% while the same amount of water in 1 m³ of air at a temperature 5°C corresponds to a RH of 50%.

[9] Philippa Howden-Chapman, “Housing standards: a glossary of housing and health”, *J. Epidemiol Community Health*, Issue 58, 2004, p.163.
[10] William B. Rose, *Water in buildings: an architect’s guide to moisture management and mould*. Hoboken, New Jersey, USA: John Wiley & Sons, c2005, p.48.
[11] Frank Frössel, *Masonry drying and cellar rehabilitation*. Stuttgart, Germany: Fraunhofer IRB Verlag, 2007, p.39.
[12] New Zealand National Institute of Water & Atmospheric Research (NIWA), National Climate Database, Auckland, New Zealand, Retrieved November 11, 2008 from the World Wide Web: http://cliflo.niwa.co.nz.

The vapour pressure as an exponential function of the air temperature is another factor that affects the RH. Generally, water has the tendency to evaporate into a gaseous form, known as water vapour, and water vapour has the tendency to condensate back into its original form, into liquid water that is known as condensation. This behaviour is related to the given temperature, as there is a particular pressure for water at any given temperature at which the water vapour is in dynamic equilibrium with its liquid form. In simple words, when the air temperature increases, the vapour pressure increases as well which lowers the normal boiling point of the water. This leads to a higher value of water vapour that the indoor air can take up and, therefore, to less moisture in a building structure or material.

The last factor that is related to the RH is the dewpoint (dewpoint temperature). The dewpoint marks the temperature at which the indoor air temperature has to be cooled down so that the contained water vapour can condense into liquid water. The condensed water which can be found e.g. on glass, metal or any material that provides an appropriate surface for the change from the vapour to the liquid phase is called "dew" and, therefore, the dewpoint is known as the saturation point. [13] For example, a RH of 100% has a dewpoint that is equal to the current indoor air temperature as the air is saturated with water to its maximum. In simple words, a dewpoint that stays relative equal to the current indoor air temperature indicates a high relative humidity. If, however, the dewpoint stays at a constant level while the indoor temperature increases, it indicates a decreased RH. The dewpoint temperature describes simply the inside surface temperature when condensation appears on the surface. In this context it has to be mentioned that methods to measure the moisture concentration that are unaffected by the air temperature are also very important as the indoor and outdoor air tend to be equal in terms of the moisture concentration, as well as in terms of the dewpoint temperature. [14]

3.1.2 MOISTURE PROBLEMS IN BUILDING STRUCTURES

Moisture in a building structure can derive from various sources and, therefore, it is necessary to carry out a "dampness survey". The objective of a dampness survey is to identify the lead source of moisture which is necessary to allow any recommendation of actions to terminate such source of moisture and to remedy the dampness problem. Usually, a dampness survey comprises objective measurement of dampness including e.g. spot temperature and relative humidity measurement within each room in order to identify the lead source. It can also involve monitoring which is usually known as a process of elimination, as

[13] William B. Rose, c2005, p.81.
[14] William B. Rose, c2005, pp.47-48.

all possible sources have to be checked and, when occur to be eliminated. [15] For example, if water, such as rainwater enters through an external wall it is never uniformly distributed across a building surface. It is mostly concentrated at places where openings can be found that allow the rainwater to enter the building structure and where the load of water penetration by weather is greatest. Therefore, water problems in walls occur locally when the water comes from the outside.

When a water problem occurs, it can produce patterns that can be interpreted from the inside of the building in order to determine the source of the water, as well as its strength and how recently the problems occurred. These patterns can also be used to indicate a kind of a gradient which is usually a point, line or area that has the densest deterioration. Furthermore, such zone of the greatest density is usually marked by mould growth, discoloration, or corrosion and known as ground zero for the water source. [16] After the identification of such water source, it is possible to control it by fixing the openings that allow the rainwater to enter the building structure. This needs to be done in order to reduce the moisture content to an acceptable level, as the lead source is normally responsible for the greatest amount of moisture in the building structure. [17]

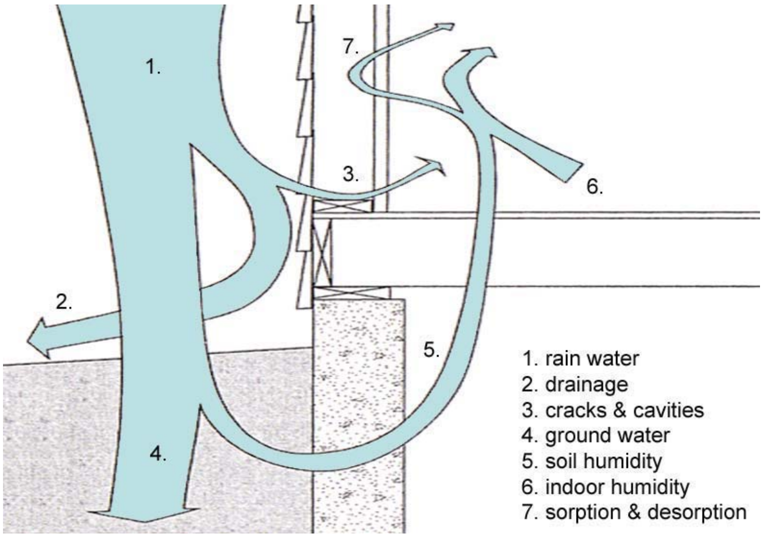

Figure 3.3
Water and Moisture Movement:
The largest amount comes from the outside (3). But also the foundation area can be a large contributor to the indoor humidity (5) compared to a relatively small amount that enters the walls by sorption and desorption (7).

In order to support surveyors and other professionals, such as architects and engineers to create dry, healthy environments, it is more important to use a more general division of moisture sources, as most sub-sources are related to each other in terms of their cause and impact. Such general division can be air moisture condensation, penetration dampness, below ground moisture and internal plumbing leaks, as well as site specific sources (refer to

[15] Ralph Burkinshaw, Mike Parrett, c2003, p.17.
[16] William B. Rose, c2005, pp.171-172.
[17] Ralph Burkinshaw, Mike Parrett, c2003, p.17.

figure 3.3). [18] These five main sources also include sub–sources of moisture such as cooking, washing, burst pipes or building on flood plains, as well as wet timber constructions or inadequate drying-out phases during construction. Moisture from the outside, usually enters the building as liquid water through cracks and cavities in the building, and requires drainage or evaporation to move through the entire building envelope. Many buildings with moisture problems in New Zealand though also have wet foundation areas which can lead to water damages and - when the moisture enters the building - to a high indoor humidity level.

The construction industry has proven that moisture in building materials in combination with different chemical compounds and physical influences in the environment, including temperature, rainfall, soil, landscape and wind, can also cause damages to a building structure. Therefore, moisture can have a very high influence on the durability of materials and structures on the one site, and plays a major role in the reduction of heating and energy performance on the other hand which will be explored later. [19] Generally, the process of the destruction of a building material and the influence of moisture on a building structure can be classified into 3 categories: physical, chemical and biological. The physical category describes thermal and static influences, such as movements in the subsoil, frost damages and temperature changes that are caused by the weather. [20] These influences are the most significant damage factors, as they affect the indoor temperature, moisture and UV-radiation, as well as thermal loadings, e.g. fire and high outdoor temperatures. The chemical reactions can be e.g. binder reactions, pollutants loading and salt damages, which also include structural changes, rust stains or chemical corrosion. Especially chemical damages caused by acids and bases can have an influence on the building structure. For example, if wood or timber is properly built in and it is also properly maintained, it can exhibit a life expectancy of over 800 years for softwood. Hardwood such as oak can even exhibit far more than 1000 years and can be seen as a material that provides nearly unlimited life expectancy. [21] Finally, the biological category is the most interesting in the context of this thesis as it can have a high influence on the static and structure of a building. The biological indoor environment exposures are characterised by the biogenic influences of moisture, e.g. mould growth, microorganisms and mould spores as indoor air pollutants. However, all three categories together describe the substance destruction of building materials of which the main cause is - directly or indirectly - moisture. [22]

[18] William B. Rose, c2005, pp.171-172
[19] Refer to chapter 3, pp.32-35.
[20] Frank Frössel, 2007, pp.16-17.
[21] Frank Frössel, 2007, pp.234.
[22] Frank Frössel, 2007, pp.16-17.

Wood is a good example of building material to describe the physical, chemical and biological category. As known, wood is a hygroscopic material that can take up moisture from the atmosphere as well as other adjacent materials, and its moisture content can also change without the direct contact with water. Generally, freshly cut wood contains approximately about 50 to far over 100% of moisture. 30% of this moisture content is chemically bound in the fibres itself, while the rest of it is stored in form of capillary water within the cell cavities. Therefore, wood looses the capillary water, known as free water first and maintains its volume. When the bound water is subsequently released, the micells start to move closer together which is known as shrinking or contracting. On the other site, dry wood can also take up water again when there is high atmospheric moisture, which pushes apart the micells, called swelling. This behaviour of swelling and shrinking in relation to moisture migration is one of the most important characteristics of wood. [23]

3.2. MOULD AND SPORES IN BUILDINGS

The lack of visible mould as an indicator of moisture problems does not automatically mean that there is no ongoing condensation problem caused by e.g. a critical RH inside the house. Frequently, condensation and mould damages can be periodically removed from the surface that is usually redecorated by the occupants. Also condensation problems that occur within or between building materials are out of view and, therefore, it might be that it is not possible to identify such a problem at first. [24] However, as stated at the beginning of the chapter, damp housing is one of the biggest problems in New Zealand's architecture and, therefore, mould and spores in homes are one of the greatest hazards to occupants. [25]

Chapter one illustrated that damp conditions can affect the respiratory conditions of adults and especially of children, as a child has up to a 25% higher risk of severe ill-health and disability during childhood and early adulthood. [26] Furthermore, multiple studies have shown that visible mould in New Zealand homes is relatively common. The outcome indicated that over one-third of New Zealand homes have been identified with mould in a national survey. Especially amongst low-income communities, tertiary student accommodation and Pacific communities, the prevalence of reported visible mould in housing is definitely higher than the national average. [27] In order to keep these contaminants and key triggers for allergic reactions under control it is necessary to explore and to understand mould growth and the affect of spores on our immune system.

[23] Frank Frössel, 2007, pp.233-234.
[24] Ralph Burkinshaw, Mike Parrett, c2003, p.19.
[25] William B. Rose, c2005, p.237.
[26] BBC News. *Meningitis 'link' to poor housing*. USA, Retrieved November 06, 2008 from the World Wide Web: http://news.bbc.co.uk/2/hi/health/5337580.stm.
[27] Department of Public Health: Housing and Health Research Programme, 2007, p. 29.

Generally, the building surface condition for initial mould growth can be quite different to the condition under which mould growth continues. In most cases, the condition for initial mould growth requires a higher RH level. In order to measure the amount of available water present on the building surface, biologists use the term surface water activity, also known as a_w. This allows limitations of available water to be expressed in a universal form which permits designers, engineers, building scientists or architects to design and construct buildings where these limitations can be controlled. The measurement a_w is expressed as a decimal less than 1 that corresponds to surface relative humidity. In this context, the International Energy Agency (IEA) Annex 14 on "Condensation and Energy" (1991) stated a threshold value of 80% surface relative humidity, $a_w < 0.8$. This value describes an average monthly value that indicates a risk of mould growth when it is above this threshold. [28]

Mould is a fungus that affects the surfaces of organic materials that are supporting a fungal colonisation. It continues to grow on building surfaces that provide such dependable moisture content without actually having a real water flow on the surface. Furthermore, the spreading ground has to contain sufficient food and no significant inhibiting chemicals or treatments. Apart from that, the RH has to be high or critical, as different organisms require different thicknesses of water films for their digestion. This film is needed to permit diffusion of enzymes outward and simple hydrocarbons back to the organism. Penicillium and Cladosporium e.g. need a thin film and, therefore, they can thrive where the RH in the air is around 80%, compared to Stachybotrys that requires a RH on the surface by up to 95% to produce a thicker film. [29]

Spores instead can be found even under dry conditions in the air and on surfaces inside a house. Mould spores are different in their size, shape and colour among species and responsible for human respiratory allergies in indoor environments (refer to figure 3.4). [30] Therefore, mould is measured in relation to the content of spores in the indoor air (spores/m³) but the infestation of visible mould is mostly measured by the mass of active colonies and the size of mould patches that can be indicated by a mould smell. [31] Significant concentration of spores of various mould and fungi can also be contained in the outdoor air, as well as in the outdoor soil. They can travel by air or water and by transportation of infected materials. These mould spores of individual species have to encounter a building surface that provides suitable condition before mould or rotting fungi can be present in a building. [32]

[28] William B. Rose, c2005, p.237.
[29] William B. Rose, c2005, pp.235-237.
[30] Yuanhui Zhang. *Indoor air quality engineering*. Boca Raton, Florida, USA: CRC Press, 2005, pp.28-29.
[31] Philippa Howden-Chapman, 2004, p.163.
[32] William B. Rose, c2005, pp.233-234.

In this case, the contamination of a central air ventilation system e.g. can become a breeding ground for mould, mildew and other sources of biological contaminants. The ventilation system can distribute these contaminants through the entire building. [33] Common types of mould spores that have a high chance of initiating growth are Penicillium, Alternaria and Cladosporium. Less common mould spores can require days or even month before they start to infiltrate a suitable building surface. [34]

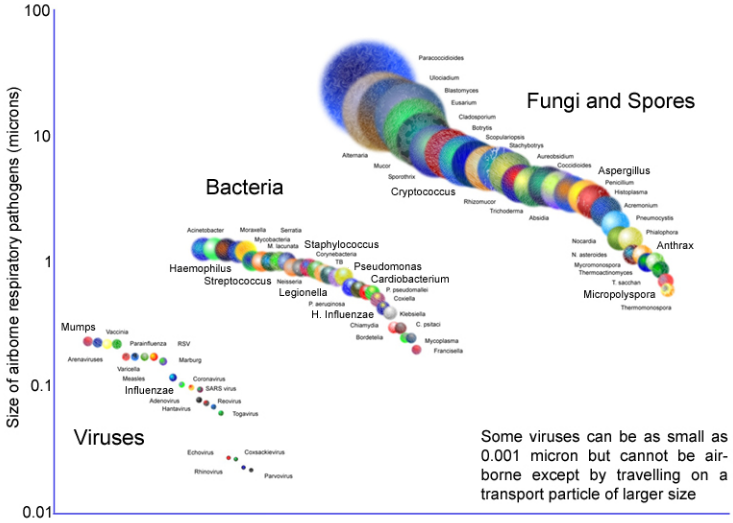

Figure 3.4
Fungi and Spores
Demonstration of the relative sizes of airborne respiratory pathogens.

Today, 60 varieties of mould types are known which can release spores into the indoor environment and can cause serious health problems. [35] In order to solve the problem of mould and mould spores in buildings we have to understand how these spores are released into the indoor environment. First of all, it must be clear that mould cannot be treated like dirt. Mould is a member of the fungus family and a living organism that can grow under the right conditions. In other words: it is not an inorganic compound. Mould produces and releases spores for its reproduction and to colonise other suitable surfaces. These spores can carry toxins that are capable of destroying other existing colonising organisms and can have health effects. For example, Penicillium releases spores that can poison bacteria in its neighbourhood with penicillin and spores of Stachybotrys mould contain tricothecenes to wipe out the indigenous local bacteria, such as fungi. [36] Of course these are just a few examples, but more research is required to identify the actual respired doses of the biologically hazardous components of spores. In the mean time, architects, engineers,

[33] Jim North, 2006.
[34] William B. Rose, c2005, pp.233-234.
[35] Alexander Greig, "Indoor Air Quality and Health" in *A deeper shade of Green: Sustainable Urban Development, Building and Architecture in New Zealand*. Auckland, New Zealand: Balasoglou Books, 2008, pp.56-57.
[36] William B. Rose, c2005, p.236.

builders, and developers have to focus on designing buildings as dry as possible and do not support the active growth of mould and other decay microorganisms. [37]

3.3. MOULD GROWTH CAUSED BY CONDENSATION

Compared to mould which is caused by wet building materials, the development of visible mould, e.g. on wall surfaces, is frequently related to a persistent condensation problem. For example, mould tends to grow in colder parts of rooms where the surface temperature of the building envelope is below the dewpoint. This can be viewed e.g. in colder corners, behind furniture or as usual in unheated rooms as water vapour will change to liquid water when it comes in contact with a cold surface. Therefore, condensation as a source of mould can also cause health problems. Strictly speaking, condensation is the consequence of moisture movement and not a cause, which is instead a critical RH level in the indoor air. Therefore, it is necessary to reduce the RH in order to get the mould problem under control. In this context, it is commonly known that the RH varies according to climate or seasonal conditions, the building design and condition, as well as the activities of the occupants (refer to figure 3.5). Especially the lifestyle factors can have a huge impact on moisture generation within the home. For example, cultural differences regulate activities such as cooking, cleaning, washing and heating which also undoubtedly influence condensation problems. [38]

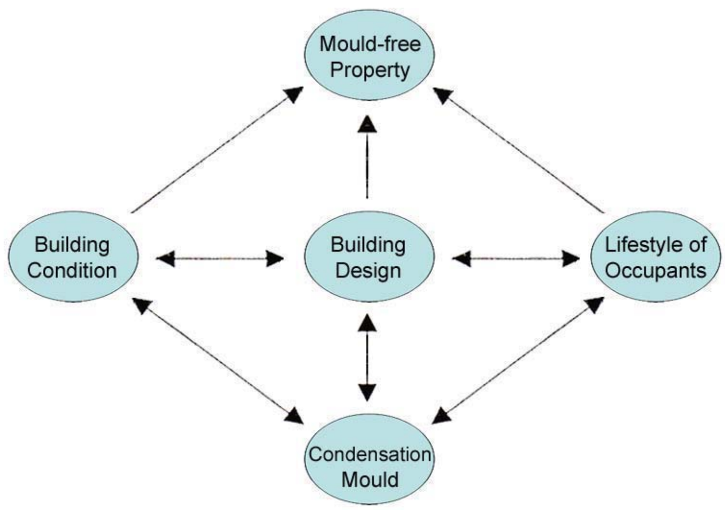

Figure 3.5
Condensation Diamond
The condensation diamond shows inter-related factors, such as the building design and conditions, as well as the lifestyle that can produce or remedy condensation and mould problems in buildings.

How does condensation occur and what exactly does the term "condensation" mean? William Rose, a research architect at the University of Illinois at Urbana-Champaign, states that the term "condensation" is commonly used to describe the change of water from the gas phase (vapour) to the liquid phase and claims that the term itself may be the most improperly used term in all building sciences. He argues that condensation simply describes liquid water

[37] Reuters, 2004.
[38] Ralph Burkinshaw, Mike Parrett, c2003, pp.18-19.

what can be found e.g. on a single layer window in the early morning, as well as on glass, metal and plastic that provides an appropriate surface for water change from the vapour to the liquid phase. [39] But the sorption of water by porous and hygroscopic building materials cannot be considered as condensation in Rose's mind. [40] Compared to condensation, the change from the liquid phase back to the gas phase is known as "evaporation". This process can be viewed e.g. after a rain when a wetted wall dries, influenced by temperature and air movement. [41]

Generally, when the indoor temperature increases, the indoor air is capable to take up more water vapour which does not automatically lead to a higher RH. Diffusion or air currents then can cause the water vapour to move from its original source in all directions inside the building. When it comes in contact with a surface such as the surface of single layer windows or bathroom tiles that have a temperature at, or below, the dewpoint, the water vapour condensates, depositing liquid water on the surface. This can usually be described as water droplets that are streaming down the surface (refer to figure 3.6). Surface condensation is well known and probably the most common type of condensation problems in New Zealand homes, but there are also other types of condensation which can cause serious moisture problems. Interstitial condensation is another type of condensation, which can occur within or between different layers of the building envelope when the dewpoint lies within a construction element or building material. For example, when the water vapour has moved up into the roof void it can condensate underneath the cold underside of the thin covering roof material which can be below the dewpoint temperature. [42]

Figure 3.6
Condensation on Windows
Abiding condensation around a window sill can be enough to provide good conditions for mould growth.

[39] William B. Rose, c2005, p.81.
[40] William B. Rose, c2005, p.38.
[41] Ralph Burkinshaw, Mike Parrett, c2003, p.10.
[42] Ralph Burkinshaw, Mike Parrett, c2003, pp.18-21.

The opposite of these two types of condensation is the reverse condensation, also known as "summer condensation". This type of condensation can occur e.g. when a northern faced wall is affected by sunlight after a period of rain. The water vapour moves inwards through the wall instead of outwards because the coldest part of the wall is located within the wall. Therefore, condensation can occur e.g. on the inside of the vapour check of an un-insulated wall as it is the coldest part. Also effected by the sun is radiation condensation that is also known as "clear night condensation" and noticed as another form of interstitial condensation. Radiation condensation is related to the changes of the atmosphere temperature during the night time. When the atmosphere loses heat during a clear night by radiation, condensation on building structures facing the sky can occur which is usually caused by the rapid heat loss. Radiation condensation can be found e.g. on the underside of a skylight whereas condensation on vertical surfaces is very small. Surface and interstitial condensation can be a sign of a poor building construction e.g. as a result of existing cold bridges or thermal breaks in the building envelope. Another reason can be a lack of proper insulation in the building envelope which can cause a cold internal surface, that can typically be found at the head of windows and doors that are supported by a concrete lintel. [43]

Overall, there are more than a dozen of common moulds that are related to condensation problems and some of them, such as the Black Spot Mould are known as typical condensation moulds even if they are not always moisture source specific. Other factors such as dampness or internal leaks, as already stated at the beginning of this chapter, can also play a major rule in this context. However, all types of condensation have to be noticed as a serious problem that is the result of a complex network of contributory factors. Therefore, as mentioned in the beginning of this chapter a dampness survey has to include an investigation into those contributory factors, affecting the indoor air quality (IAQ) and, finally, causing serious health problems to the occupants. [44] Thus, it is quite important to understand the relationship of all factors that contribute to the process of condensation.

3.4. SORPTION AND DESORPTION OF MOISTURE

After the process of condensation is clarified, it is possible to underline the argument of William Rose again who says that the term "condensation" is the most improperly used term in all building science. [45] In fact, water of sorption in porous and hygroscopic building materials need to be considered as another phase that is different from the three phases of pure material (refer to figure 3.7), [46] also known as aggregate states: liquid (water; 0 to

[43] Ralph Burkinshaw, Mike Parrett, c2003, p.20.
[44] Ralph Burkinshaw, Mike Parrett, c2003, p.19.
[45] William B. Rose, c2005, p.38.
[46] William B. Rose, c2005, p.251.

100°C), solid (ice; < 0°C) and gaseous (water vapour; > 100°C). [47] The embedment of water molecules by sorptive material is simply a result of the conversion of water from water vapour to sorbed water through capillary condensation. The specific amount of capillary condensation depends on the contact angle of a material that indicates the strength of the capillarity that permits absorbed water to distribute into a building material. In this context, it has to be realised to water always moves from larger to smaller pores and never from smaller to larger ones.

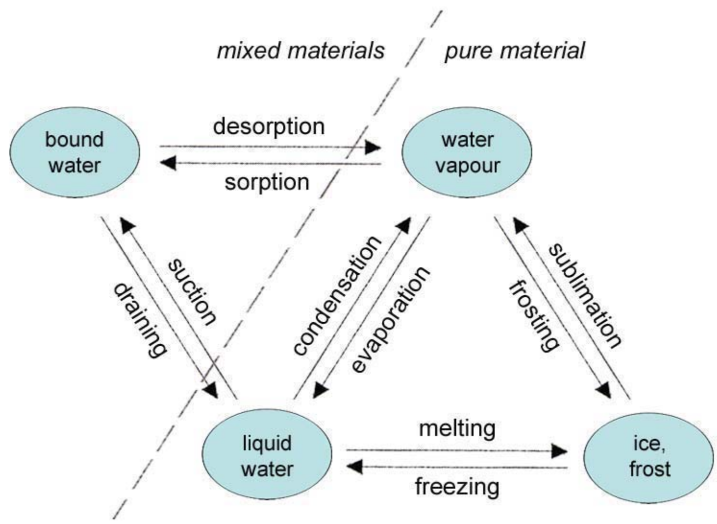

Figure 3.7
Phases of Water
Change of phase for pure materials (gas, liquid, and solid water) and for mixtures (bound water).

The embedment of water molecules by a building material is known as sorption which can be divided into "adsorbed" and "absorbed". Building materials can bind water vapour to the material surfaces of the pores with varying strength that is held tightly and is called "adsorbed". The term "absorbed" describes the water molecules which are held less tightly in the material rather then directly on the surface. [48] Therefore the embedment of water molecules by sorptive material is a result of the conversion of water from water vapour to sorbed water through capillary condensation (refer to figure 3.8). This activity is described as "sorption" and refers simply to the take-up of moisture which occurs 50% of the time. The other 50% of the time the material normally is desorbing which means it is giving off moisture. The sorption and desorption of moisture by a sorptive material, such as concrete is, therefore, constant and the water content of the material increases with increasing RH. As long as the actual moisture content of the sorptive material is equal to the RH it is in a physical state of equilibrium. But when the moisture content lies above the RH, wall moisture is present and the risk for mould growth is given. [49] Such moisture content can occur e.g.

[47] Frank Frössel, 2007, p.29.
[48] William B. Rose, c2005, p.251.
[49] Frank Frössel, 2007, p.40.

when openings in the building envelope allow rainwater to enter and to wet constantly the building structure, as well as burst pipes or building on flood plains can occur such situation.

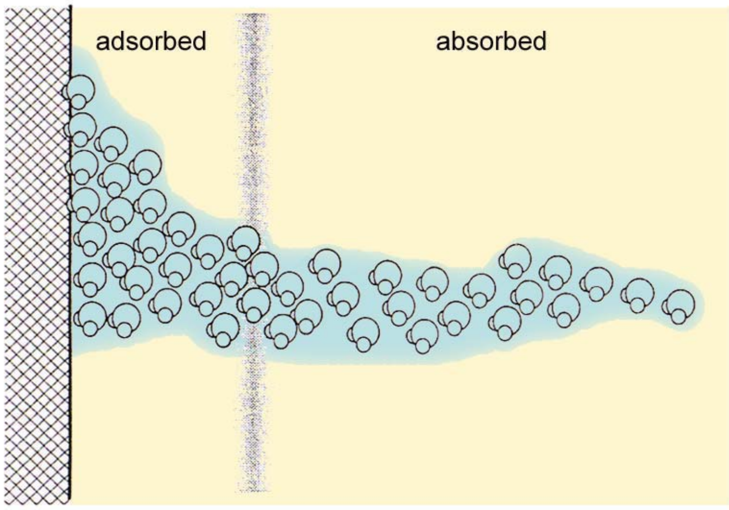

Figure 3.8
Adsorbed and Absorbed
Water molecules in immediate contact with a surface of a building material are adsorbed compared to water molecules that are more loosely attracted to the surface and are absorbed.

Therefore, even in a dry building nearly all building materials contain still a certain amount of water under normal conditions that is known as the practical moisture content and should not be a concern. For example, brick contains approximately 1.5%, wood 1.5% and gypsum 2.0% of water which can only be completely dried with a water content of 0% in a laboratory after it was oven-dried for several hours at 50 to 100°C. However, the practical moisture content of such material is only affected by the RH and, therefore, this content is never constant. [50] But a building material can suffer a moisture problem when it is subject to persistent high RH, usually above 75% RH or when a water leakage occurs and the material gets wet, e.g. by rainwater. [51] However, in order to get the water out of the structure, it has to be assisted in drying again. Many factors have an influence on this process of drying, such as the air temperature which allows heating up a building material and is called the thermal heat factor. In fact, it is well known that warm and wet material dries much quicker than a material that is left at a cold temperature. [52] In this case, the thermal heat factor affects the capillary movement of building materials which allows water molecules on the warm surface to evaporate much quicker. In other words, under cold conditions the surface temperature assists the capillary movement and keeps the materials wet. This is in contrast to warm conditions, which keep the surfaces drier and lower the capillary rise. [53]

Related to the thermal heat factor is also the vapour pressure. Moisture can occur in an external wall through condensation, when the water vapour pressure is equal or higher as

[50] Frank Frössel, 2007, pp.29-30.
[51] Ralph Burkinshaw, Mike Parrett, c2003, p.9.
[52] William B. Rose, c2005, p.172.
[53] William B. Rose, c2005, p.55.

the saturated vapour pressure. That in turn, explains why cold porous materials are wetter at the same vapour pressure than warm materials, which is commonly known as “thermal wetting” and “thermal drying”. The airflow above the surface of a building material is the third factor that has influence on the drying process. Generally, the site of a water leakage that is wet is out of equilibrium with the indoor and outdoor air. In order to dry, it has to give up water vapour to the indoor or to the outdoor air. If the airstream above the surface is constant it supports the building material to dry faster and to be in equilibrium with the indoor or outdoor air again. [54]

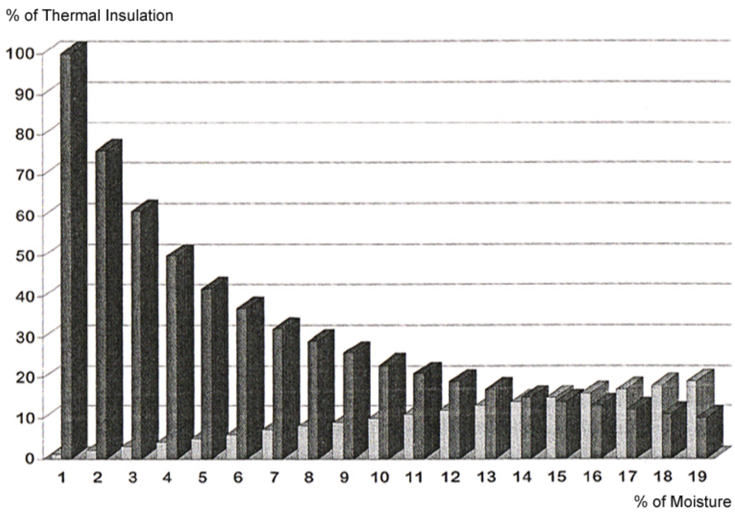

Figure 3.9
Thermal-Influence of Moisture: Thermal insulation related to moisture content.

Overall, if a building material is not assisted in drying again, it can support mould growth on the one hand, but it can also have an impact on the insulation quality of the building material on the other hand. The uptake of moisture by a building material has always an affect on its thermal resistance, known as the R-value (K·m²/W). Generally, the higher the R-value is, the better is the building insulation's effectiveness, but this value can be reduced through the moisture content. For example, possesses the thermal resistance of a brick stone depends on its porosity and a brick that has a cold surface has also a higher capillary rise than usual. When water can enter the brick stone and has completely filled its pores, it reduces the characteristic R-value of the brick to almost equal to 0 (K·m²/W). As shown in figure 3.9, a moisture uptake by a brick stone of only 4% can e.g. reduce the R-value by 50%. [55] The result is a house with dampness problems which reduce its inadequate thermal insulation value and, therefore, lead to a lack or a low quality of insulation. Furthermore, the house then cannot keep the thermal heat inside in order to assist its building material in drying again as it mostly misses an adequate heating system. The result is a cold and damp house.

[54] William B. Rose, c2005, pp.172-173.
[55] Frank Frössel, 2007, p.16.

4. VENTILATION IN RESIDENTIAL BUILDINGS

4.1. VENTILATION

A human breathes approximately 11,000 litres of air every day or in other words 10 to 20 litres per minute at a moderate workload while spending 50 to 90% of this time indoors. [1] Occupants, therefore, need “fresh air” in their homes which can be described as the exchange of contaminated air by fresh air coming from the outside. Throughout the first part of the twentieth century, the air exchange rate, also known as the ventilation rate was simply driven by odour control. The ventilation rate in schools, for example, was related to how often the students could bathe which depended mostly on their social class. These days are gone but other problems that are related to the control of indoor air quality (IAQ) have replaced the old ones. [2] Such problems can be the contamination of the indoor environment caused by material off-gassing in association with the occurrence of sick building syndrome (SBS) as well as house dust mite (HDM) allergy or other health effects which can be related to off-gassing of hydrocarbons by building materials. Therefore, it is important that a continual supply of fresh outdoor air is provided to all rooms in a building. [3]

Especially in bedrooms, the ventilation rate is of interest as it affects human health most. Buildings with natural ventilation in individual bedrooms can be considered to have a lower ventilation rate in the bedrooms than that of the overall house as the bedrooms are usually closed during the day. [4] Furthermore, apartment buildings can present the same IAQ problems as single houses of the same period as many of the typical pollution sources are similar, including interior, off-gassing building materials, furnishings and household products. Problems in apartment buildings that are similar to those in offices are normally caused by contaminated ventilation systems that have improperly placed outdoor air intakes or maintenance activities. [5] Indeed, the maintenance of a ventilation system is often substandard as it is not perceived to be important. Therefore, it is necessary that a ventilation system is constructed and designed so that is does not require exacting maintenance in order to work properly for many years. However, the technology of ventilation systems has

[1] Alexander Greig, “Indoor Air Quality and Health” in *A deeper shade of Green: Sustainable Urban Development, Building and Architecture in New Zealand*. Auckland, New Zealand: Balasoglou Books, 2008, p.56.
[2] William B. Rose, *Water in buildings: an architect’s guide to moisture management and mould*. Hoboken, New Jersey, USA: John Wiley & Sons, c2005, pp.220-221.
[3] National Institute of Public Health. *Indoor Environment and Health: A book for everyone who cares about a healthy indoor environment*. Trelleborg., Sweden: Berlings Skogs, 1999, pp.65-67.
[4] National Institute of Public Health, 1999, p.67.
[5] Jim North, “Should you be concerned about the indoor air quality? - Part 1”, *Healthy Options*, March, 2006.

varied over time in its quality and efficiency, but it has also been proved that ventilation rates in homes have been reduced during the last decades to achieve a better building performance in order to improve energy conservation. Creating healthier indoor environments has become essential to architects and engineers which means to minimise and eliminate health stressors in buildings. [6] The implementation of ventilation and filtration systems, as well as the removal of airborne contaminants can help to reach this goal, as these systems can provide fresh air to the occupants, balance the indoor air temperature and control the level of particular airborne pollutants. But the question is which ventilation rate has to be provided to achieve a healthier indoor environment.

4.1.1 VENTILATION RATE

The ventilation rate itself is the outcome of a preceding analysis which defines the minimum ventilation rates for the control of the indoor temperature, relative humidity (RH), and a specific pollutant. The minimum ventilation rate, known as Q_{min} is usually the highest of these three ventilation rates in order to control and balance sensible heat, moisture, and the given pollutant. All these three rates are related to the air temperature which makes it possible to plot the ventilation requirements in association to the outside temperature at given indoor conditions. Such a plot, also known as a ventilation graph (refer to figure 4.1) includes the required temperature inside the house, as well as the RH and the acceptable level of a specific pollutant, e.g. carbon dioxide (CO_2). The ventilation graph simply presents the minimum ventilation rates which are required to maintain and to achieve acceptable conditions of IAQ. Therefore, the minimum ventilation rate usually follows the uppermost portion of each curve which has been calculated for the balances of temperature, moisture, and specific pollutant concentration. [7]

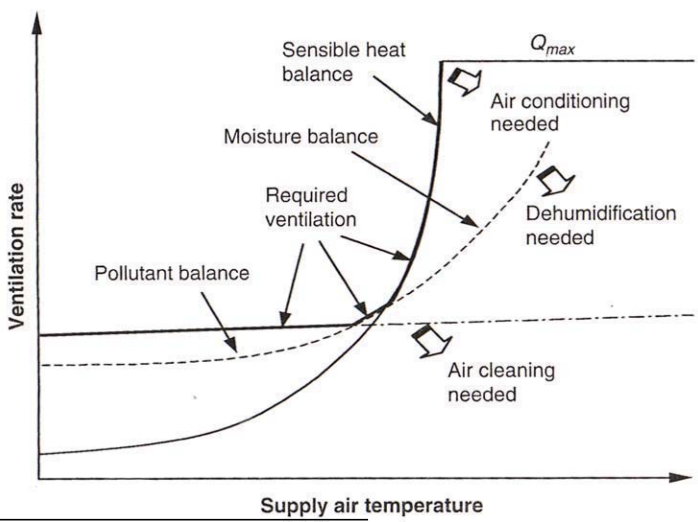

Figure 4.1
Ventilation Graph
The minimum ventilation rate must follow the uppermost portion of the three curves (sensible heat, RH, and a specific pollutant) to maintain and achieve an acceptable indoor air quality.

[6] Alexander Greig, 2008, p.56.
[7] Yuanhui Zhang, *Indoor air quality engineering*. Boca Raton, Florida, USA: CRC Press, 2005, pp.447-448.

The common measurement for ventilation rates is the number of times which is needed to replace the interior volume of air per hour (1/h), called air changes per hour (ACH). Ventilation rates for living areas in New Zealand homes are based around 0.35 ACH and stated under the New Zealand Standard (NZS) 4303. [8] The air change rate of 0.35 ACH is related to the volumetric area of the occupied space of the home, but kitchens, bathrooms and laundries require a higher ventilation rate than living areas. The air change rate for living rooms should generally be between 0.35 and 0.6 ACH, and about 1.5 ACH for bathrooms and kitchens to control the level of indoor pollutants. [9]

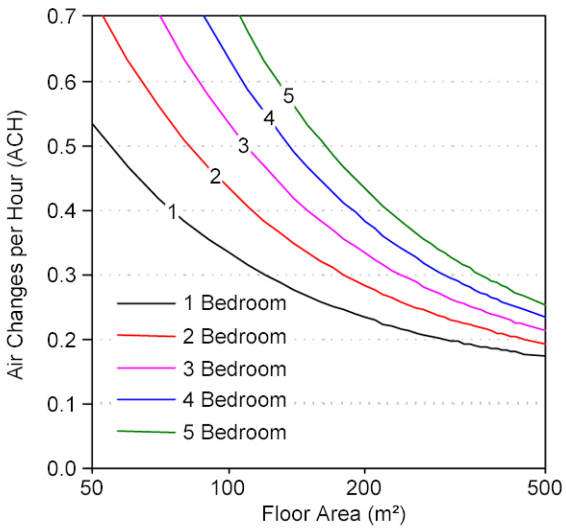

Figure 4.2
Ventilation Rates
Required ventilation rates for houses with 1 to 5 bedrooms of varying floor area size.

In order to define minimum international standards for mechanical and natural ventilation systems in homes, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has developed the ASHRAE Standard 62.2: 2004. [10] When applied to spaces within single-family houses and low-rise multi-family structures, this standard recommends ventilation rates that depend on the total floor area and number of bedrooms (refer to figure 4.2). [11] However, the minimum ventilation rate for living spaces is 0.35 ACH, but ventilation rates are still a source of continuing controversy and concern because conditioned air can also be expensive, as air conditioning systems are usually the largest energy consumers in buildings. Therefore, the IAQ requirements have to be satisfied economically, especially in relation to the rising power costs in New Zealand [12] where homes

[8] Peter Hutson, "Ventilation and IAQ with total enthalpy ERV fixed plate heat exchangers", Journal of the Institute of Refrigeration, Heating & Air Conditioning Engineers (IRHACE) New Zealand, January/February, 2009, p.9.
[9] Robyn Phipps, Jeremy Warnes, "Report TE220: Indoor Environment Quality". Auckland, New Zealand: Beacon Pathway Ltd, 2007, p.54.
[10] Robyn Phipps, Jeremy Warnes, 2007, p.6.
[11] Max Sherman, "ASHRAE's Residential Ventilation Standard: Exegesis of Proposed Standard 62.2". Berkeley, California, USA: Lawrence Berkeley National Laboratory, 2000, pp.136-137.
[12] Atila Novoselac, Jelena Srebric, "A critical review on the performance and design of combined cooled ceiling and displacement ventilation systems" *Energy and buildings*, Volume 34, 2002, p.497.

consume around 35% of the over all energy supply. [13] Therefore, specified ventilation rates can be provided by using different kind of ventilation systems which are not defined by the ASHRAE Standard but it allows both mechanical and natural ventilation methods. [14]

4.1.2 NATURAL AND MECHANICAL VENTILATION

Natural ventilation can be provided by openable windows or shutters but it has to be realised that natural ventilation mostly does not provide an adequate air exchange which can make it difficult to control the indoor humidity. [15] In order to avoid this problem, the integration of a passive ventilation system can be an alternative. Such system can be driven by using the stack effect, meaning the rise of air that is warmer and less dense than surrounding air. Such systems are mostly introduced in buildings which design is based on passive solar design as they have to be an integral part of the overall building design. In order to provide an acceptable ventilation rate for homes which are not suitable for the integration of a passive ventilation system, it is necessary to introduce a mechanical ventilation system.

Passive Ventilation	
Strengths	Weaknesses
- Good at providing un-targeted background ventilation - Low cost at construction stage - Easily integrated with window hardware - Minimal maintenance	- Difficult to control for a particular contaminating event - Not compatible with filters and heat recovery - Some problems attenuating sound from outdoors

Table 4.1
Passive Ventilation - Pros and Cons

During the 1920s, mechanical ventilation systems were introduced in office buildings which also had an influence on the architectural style in the following decades. For example, bathrooms were built without windows which made it impossible to provide any air exchange through an openable window. [16] Today, new residential buildings in Europe are designed and built with airtight building envelopes with the emphasis on energy conservation and efficiency. That makes it difficult to imply natural ventilation or to install a passive ventilation system that is functional and satisfies the occupants throughout the whole year. Therefore, mechanical ventilation systems, such as vented fans are installed within these residential buildings to provide an adequate ventilation rate which can help to provide fresh outdoor air to the occupants and to control indoor humidity therefore the IAQ.

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[13] Cliff Taylor. *Toxic houses ruining occupants' health*. New Zealand Herald, New Zealand, Retrieved November 30, 2008 from the World Wide Web: http://www.nzherald.co.nz/nz/ news/article.cfm?c_id =1&objectid=10545734.
[14] Max Sherman, 2000, pp.136-137.
[15] Clemens Richarz, Christina Schulz, Friedmann Zeitler, *Detail Practice: Energy-Efficiency Upgrades - Principles, Details and Examples*. Basel, Switzerland: Birkhäuser, 2007, p.14.
[16] National Institute of Public Health, 1999, pp.65-67.

Mechanical ventilation	
Strengths	Weaknesses
- Easily controlled to target a particular contaminant	- Maintenance is essential, particularly of filters
- Relatively inexpensive and easy to retrofit to existing buildings	- There is an ongoing operational costs
- Hardware, design and installation supported by an established industry	- Fan noise must be addressed
- Easily integrated with filtration, heat recovery and space conditioning	- Wind pressure must be considered in fan specification

Table 4.2

Mechanical Ventilation - Pros and Cons

A failure of a ventilation system, it does not matter if passive or mechanical system has been introduced, will lead to a ventilation rate that is too low with risk of HDM infestation, moisture problems and high concentration of airborne pollutants. [17] Therefore, a ventilation requirement is always related to the minimum ventilation rate of a building that has to be maintained to guarantee acceptable levels of fresh air, indoor air temperature and particular airborne pollutants. For most residential buildings this minimum ventilation rate is based on temperature control. [18]

4.1.3 INFILTRATION AND EXFILTRATION

Compared to natural ventilation which refers to the air that moves through opened windows, shutters and doors, infiltration simply describes the uncontrolled passage of outdoor air into a building through unintended leaks in the building envelope such as openings, joints and cracks in walls, floors and ceilings, as well as around windows and doors. Exfiltration is the opposite of this process. This kind of ventilation is normally driven by wind and air pressure differences between the indoor and outdoor air. Especially older buildings, such as the New Zealand villas, built between 1880 and 1920 without insulation and any kind of membranes within the building envelope can be described as leaky and draughty buildings. These buildings are not airtight and ventilation occurs mostly by air infiltration and exfiltration at a very high rate which cannot be controlled at any time. [19] But also other existing buildings which have been built in New Zealand after 1920 provide infiltration of air through the building envelope.

It has to be clear that air infiltration and exfiltration can provide a high uncontrolled air exchange rate that extracts the thermal energy out of the house and leads to housing

[17] National Institute of Public Health, 1999, p.68.
[18] Yuanhui Zhang, 2005, p.442.
[19] National Institute of Public Health, 1999, pp.65-67.

problems such as damp housing. [20] Furthermore, air infiltration and exfiltration can have a substantial effect on a ventilation system and its effectiveness, as it allows air to enter or to leave the building by un-designed passages. Theoretically, an excessive air leakage can cause the failure of an entire ventilation system. Therefore, the determination of an air leakage rate and source is important to identify problems that can affect the effectiveness of the ventilation system. [21] In order to prevent the infiltration and exfiltration of air it is recommend retrofitting the existing building envelope with a vapour barrier or retarder to achieve an airtight layer. In combination with thermal windows and weather-stripping, this action can reduce the uncontrolled exchange of air to a minimum and the retrofitted external wall, ceiling and the floor construction will also resist the diffusion of moisture from the inside to the outside. [22]

4.2. THE PASSIVE HOUSE

Architects, engineers and others involved in the design process of buildings have developed the passive house concept (German: Passivhaus) that conforms to the rigorous passive house standards for energy use in buildings in the northern hemisphere. According to Wolfgang Feist, founder and director of the German Passive House Institute in Darmstadt, over 10,000 passive houses are already built in Europe since the concept became a resounding market success in Germany, Austria, Switzerland and Sweden. [23] The goal of the concept is to allow a house to heat and cool itself and therefore it is called "passive house". The construction of a passive house is specifically about energy conservation purposes and savings, as well as a comfortable indoor climate that can be maintained without additional active heating and cooling systems. [24] Therefore, a passive house is constructed with a vapour barrier and high insulation level that are used to create an airtight building envelope that minimises the amount of outdoor air that can move into and out of the building in order to retain the thermal energy inside the house and to lower the energy costs for heating during winter time. In this context, passive houses can usually achieve a ventilation rate that is less than 0.35 ACH (refer to figure 4.3).

[20] Ralph Burkinshaw, Mike Parrett, *Diagnosing Damp*. Coventry, UK: RICS Business Services, c2003, p.10.
[21] Yuanhui Zhang, 2005, pp.441-442.
[22] William B. Rose, c2005, p.250.
[23] Wolfgang Feist. Interview: "Passivhäuser sind keine Exoten". Focus, Germany, Retrieved May 19, 2009 from the World Wide Web: http://www.focus.de /immobilien/bauen/interview-passivhaeuser-sind-keine-exoten_aid_346838.html.
[24] Wolfgang Feist, *Passive House Institute: Research and development of high-efficiency energy systems*. Darmstadt, Germany, Retrieved January 28, 2009 from the World Wide Web: http://www.passiv.de.

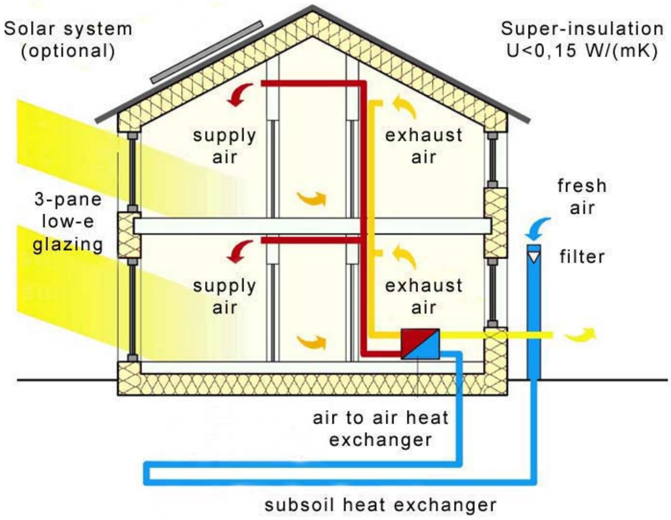

Figure 4.3
Passive House Section
Passive House building system that suits the Central European climate.

A mechanical ventilation system is always necessary within a passive house to control the air exchange rate and indoor humidity which is usually provided by an energy efficient air-to-air heat exchanger. An air-to-air heat exchanger is a device that recovers thermal energy from the exhausted ventilation air and recycles that energy into the fresh air makeup stream. [25] Typical air-to-air heat exchanger devices are Heat Recovery Ventilator systems (HRV) and Energy Recovery Ventilator (ERV) systems. A HRV system provides fresh air and is used to recover thermal energy by conduction between inbound and outbound air flow for heating. Therefore, this system has a core material that is impervious to moisture such as aluminium, steel, or plastic (refer to figure 4.4). [26]

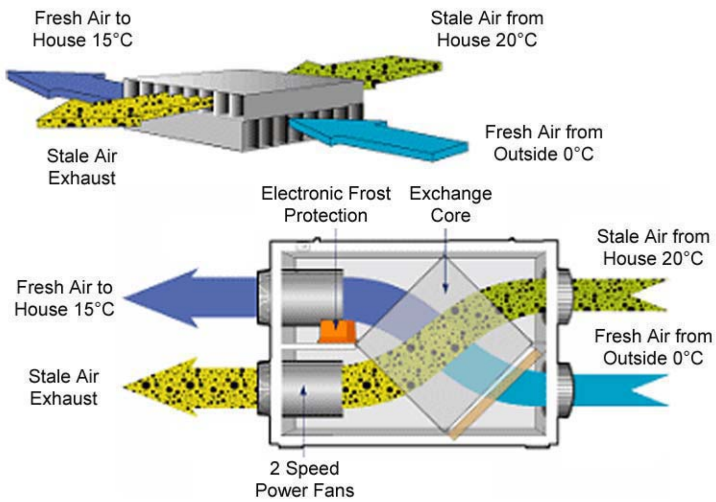

Figure 4.4
Heat Recovery Ventilator
HRV systems are efficient at removing moisture but can also reduce humidity levels below comfort conditions under certain conditions.

Compared to an HRV system which recovers only the sensible heat component, an ERV system is able to recover both: the sensible heat and the latent heat component from the

[25] William B. Rose, c2005, p.176.
[26] Warmair.com Inc. *Air Exchanger: Basics and Rating*. Air Exchangers Info, USA, Retrieved January 28, 2009 from the World Wide Web: http://www.airexchangers.info.

exhausted ventilation air (refer to figure 4.5).[27] This ability increases the total effectiveness in most conditions. However, both systems are able to save up to approximately 80% of the thermal energy consumption which improves the energy performance of a passive house by reducing the amount of energy that is used for additional heating or cooling.[28]

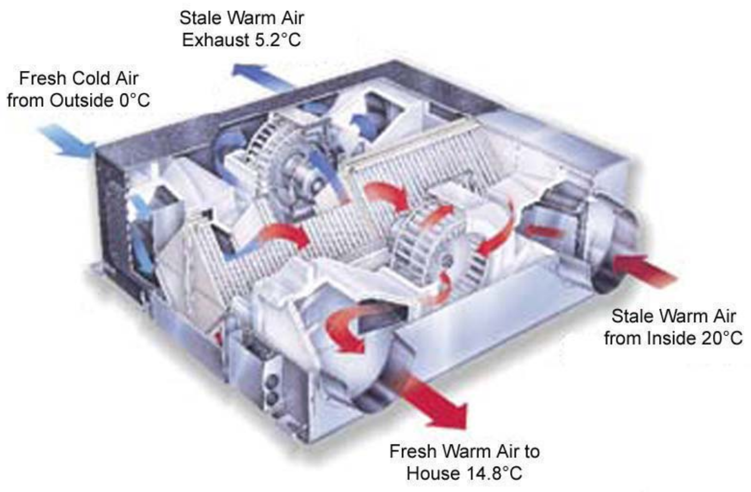

Figure 4.5
Energy Recovery Ventilator
ERV systems move sensible heat and moisture from one air stream to another due to vapour pressure difference transferring latent heat energy.

Generally, and as mentioned before, a passive house concept always includes the introduction of a mechanical ventilation system. Assuming no such system is installed into a passive house, the level of indoor air pollutants and indoor humidity would increase. This situation would become critical once the RH reaches up to and beyond 80% and persists over several days or more than six hours a day at this level. This would result in mould growth which can be encouraged to such an extent that concentrations hazardous to health can occur.[29] In simple words, the building would not be able to provide fresh air to its occupants and, therefore, would not allow the movement of water vapour from the inside to the outside which adversely affects the IAQ.

Therefore, mechanical ventilation is an integral part of the passive house concept and makes the argument of William Rose, research architect at the University of Illinois, questionable as he argues that a moisture problem is not a contaminant that requires “dilution” with ventilation. He assumes that a high indoor humidity requires source control instead of ventilation to stop the water before entering the building and Rose explains that ventilation rates are necessary for odour control that is usually sufficient for moisture control as well.[30] However, his argument may be right when the moisture problem is related to a water source from the outside that has to be controlled but the indoor humidity of a passive house occurs

[27] Peter Hutson, 2009, pp.10-11.
[28] Warmair.com Inc., 2009 from the World Wide Web: http://www.airexchangers.info.
[29] Clemens Richarz, Christina Schulz, Friedmann Zeitler, 2007, p.14.
[30] William B. Rose, c2005, p.221.

from it occupants. Therefore, the development of the passive house concept shows that a mechanical ventilation system is able to be used to control the indoor humidity. Nevertheless, it must be noted that there are no passive houses in the southern hemisphere to date.

4.3. MOISTURE AND INDOOR AIR POLLUTANTS CONTROL

Generally, ventilation in combination with moisture source control is the key factor to control the RH and to achieve a proper moisture protection in buildings. Research studies which explore the correlation between health effects and ventilation rates in residential buildings are almost non-existent, but literature on damp-housing indicates that inadequate ventilation rates in homes are a major health risk factor and can lead to various illnesses such as coughing, wheezing, asthma and airways infections. However, there are also limits in terms of controlling the indoor humidity, air pollution and air temperature of a ventilated airspace. This uppermost limit is called the maximum ventilation capacity (Q_{max}) and it can be reached e.g. when the indoor temperature exceeds the required temperature and an air conditioner has to be used to balance the desirable temperature. Another limitation can be a RH level that is too high despite maximum ventilation and a dehumidifier has to be implied to keep this RH under control. When a specific indoor air pollutant exceeds the acceptable level of concentration, a filtration system needs to be added to the ventilation system. [31] But filtration cannot be used to control a high indoor concentration of mould spores which usually indicates mould growth within the house. This mould problem requires fixing as soon as possible as ventilation or filtration cannot be seen as a solution in this case. [32]

4.3.1 AIR CONDITIONER

An air conditioner (AC) is a system or mechanism that is designed to control the indoor air temperature within an air space. It can be used for cooling as well as heating depending on the indoor air conditions at a given time. The term “air conditioning” itself refers to cooling an indoor air space for thermal comfort and there are various types of AC systems available on the market. However, the easiest air conditioning system usually implies a refrigeration cycle which can be find e.g. in a typical central AC system (refer to figure 4.6). Such a system, also known as a split system consists of an outdoor air conditioning, or compressor bearing unit and an indoor coil. The compressor which uses electricity as its power source drives refrigerant through the central air system to collect excess heat and moisture from an indoor space. Afterwards, the collected warm air from inside the house is then blown over a cooled indoor coil which removes the excess heat and moisture from the air. The heat which has

[31] Yuanhui Zhang, 2005, p.448.
[32] William B. Rose, c2005, p.221.

been transferred by the coil is then removed to the outside compared to the cooled air that is moved back inside the house in order to maintain a comfortable indoor air temperature. [33]

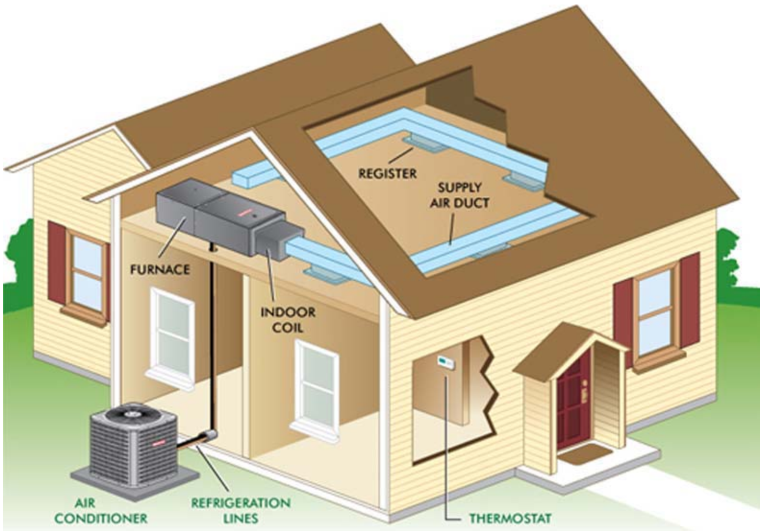

Figure 4.6
Central Air Conditioner
A typical central air conditioning system, known as a split system consists of an outdoor air conditioning and an indoor coil.

4.3.2 DEHUMIDIFIER

A dehumidifier is used to lower the humidity level of the indoor air. A very high humidity level is also unpleasant for human beings and, therefore, a dehumidifier is usually implied for both health and comfort reasons. A dehumidifier can also remove dampness that has accumulated in the wall linings, furnishings and bedding. Therefore, it is important that a dehumidifier runs constantly, especially in damp houses for the first few weeks, until the desired humidity level is reached. Afterwards, the dehumidifier can be used to maintain a specific humidity level inside the dwelling (refer to figure 4.7). [34]

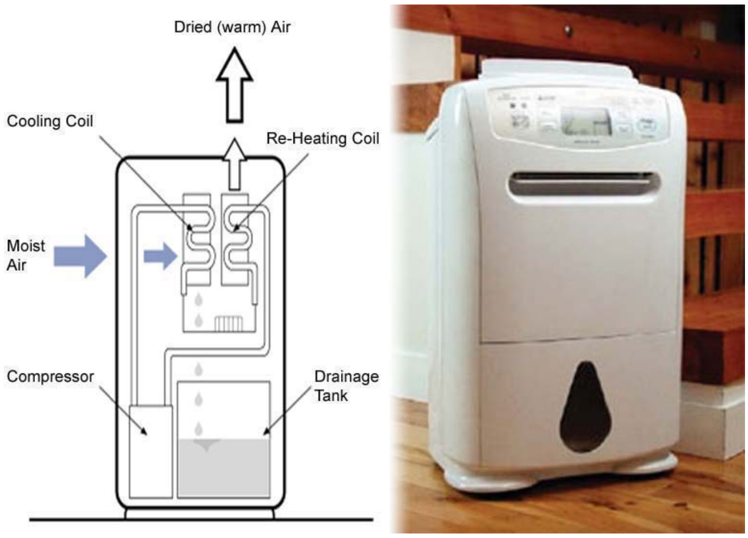

Figure 4.7
Typical Dehumidifier
A dehumidifier is used to lower the humidity level of the indoor air and can help to remove dampness that has accumulated in wall linings, furnishings and bedding.

[33] Goodman Manufacturing Company. *How a Central AC Works*. Houston, USA, Retrieved January 12, 2009 from the World Wide Web: http://www.goodmanmfg.com.
[34] Black Diamond Technologies Ltd. *Mitsubishi OASIS Dehumidifier*. Wellington, New Zealand, Retrieved January 12, 2009 from the World Wide Web: http://www.bdt.co.nz/oasis/technical.asp.

The most common type of a dehumidifier is mechanical dehumidifiers which draws moisture laden air with a small fan into the dehumidifier and passes it over a refrigerated coil.. The warm damp air then condenses on the cold coil into water droplets, as the saturation vapour pressure of the water decreases with a decreasing temperature. Afterwards, the water droplets pass into a water container or drainage tank. The cool and dry air is then passed over the warm coil to reheat the air by the warmer side of the refrigeration coil and is expelled from the dehumidifier to the room afterwards. Dehumidification with a dehumidifier is usually implied at a RH over 45% and works most effectively when a high temperature and high dew point temperature is given. [35]

4.3.3 FILTRATION AND DUST SOURCE CONTROL

The ventilation rate is unavoidable to control the level of airborne pollutants but the control of particular airborne pollutants can be different from the control of gaseous pollutants. Particle pollution, also known as particulate matter (PM) is a complex mixture of extremely small particles and liquid droplets which have distinct properties. Furthermore, PM can require a combination of different techniques to keep these at an acceptable level. These techniques can be filtration and dust source control, in relation to the minimum ventilation rate. [36] Filtration is a mechanical or physical process which is commonly implied in many applications of air cleaning and air samplings systems. Almost all mechanically ventilated buildings are equipped with some kind of filter. In order to provide a healthier environment to the occupants such filters use fibrous or other particle-capturing materials to separate particles from the indoor air. Air filters can be easily produced in different shapes with different efficiencies in terms of particle collection (refer to figure 4.8). [37]

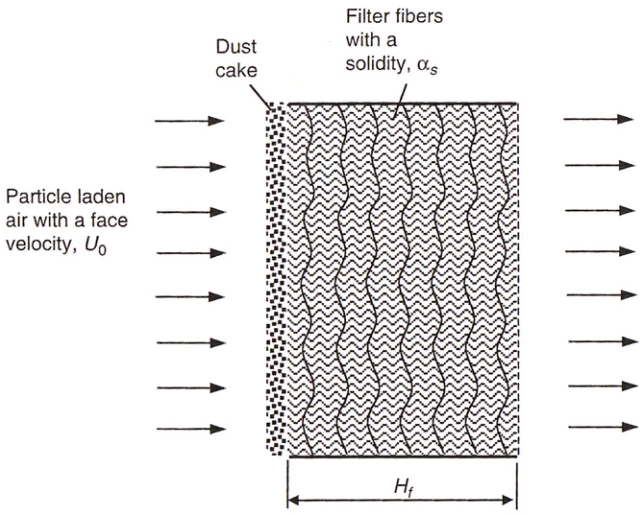

Figure 4.8
Fibre Filter
A simplified illustration of a fibre filter and its parameter that are used in a performance evaluation.

[35] Black Diamond Technologies Limited, 2009 from the World Wide Web: http://www.bdt.co.nz/oasis/technical.asp.
[36] Yuanhui Zhang, 2005, p.441.
[37] Yuanhui Zhang, 2005, pp.279-280.

The most common operating characteristics that are used to compare and to distinguish different air filter systems and types of air cleaner are the filtration efficiency and airflow resistance across the filter, as well as the dust holding capacity. The filtration efficiency simply presents the capability of an air filter to remove particles from an air stream but the efficiency of many dry-type filters is going to increase with dust load. Therefore, the average filtration efficiency during the economical life time of an air filter might be considered as the most meaningful parameter for most of the different filters and air cleaning applications. However, the initial efficiency of a clean air filter has to be considered during the design period in order to ensure the IAQ with low dust concentrations as well. The airflow resistance describes the static pressure drop across an air filter during a specific airflow rate. Therefore, the term “resistance” is used as a synonym for the pressure drop. The last common characteristic, the dust holding capacity describes a particular type of dust which an air filter can collect and hold during operation in context to a specified airflow rate and a maximum pressure drop. [38]

[38] Yuanhui Zhang, 2005, p.290.

5. REVIEW ON INTERNATIONAL AND NATIONAL STUDIES ON INDOOR AIR POLLUTANTS AND HEALTH

5.1. A RESEARCH REVIEW TO ASSESS PRACTICAL ACTIONS AND INTERVENTIONS

Damp housing and mould experience an increasing interest due to their wide range of health effects as they become widely recognized as significant health hazards. Regarding this, a constant amount of international and national research studies and reports are reviewed for this master thesis. This represents an assessment of information covering the affects of dampness on human health in homes. The aim of this review is to assess practical actions and interventions that can be undertaken to prevent health relevant problems of dampness and mould growth in New Zealand homes. Nevertheless, the review shows that many of these publications indicate an association between mould, damp and respiratory symptoms but they do not show which dampness related exposures are responsible for health effects. Therefore, from wider analysis, six studies deemed relevant are selected in order to address the major causes of damp housing and health problems in New Zealand homes.

The selected studies are divided into three categories: thermal comfort, indoor humidity and ventilation. These categories are chosen in relation to their dependency and effect on indoor air quality (IAQ) and damp housing (refer to table 5.1). The information gathered from these six studies is used to assess potential effects in the New Zealand context by identifying common housing problems which support mould growth in indoor environments. The outcome shows that data from the selected national studies in New Zealand are consistent with the international literature which indicates that mould and damp housing is associated with various health effects.

Three of the selected national studies illustrate that mould growth in New Zealand homes is relatively common as reported mould problems in New Zealand homes seem to be higher than in other countries. Two of the studies, international and national, indicate that there are many limitations in the quality of the evidence on associations between specific types of mould exposure and various health outcomes as well as exposure to particles in buildings. Furthermore, two research studies conclude that there is a strong need for more multidisciplinary reviews including expertise from all relevant areas. Therefore, the general recommendation of this review given to the New Zealand public is to remediate damp buildings and to avoid indoor air exposure.

Category	Topic (Author)	Year	Country	Results by Author	Comments
Thermal Comfort	Research study on housing insulation and health effects (University of Otago)	2002	New Zealand	Retrofitting insulation is a cost effective intervention to reduce health problems in homes that leads to significantly warmer and drier indoor environments.	Independent housing inspectors judged the existing houses to be in worse condition than the occupants themselves did.
Indoor Humidity	Interdisciplinary literature review on health effects, dampness and HDM exposure (EUROEXPO)	2003	Denmark, Italy, Netherlands & Sweden	An association between damp housing and health, and suggests HDM, microbiological agents and organic chemicals as causative agents.	Did not prove that interventions can minimise the effects on health in a conclusive manner.
	Telephone survey to determine mould problems in homes (University of Otago)	2005	New Zealand	There are a number of potentially modifiable risk factors for mould that could be reduced by a range of policy responses.	More research is required to identify the actual respired doses of the biologically hazardous components of spores.
	Review on mould and health effects in leaky buildings (University of Otago)	2007	New Zealand	The relationships between mould and HDM need further clarification as their associated allergens are important factors in terms of housing and health.	Multiple studies from New Zealand data suggest that mould in New Zealand homes is common and, therefore, may be underestimated.
Ventilation	Interdisciplinary research review on particle exposure in homes and related health effects (EUROPART)	2002	Denmark, Finland, Germany, Norway, Sweden & United Kingdom	Inadequate scientific evidence supporting that particle mass or number concentrations can be used as generally applicable risk indicators of health effects in homes.	Cannot be used to establish limit values or guidelines for particulate mass or number concentrations.
	Research study on dampness and health effects in association with low ventilation rates (Karlstad University)	2005	Denmark & Sweden	Damp problems in buildings in combination with low ventilation rates are a risk factor for asthma and allergic symptoms.	The findings are in good agreement with other research reviews and reports.

Table 5.1

International and National Studies on Associations between IAQ and Health

5.2. THERMAL COMFORT

The quality of a thermal insulation layer within a building envelope affects the well being of the occupants and, therefore, improvements in thermal insulation can potentially prevent the health of the tenants. The research study on housing insulation and health effects of the University of Otago has been selected as relevant in relation to the subject of this master thesis. The study explores retrofitting insulation as a cost effective intervention that can lead to significantly warmer and drier indoor environments and may reduce health problems in New Zealand homes. It also shows that occupants and homeowners usually underestimate the problem of mould within their homes as independent housing inspectors judged the existing houses to be in worse condition than the occupants themselves.

5.2.1 HOUSING INSULATION AND HEALTH: RESEARCH STUDY, 2002

Compared to other developed countries of the Organisation for Economic Cooperation and Development (OECD), residential buildings in New Zealand, commonly built as timber frame constructions, are inadequately heated and mostly colder than recommended by the World

Health Organisation (WHO). [1] Poor insulation and maintenance practices as well as low thermal comfort with high indoor humidity levels in many New Zealand households lead to damp and cold living conditions. Facing this problem, a study on the relation between housing insulation and health is carried out between 2001 and 2002 by the University of Otago. This study specifies that the percentage of the household budget spent on energy in New Zealand homes is similar to those in developed countries but New Zealand households are used to consume less energy for heating. This may be related to the fact that 30% of New Zealand residential building stock was built before the introduction of the mandatory insulation practice in 1978. Therefore, the aim of this study is to determine whether insulating existing homes increases thermal comfort and improves the health and well-being of occupants. [2]

The study obtains baseline information from 1310 existing houses, containing 4413 participants whom are 49% Maori and 25% Pacific people, from Samoa, Tonga and other smaller island states. The households are recruited from seven low income communities in New Zealand and randomised to receive retrofitted insulation either during or after the study. The insulation package is a standard New Zealand Energy Efficiency and Conservation Authority (EECA) package, consisting of insulation in the ceiling, draught-stopping around framing, insulated foil strapped under the floor joists and a polyethylene covering over the ground. All measurements refer to the three coldest winter months in 2001 (June, July and August) and follow-up in 2002 which include measures of house condition, air temperature, relative humidity (RH), mould and house dust mite (HDM) allergens as well as energy consumption. [3]

Focused on low income communities and poor quality housing, the results show that retrofitting insulation is a cost effective intervention to reduce health problems in New Zealand homes. The study concludes that retrofitted insulation leads to a significantly warmer, drier indoor environment and improves days off school and work, visits to general practitioners as well as a trend for fewer hospital admissions for respiratory conditions. [4]

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[1] Refer to chapter 1, p.7.

[2] Philippa Howden-Chapman, Julian Crane, A. Matheson, H. Viggers, Malcolm Cunningham, T. Blakely, D. O'Dea, C. Cunningham, A. Woodward, K. Saville-Smith, M. Baker, and N. Waipara, "Retrofitting houses with insulation to reduce health inequalities: Aims and methods of a clustered, randomised community-based trial", *Social Science & Medicine*, Volume 61, Issue 12, December, 2005, pp. 2600-2610.

[3] Philippa Howden-Chapman, Julian Crane, A. Matheson, H. Viggers, Malcolm Cunningham, T. Blakely, D. O'Dea, C. Cunningham, A. Woodward, K. Saville-Smith, M. Baker, and N. Waipara, 2005, pp. 2602-2603.

[4] Philippa Howden-Chapman, "Effect of insulating existing houses on health inequality: cluster randomised study in the community", *British Medical Journal (BMJ)*, Volume 334, Number 7591, pp.460-464.

5.3. INDOOR HUMIDITY

Intervention studies show that reducing the indoor humidity to an acceptable level is associated with various health improvements. But these intervention studies have not identified the specific benefit of mould removal on these improved health outcomes. Therefore, two reviews and one survey are selected to address this gap of information in this master thesis. The first review is an interdisciplinary literature review on health effects, dampness and house dust mite (HDM) exposure by EUROEXPO. This review indicates an association between damp housing and health, and suggests HDM as causative agents but it does not prove that interventions can minimise the effects on health in a conclusive manner. This follows a telephone survey to determine mould problems in homes by the University of Otago. The survey shows that there are a number of potentially modifiable risk factors for mould that could be reduced, but more research is required to identify the actual respired doses of the biologically hazardous components of spores. The third research publication in this category is a review on mould and health effects in leaky buildings which is also carried out by the University of Otago. This review shows that the relationships between mould and HDM need further clarification as their associated allergens are important factors in terms of housing and health. Furthermore, it suggests that mould in New Zealand homes is common and, therefore, may be underestimated.

5.3.1 DAMPNESS IN BUILDINGS AND HEALTH: LITERATURE REVIEW, 2003

A multidisciplinary review is done by a European group of eight scientists, called EUROEXPO. The literature shows that the evidence for an association between damp housing and health effects such as cough and allergic hypersensitivity as well as asthma is strong. But it is not conclusive which causative agents in the indoor air due to dampness are responsible for health effects. Such agents can be HDM, microbiological agents and organic chemicals from building materials. Therefore, an interdisciplinary review of scientific literature on health effects caused by damp housing and HDM exposure is done over the period 1998 to 2000. The aim of EUROEXPO is to update an existing review of research publications on damp housing and related health effects and to include research articles that deal with HDM exposure. [5]

The research papers that are reviewed by EUROEXPO include only peer-reviewed articles that are published in scientific journals. The total number is about 92, but 52 of these articles

[5] C.G. Bornehag, J. Sundell, S. Bonini, A. Custovic, P. Malmberg, S. Skerfving, T. Sigsgaard, and A. Verhoeff, “Dampness in buildings as a risk factor for health effects, EUROEXPO: a multidisciplinary review of the literature (1998–2000) on dampness and mite exposure in buildings and health effects”, *Indoor Air: International Journal of Indoor Environment and Health*, Volume 14, 2004, pp.243-244.

are excluded again as they are judged as “non-informative” or “inconclusive”. The remaining 40 research studies that are judged as “relevant” are used to draw the conclusions of the review. Therefore, the studies are divided into four categories that depend on the type of data for exposure and health effects: self-reported, inspections, exposure measurements and objective findings. Data from self-reported dampness and symptoms are presented in 15 studies which mostly underline the association between reported dampness and health affects. Five studies present data from inspections on observed dampness and dampness related exposures as well as self-reported symptoms which highlight the association between objective dampness and symptoms. Furthermore, 18 studies, including three intervention studies that demonstrate preventive measures to reduce HDM exposure, present data on HDM exposure in homes and related health effects, such as sensitization, lung function and symptoms. [6]

The multidisciplinary review shows that there is evidence for an association between damp housing and health, and suggests HDM, microbiological agents and organic chemicals as causative agents in damp buildings. However, the studies do not prove that interventions can minimise the effects on health in a conclusive manner on one hand, but conclude that the chosen time of intervention was too short to present any differences on the other. Therefore, EUROEXPO underlines a strong need for multidisciplinary studies as most review studies investigate microbiological agents and not chemical substances which can be associated with damp housing as well. Furthermore, EUROEXPO calls for more multidisciplinary reviews in scientific journals of articles, including expertise from all relevant areas which deal with IAQ and health effects. [7]

5.3.2 RISK FACTORS FOR MOULD IN HOUSING: NATIONAL SURVEY, 2005

The Faculty of Health Studies of the Auckland University of Technology carried out a study which shows that 37% of Pacific Island respondents report dampness and mould problems in their homes. [8] The strong evidence for an association between damp housing and health effects, as well as the risk of mould in New Zealand homes has not been clarified to this stage. Therefore, and in order to prove the outcome of the Pacific Island study, a national random telephone survey is undertaken. The goal of this survey is to determine the

[6] C.G. Bornehag, J. Sundell, S. Bonini, A. Custovic, P. Malmberg, S. Skerfving, T. Sigsgaard, and A. Verhoeff, 2004, pp.244-249.

[7] C.G. Bornehag, J. Sundell, S. Bonini, A. Custovic, P. Malmberg, S. Skerfving, T. Sigsgaard, and A. Verhoeff, 2004, pp.249-254.

[8] Sarnia Butler, Maynard Williams, Colin Tukuitonga, Janis Paterson, “Problems with damp and cold housing among Pacific families in New Zealand”, *Journal of the New Zealand Medical Association*, Volume 116, Number 1177, 2003.

distribution and risk factors of mould in New Zealand homes by the School of Medicine and Health Sciences of the University of Otago. [9]

A total number of 613 households respond to this survey, providing information about self-reported mould growth in their homes. 35.1% of the respondents report visible mould in one or more rooms (bathrooms: 48.4%, bedrooms: 46.5%) and 32.9% highlight the usage of inadequate heating systems. The telephone survey underlines the association between the number of residents and reported mould as well as an increased number of reported mould problems in homes with three or more bedrooms. This may also be affected by the different climate zones in New Zealand as households which are located in the Northern New Zealand climate zone report significantly more mould problems than other households in New Zealand. However, significantly less mould is reported in well insulated homes but most respondents cannot give information about the insulation status of their house. [10]

Generally, the outcome of the telephone survey can be described as reasonably representative of the New Zealand population, but the current situation may be worse because the sample contains more households on a higher income than households on a lower income. Those on higher incomes usually live in better constructed and located homes which normally have fewer mould problems. However, the survey illustrates that a number of risk factors for mould can be reduced by a range of possible retrofit solutions which can also include additional policy responses by the New Zealand government. That can be e.g. a review of housing design regulations, regarding requirements of higher thermal insulation levels, and the extension of low interest loans for retrofit solutions. Furthermore, the survey concludes that New Zealand's population has to be informed about risk factors for mould growth and dampness in homes and, therefore, further studies are needed to determine the burden of mould in New Zealand homes. [11]

5.3.3 POTENTIAL HEALTH IMPACTS ASSOCIATED WITH MOULD: LITERATURE REVIEW, 2007

Apart from the poor insulation and maintenance practices, a considerable number of homes are built with flat roofs, minimal eaves and a white or beige plaster finish to provide a "Mediterranean look" during the 1990's. Unfortunately, some of these homes are taking in water through the exterior finish which is known as monolithic plaster and may affect 30,000 to 90,000 houses in New Zealand. Regarding this, a report is commissioned by the Auckland

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[9] Philippa Howden-Chapman, K. Saville-Smith, Julian Crane, and N. Wilson, "Risk factors for mould in housing: a national survey", *Indoor Air: International Journal of Indoor Environment and Health*, Volume 15, Issue 6, September, 2005, pp. 469-476.

[10] Philippa Howden-Chapman, K. Saville-Smith, Julian Crane, and N. Wilson, 2005, pp. 469-473.

[11] Philippa Howden-Chapman, K. Saville-Smith, Julian Crane, and N. Wilson, 2005, pp. 470-476.

City Council (ACC) to cover international and national literature which considers health effects of leaky buildings. The aim of the report is to provide a systematic review of medical and health literature which looks particularly at the effects of mould on occupants' health. [12]

The report considers literature and research reviews that are published after January 2004. Generally, the international literature on mould, damp and health is rapidly evolving and, therefore, the report considers that some studies may not be identified in the literature search that is undertaken for this report and which may be a limitation in terms of the outcome. Regarding this, the review recommends that the ACC should undertake regularly reviews. Nevertheless, particular key studies that are carried out in New Zealand and most substantive recent reviews are identified and included. [13]

The outcome of the report shows that homeowners and occupants as well as local and national governments may have reasons for being concerned about mould and dampness in houses. This includes to prevent damages to building materials and to extend their functional lifetime which is a relevant issue for homeowners and agencies who own social housing stock. The review also illustrates that there are various potential limitations with assessing exposure levels that are based on self-reported data as most New Zealand studies on mould only focus on visible mould on walls and ceilings. Therefore, the report concludes that the complex relationships between mould and HDM need further clarification as their associated allergens are an important factor in terms of housing and health. [14]

5.4. VENTILATION

Reviews of the scientific literature on relations between indoor exposure, asthma and allergies indicate that the underlying causal factors that are responsible for increases in health problems are unknown. But it is stated that the risk of allergic symptoms in young children can be lowered through adequate ventilation rates in homes. An interdisciplinary research review on particle exposure in homes and related health effects by EUROPART is selected to address this problem. The review indicates that there is only inadequate scientific evidence which supports that particle exposure can be used as a generally applicable risk indicator of health effects in homes. Therefore, it cannot be used to establish limitation values or guidelines for particulate concentrations in homes. The last publication that is chosen in this category is a research study on dampness and health effects in association

[12] Department of Public Health: Housing and Health Research Programme. *Potential Health Impacts Associated with Mould in „Leaky Buildings": A review commissioned by the Auckland City Council*. Wellington, New Zealand: University of Otago, 2007, p.8.
[13] Department of Public Health: Housing and Health Research Programme, 2007, pp.34-35.
[14] Department of Public Health: Housing and Health Research Programme, 2007, pp.41.

with low ventilation rates by the Karlstad University. This study underlines that damp problems in residential buildings in combination with low ventilation rate are risk factors for asthma and allergic symptoms. Generally, the findings of both selected publications are in agreement with other research reviews and reports.

5.4.1 AIRBORNE PARTICLE IN THE INDOOR ENVIRONMENT: RESEARCH REVIEW, 2002

In order to improve IAQ, airborne particulate matter (PM) in the indoor air is often considered to be an important factor affecting health. However, it is not proven that airborne PM, (quantified as weight, surface area or number per volume of air) is associated with sick building syndrome (SBS) symptoms or other health effects. Therefore, an interdisciplinary review of scientific evidence on associations between exposure to particles in residential buildings and health effects is done by a European group of researchers, called EUROPART (European Research Programme for the Partitioning of Minor Actinides). The goal of EUROPART is to review research publications to assess the relevance of particle mass, surface area or number concentration as risk indicators for health effects in homes in order to establish a scientific consensus. [15]

The total number of research papers that are reviewed is about 70, including ten conference abstracts and papers. 62 papers are judged as “non-informative” or “inconclusive” as many of the excluded research studies have other peruses. The eight papers that are identified for the final review include five experimental studies involving mainly healthy subjects, two office studies and one study among elderly on cardiovascular effects. Nevertheless, the reviewed research studies do not find a relation between SBS symptoms and airborne PM concentration, and, as there are also limitations in the exposure assessment EUROPART is not able to give a clear answer. [16]

Therefore, the review declares that measurements of mass or number concentrations of airborne PM can be used to identify airborne particle concentration over time and across rooms but cannot be used to interpret results in relation to health. Regarding this, the study shows that there is only inadequate scientific evidence that proves that mass or number concentrations can only be used as generally applicable risk indicators of health effects in homes. These data can also be part of investigations to improve IAQ by establishing

[15] T. Schneider, J. Sundell, W. Bischof, M. Bohgard, J. Cherrie, P. Clausen, S. Dreborg, J. Kildesø, S. Kjærgaard, M. Løvik, P. Pasanen, and K. Skyberg, “EUROPART. Airborne particles in the indoor environment. A European interdisciplinary review of scientific evidence on associations between exposure to particles in buildings and health effects”, *Indoor Air: International Journal of Indoor Environment and Health*, Volume 13, 2003, pp.38-39.

[16] T. Schneider, J. Sundell, W. Bischof, M. Bohgard, J. Cherrie, P. Clausen, S. Dreborg, J. Kildesø, S. Kjærgaard, M. Løvik, P. Pasanen, and K. Skyberg, 2003, pp.39-42.

ventilation rates in homes. Regarding this, EUROPART concludes that this inadequate scientific evidence cannot be used to establish limit values or guidelines for particulate mass or number concentrations. Furthermore, the outcome underlines a need for further research to be able to establish such limits of exposure that can be used by occupational hygienists and other practitioners. [17]

5.4.2 VENTILATION RATES AND ALLERGIC SYMPTOMS IN CHILDREN: RESEARCH STUDY, 2005

Another problem can be viewed in terms of increasing energy costs in Europe during the last years. Occupants try to reduce heat and energy costs which leads to the design of homes which are highly insulated and built with an airtight building envelope to minimise heat and energy loss. However, this improvement is also reducing the ventilation rates in cold climate. Coincides in time with a higher incidence of asthma and allergies which have increased among children and adults over the past 30 years, this is affecting a large part of the population in industrialised countries today.

Especially young children and older people are affected by a number of risk factors in the indoor environment which can cause allergies. Representing a large burden to society worldwide, it has to be asked what has changed in environmental exposures as the short time interval over which this increase has occurred is too short for important genetic changes. In order to investigate this question many factors have to be considered, including off-gassing building materials and ventilation rates. Therefore, an epidemiological study called ‘‘Dampness in Buildings and Health’’ (DBH) id initiated by the Karlstad University in Sweden to identify health relevant exposures in homes [18] and to prove that low ventilation rates can be associated with asthma and allergic symptoms. [19]

The first stage of the research study includes an epidemiological questionnaire on housing and health that is distributed to the parents of 14,077 children aged between 1 and 6 years in Värmland, Sweden in 2000. [20] This is followed by a case-control study during the second step, which involves 198 children with symptoms and 202 health controls in 2002. It also

[17] T. Schneider, J. Sundell, W. Bischof, M. Bohgard, J. Cherrie, P. Clausen, S. Dreborg, J. Kildesø, S. Kjærgaard, M. Løvik, P. Pasanen, and K. Skyberg, 2003, pp.42-43.

[18] C.G. Bornehag, J. Sundell, and T. Sigsgaard, “Dampness in buildings and health (DBH): Report from an ongoing epidemiological investigation on the association between indoor environmental factors and health effects among children in Sweden”, *Indoor Air: International Journal of Indoor Environment and Health*, Volume 14, 2004, pp. 59-66.

[19] C.G. Bornehag, J. Sundell, L. Hägerhed-Engman, and T. Sigsgaard, “Association between ventilation rates in 390 Swedish homes and allergic symptoms in children”, *Indoor Air: International Journal of Indoor Environment and Health*, Volume 15, 2005, pp.275-280.

[20] C.G. Bornehag, J. Sundell, L. Hägerhed-Engman, T. Sigsgaard, S. Janson, N. Aberg, and the DBH Study Group. “Dampness at home and its association with airway, nose, and skin symptoms among 10,851 preschool children in Sweden: a cross-sectional study”, *Indoor Air: International Journal of Indoor Environment and Health*, Volume 15, 2005, pp.48-49.

includes extensive inspections and measurements on ventilation rates, temperature and relative humidity (RH), as well as taking samples of dust and air. In 2005, a follow-up questionnaire investigation is initiated, that involves the 10,852 parents who already responded in 2000 to the same questionnaire used in the first phase. Finally, in a fourth phase, controlled experimental studies in climate chambers follow between 2004 and 2008. These experimental investigations are based on the outcomes of phase one and two. [21]

The results of the first phase show that environmental tobacco smoke (ETS), allergic heredity, urban living, pet keeping as well as short breast feeding can be identified as risk factors for asthma and allergic symptoms amongst young children. Furthermore, self-reported damp problems in homes can cause asthma, allergic symptoms, and airway infections among children and adults. [22] The second step proves that low ventilation rates in homes are a risk factor for allergies and that the air change rate has to be considered when investigating the associations between environmental factors and allergies. [23] Overall, the DBH study concludes that moisture problems in buildings in combination with low ventilation rates are a risk factor for asthma and allergic symptoms among preschool children. [24]

5.5. SUMMERY

The review shows that high indoor humidity in combination with indoor air exposure and low ventilation rates presents a risk factor for asthma and allergic symptoms. Furthermore, it indicates that dampness problems can fluctuate in relation to the different climate zones in New Zealand. Therefore, this master thesis proposes that it is necessary to identify risk factors that are specific to New Zealand as well as the different climatic zones in order to understand how to reduce dampness and mould problems in homes. This information can then be used to estimate climate conditions in a particular building in relation to its specific individual location in New Zealand. Therefore, this master thesis will introduce and explore different investigation methods which can be used to address the problem of moisture transport in specific building components related to the particular climate zone.

[21] C.G. Bornehag, J. Sundell, and T. Sigsgaard, 2004, pp.59-60.
[22] C.G. Bornehag, J. Sundell, and T. Sigsgaard, 2004, pp.60-63.
[23] C.G. Bornehag, J. Sundell, L. Hägerhed-Engman, and T. Sigsgaard, "Association between ventilation rates in 390 Swedish homes and allergic symptoms in children", *Indoor Air: International Journal of Indoor Environment and Health*, Volume 15, 2005, pp.275-280.
[24] C.G. Bornehag, J. Sundell, L. Hägerhed-Engman, T. Sigsgaard, S. Janson, N. Aberg, and the DBH Study Group, 2005, p.48.

6. THE NEW ZEALAND BUILDING STOCK

6.1. THE EXISTING HOUSING STOCK

Many New Zealanders are used to buying and selling houses for investment purposes rather than for their own residence. This puts their priorities on upgrades into conflict with actually improving the house in a holistic manner which includes both, the value and the energy performance of the building. Most New Zealanders in this case try to improve the former which can be achieved by an upgrade of the kitchen, bathroom or superficial components only. Such improvements affect only the financial appraisal value of the house and do not improve the house performance and indoor air quality. However, the situation of New Zealand's housing stock market is changing. The costs of energy started to increase and, in the current economic situation, house prices are falling. Therefore, homeowners changing their attitudes towards to improve the performance of their houses regarding energy consumption and housing quality to reduce the operational housing cost. [1] In order to address and to provide information to homeowners which concern the performance improvement of homes, all different factors that have an effect on thermal comfort and indoor air quality (IAQ) need to be taken into account. These factors were explored in the previous chapters: one and two. However, the existing housing stock of New Zealand consists of a large number of different house typologies with different housing conditions and problems. Therefore, it is necessary to segment these factors into regional, social and house, as well as market factors, in order to develop optimum retrofit packages for the different building types.

The regional factors are related to the climate zone and the urban or rural situation of the house. These factors are important as they concern e.g. the outdoor humidity, sunshine hours or the amount of rain water. These data will be taken into account as "norm climate" data for the Northern New Zealand climate zone. [2] The social factors consist of the income of the occupants, their age and lifestyle, as well as the size of the household. Both these factors cannot be changed by a retrofit package as they are not linked to the house and its performance, but can affect IAQ as well. For example, the external humidity cannot be changed by a retrofit package but can have a significant influence on the internal humidity. Furthermore, a healthy IAQ cannot be achieved without considering the social factors which also determine the affect of lifestyle, cooking, or other cultural needs. These factors may be identified as moisture sources inside a home. Compared to social and regional factors, the house factors are the most important terms of the particular building typology, as they include

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[1] New Zealand Business Council for Sustainable Development (NZBCSD). *Better Performing Homes for New Zealanders: Making it Happen*. Auckland, New Zealand: NZBCSD, A-2008, p.5.
[2] Refer to chapter 7, pp.81-84.

the type and age of the residential building as well as its insulation levels and size which have a large impact on the thermal comfort and IAQ. The last factors, the market factors, depend on the financial situation of a homeowner or renovator. These factors concern a freehold or ownership of a homeowner which can also include a mortgage or describing a rental situation. [3]

Generally, this thesis shows that badly designed and constructed houses with a consequent inadequate thermal comfort and ventilation can cause problems, such as high relative indoor humidity, uncomfortable air temperature and mould growth with specific influences on health in general and possible risks of developing allergies in particular. Compared to older homes, many new and renovated homes are also designed and built with a low quality of insulation and a lack of adequate ventilation, as well as many of them not being equipped with efficient heating systems. For example, many homes which were built after insulation was mandatory by the Building Code in 1978 do not provide proper insulation to meet current insulation requirements. [4] Also, many buildings of the existing housing stock that are already renovated still do not provide a sufficient insulation level. Yet, the energy performance upgrade of the existing housing stock, ongoing since 1978, has changed the building's physical behaviour and also generated new and unexpected problems, such as condensation.

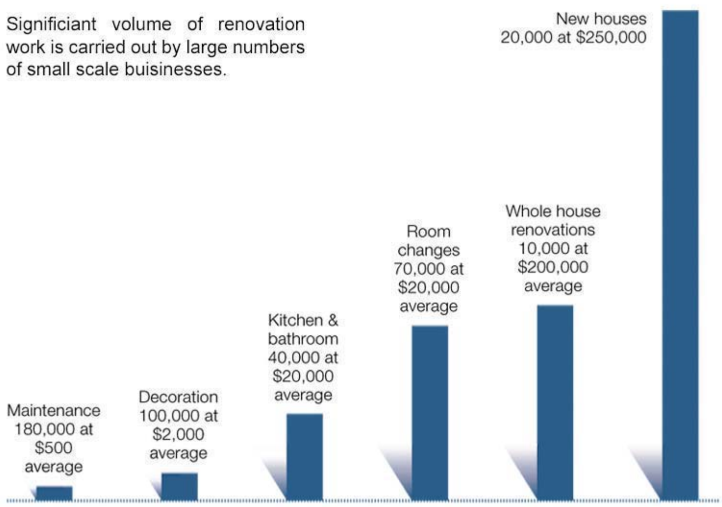

Figure 6.1
Renovation and New Houses
More than 20,000 new homes are built every year and 80,000 renovations occur at the same time. However, this has not changed the situation of the existing housing stock so far.

Currently, more than 20,000 new homes are built every year, while there are more than one million existing homes which perform poorly in terms of both energy usage and IAQ. [5] A retrofitting of these existing buildings can significantly improve their performance by using less energy and water, as well as being more comfortable, warmer in winter and cooler in

[3] L. Amitrano, I. Page, N. Kirk. "Report PR106: Market Segmentation of New Zealand's Housing Stock". Auckland, New Zealand: Beacon Pathway Ltd, 2006, p.3.
[4] Refer to chapter 1, p.4.
[5] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.2.

summer time, and providing a healthier home. It might be confusing that 80,000 renovations occur every year and do not change the situation of the existing housing stock (refer to figure 6.1). But a closer look at the situation gives an answer: New Zealand's homeowners tend to invest in improving the appearance of their houses instead of energy performance and thermal comfort. Furthermore, potential homeowners are used to designing and building their homes to apply merely to the minimum specifications required by the building code. When homeowners undertake renovations that require a building consent, they are usually not encouraged to improve the energy performance and thermal comfort of their buildings above these minimum standards. [6] In this regards, Business Council chief executive Peter Neilson stated:

> "At the moment the best way to improve your home's value is to redecorate or upgrade the kitchen and bathroom. A real estate agent will not tell you to install more insulation to get a higher price, but to turn on the heaters for an open day, because the invisible improvement will not get you a higher price." [7]

Research by ShapeNZ indicates that only few people, who are looking for a house, check housing features such as the energy performance before they buy. [8] This is confirmed by a national survey of 3.526 New Zealanders for the New Zealand Business Council for Sustainable Development (NZBCSD) reports that between 76% and 95% of people who have rented or bought a house during the past two years did not check the insulation level and heating system. [9] They did not show interest for the installed hot water cylinder and other water or energy efficient appliances that can be seen as an integral part of a house and have an affect on its thermal comfort and IAQ. However, it should be mentioned that 69% of buyers are not in the financial situation that would allow them to improve the energy performance of their homes. [10] Seen from this perspective, their lack of interest in the current house performance seems even more questionable, as they could potentially save a lot of money on reduced energy costs by taking an interest and moving into a house with a higher performance. A solution to this could be new finance packages, which have to be provided

[6] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.5.

[7] New Zealand Business Council for Sustainable Development (NZBCSD). *Media Release: Plan unveiled to upgrade New Zealand's million unhealthy, inefficient homes*. Auckland, New Zealand: NZBCSD, C-2008.

[8] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.22.

[9] New Zealand Business Council for Sustainable Development (NZBCSD). *New Zealand Housing Survey: A survey of 3526 New Zealanders on the state of their homes and future home improvement policy preferences*. Auckland, New Zealand: NZBCSD, F-2008, p.3.

[10] New Zealand Business Council for Sustainable Development (NZBCSD). *Media Release: Major new survey reveals New Zealanders' views on the state of their homes and policy solutions*. Auckland, New Zealand: NZBCSD, D-2008.pdf.

and made easily available to homeowners in order to allow them to make an afford of such improvements. [11]

6.2. THE RENTAL PROPERTY MARKET

Residential properties not owned by their occupants represent a completely different scenario. In 2001, there were approximately 360,000 rental properties in New Zealand representing about 22.5% of New Zealand's existing housing stock. Therefore, the existing house market has to be seen as two distinct markets which allow the difference between owner-occupied and tenanted housing to be considered. New Zealand's rental portion of the existing housing stock consists of three main groups which can be divided into the rent-by-choice, social renter and pre-owner group. The rent-by-choice group describes tenants who rent homes as they are either in between owned homes, having their own homes currently renovated or have chosen to retain their home in a particular location while living in another. The social renter group does not own housing property and, therefore, rents a home for economical reasons. The last group, the pre-owner group, rents homes for a specific time until they can afford to buy an own home. Traditionally, this group is mainly formed by younger people in their twenties and thirties. [12]

The New Zealand rental house market is serviced by a range of landlords which can include private owners who privately rent one or more homes, residential property manager who offer professional landlord service to property owners, as well as public landlords, such as Housing New Zealand Corporation (HNZC) and local councils who make social housing available. [13] Approximately 80% of New Zealand's tenants rent their house from a private landlord or trust who primarily see their residential rental property as an investment with the opportunity of capital gain. Most of these landlords do not see themselves as in the business of providing homes for people. [14] Regarding this fact, Peter Neilson argued:

> "New Zealanders are keen to upgrade their homes, but many do not have the financial means, and home owners and tenants lack incentives to upgrade. Landlords usually will not earn more rent for upgrading a rental property, whereas the tenant will probably get the benefit of energy savings." [15]

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[11] New Zealand Business Council for Sustainable Development (NZBCSD), C-2008.

[12] New Zealand Business Council for Sustainable Development (NZBCSD). *Mainstreaming Sustainability in Building: Prepared for the New Zealand Business Council for Sustainable Development*. Auckland, New Zealand: NZBCSD, B-2008, p.10.

[13] New Zealand Business Council for Sustainable Development (NZBCSD), B-2008, p.10.

[14] Department of Building and Housing. *Statement of Intent 2005/2008: Rental housing,* Wellington, New Zealand: Department of Building and Housing, 2005, p.18.

[15] New Zealand Business Council for Sustainable Development (NZBCSD), C-2008.

Therefore, there is often a mismatch between the needs of a landlord as an investor and the tenants who want a more stable and healthier home. [16] Compared to the 80% who rent their house from a private landlord or trust, 20% rent their house from a public landlord e.g. HNZC or a local council which own 4.5% of the total housing stock. This state owned housing estate has been accumulated over many years and has an average age of over 35 years. There have been limited investments in modernising the state housing stock during the last decades but there is some evidence that maintenance expenditure was too low to keep up with the standards of living. Furthermore, HNZC reported a mismatch in demand and supply of state housing. For example, there are around 60% of people on HNZC's waiting lists in Auckland, but only about 44% of New Zealand's state houses are located in this region. [17] In this context, the Otago Daily Times published an article that contained an interview with Housing Minister Phil Heatley, in December 2008. Mr Heatley was highly critical over the conditions of the existing state houses after receiving briefing papers by Housing New Zealand:

> "Grand statements were made about delivering new houses while existing state houses were crumbling in the background. […] The briefings highlight big pressure on New Zealanders' access to appropriate housing and the work necessary to improve the quality of state housing stock. […] The dire state of Housing New Zealand's portfolio comes at a time when the Department of Building and Housing is reporting a sharp downturn in the building and construction sector. […] The Government is committed to addressing these issues, including the role of the Resource Management Act in creating unacceptable costs and uncertainties which constrain development activity." [18]

After the briefing papers were released, Mr Heatley concluded that he was urgently considering bringing forward capital investment in state housing. New Zealand's Prime Minister John Key also supported Mr Heatley's concern about ramshackle state houses and mentioned that the local councils and, therefore, the Government had been reduced to the status of a slum landlord.

However, this interview is also interesting as all local councils are linked to the New Zealand Government which, as commonly known, is assumed to pay for public health care. To show a different perspective on the situation, it should be said that approximately 50 people each

[16] Department of Building and Housing, 2005, p.18.
[17] New Zealand Business Council for Sustainable Development (NZBCSD), B-2008, p.32.
[18] New Zealand Press Association (NZPA). "Labour's state housing legacy 'shameful' - minister", *Otago Daily Times*, 16th December, 2008.

day are sent to a hospital with respiratory illnesses that are basically caused by damp housing. Furthermore, each public hospital bed costs NZD 3.000 per night, which is about NZD 54 million per year. This, as stated above, has to be paid by the New Zealand government. [19] If local councils would invest in their rental properties in order to make them drier and more energy and water efficient, it would improve the housing performance. This would both provide significant health gains to the occupants of such rental properties, as well as improve their economic standing by reducing the number of sick days they have to take off work. [20] On the other hand this would also have an indirect effect on the local council, as the strain on the public health care system would be considerably reduced. Money would be saved on the governmental level. These saving could be potentially passed on to the local councils in the form of larger grants.

6.3. GREEN STAR RATING SYSTEM FOR HOMES

If the local councils took action it would already change the situation of 20% of 360,000 rental properties. There are still 80% outstanding private rental properties and Peter Nelson is right saying that a tenant, and not the landlord, will probably get the benefit of energy savings from improving the performance of their rental home. The argument which is used for the public housing cannot be used to encourage private landlords to improve their houses if it does not have any affect on the value of their rental property or their rental income. [21] This situation could start changing with the introduction of Green Star for Homes by the New Zealand Green Building Council (NZGBC). This rating system, which is being developed by NZGBC in partnership with BRANZ and other key stakeholders, will initially be for new homes but the aim is to extend this rating system to existing homes as well, which includes rental and private properties. [22]

Of course, there are already a number of existing home rating systems such as the Healthy Housing Index (HHI), the Home Energy Rating System (HERS) or the Water Efficiency Labelling Scheme (WELS). Compared to the HHI which is currently on trial, HERS was released in December 2007 in order to provide a platform which makes it possible to address broader energy efficiency of existing and new additions to housing stock. [23] WELS provides instead a rating system for fixtures and appliances which defines a minimum performance levels for these elements and it is the only system that will be implemented as a mandatory

[19] New Zealand Business Council for Sustainable Development (NZBCSD), C-2008.
[20] Philippa Howden-Chapman. "New Zealand research shows insulating houses results in better health", *New Zealand Herald*, 5th March, 2007.
[21] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.8.
[22] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.24.
[23] New Zealand Business Council for Sustainable Development (NZBCSD), B-2008, p.14.

rating system in early to mid 2009. [24] On the one hand, these three rating systems can give information to homeowners and buyers about the benefits and values of some sustainable features in a home but they are limited in their outcome on the other. For example, HERS is limited to energy efficiency and does not address broader sustainability issues such as water and IAQ, while WELS does not address the overall water systems which have to include the rainwater and grey water system as well. Most of all, HHI and HERS apply on a voluntary basis to new and existing homes, while the Energy Efficiency and Conservation Authority (EECA) already recognised a need to make such rating systems mandatory. [25] In this context, Jane Henley, Chief Executive at New Zealand Green Building Council asked:

> "Understanding the environmental performance of a building should be as easy as understanding the performance of your vehicle via its Warrant of Fitness. Why do we not ask how energy efficient our buildings are, how much water they use, how warm they are or what the air quality is like? Do we have faith that our Building Code can deliver a home that performs well in all of these areas?" [26]

As of yet, there is no fixed timeframe for making a rating system mandatory at any point in the changing ownership or occupancy cycle of buildings e.g. at point of sale or rental. Therefore, it is not possible for potential homebuyers to know if a particular building is code compliant, providing an acceptable thermal comfort and IAQ, or the amount of ongoing maintenance costs. [27] Therefore, it is necessary to apply one mandatory home performance ratings system over time to all new and existing homes instead of multiple, potentially confusing, systems that are only voluntary based. Such widely promoted systems can help to link the aspirations of homeowners and occupiers to improve their housing comfort, look and lifestyle while making their house performance visible to prospective homebuyers or tenants when their property assets are sold or rented out as mentioned above. This visibility can make it possible to anyone who is buying or renting a house, to understand the costs and benefits of house improvements and refurbishments which can lead to a different level of housing comfort and quality of life. In the end, the people will know if they live in an eco-home or an eco-disaster. Furthermore, a well integrated and generally applied home performance rating system can make it possible to rate all existing and new residential buildings. [28] As a final result, such a rating system can lead to the effect that certified buildings with a higher performance rating can be sold or rented at a premium rate and can

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[24] Ministry for the Environment. *Water Efficiency Labelling Scheme (WELS)*. New Zealand Government, Wellington, New Zealand, Retrieved February 17, 2009 from the World Wide Web: http://www.mfe.govt.nz/issues/water/wels-scheme.html.
[25] New Zealand Business Council for Sustainable Development (NZBCSD), B-2008, p.14.
[26] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.23.
[27] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.9.
[28] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.23.

stay on the housing market for less time than comparable homes that are not certified. This is a development that is already happening e.g. in the United States and Australia. [29] This can guarantee a direct link between the building value and retrofitting to improve the house, and its energy performance. [30]

Figure 6.2
Meridian building in Wellington
The Meridian building, called the Kumutoto Project, is a four storey building located at Wellington's waterfront, which the New Zealand Green Building Council has awarded with a 5 star Green Star New Zealand certified rating.

Therefore, the Green Star rating system for homes can change this situation like the Green Star rating system for commercial buildings already started to do in the commercial market after it was released in 2007. The Green Star rating system for commercial buildings was developed by the private sector and the Government, and was picked up by builders and developers in order to improve the performance of the commercial sector. [31] However, the success for the commercial sector was primarily dependent on the industry that had to develop acceptable solutions for the Government and which could be also adopted by the commercial building market. Today, the Green Star rating system for commercial buildings is an accepted tool in the new built market and is now being introduced in the retrofit market for commercial buildings. Proof of the effectiveness of this tool and its effects on the market is given by the new Meridian Energy Headquarters (refer to figure 6.2), called the Kumutoto Project located at Wellington's waterfront. This project was one of the first commercial buildings which received a 5 star rating under Green Star. This four storey building is designed to maximise the natural light gain and ventilation, which includes passive systems to provide energy and water efficient solutions. [32] Furthermore, the construction of a double skin façade contribute to control the indoor air temperature and ventilation requirements of

[29] New Zealand Business Council for Sustainable Development (NZBCSD), C-2008.
[30] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.23.
[31] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.2.
[32] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.24.

the building, whose HVAC system uses 100% outdoor air with an air-to-air heat recovery system to reduce heating and cooling needs in order to provide an optimal IAQ. [33]

6.4. THE RENOVATION INDUSTRY HAS TO FILL THE GAP IN INFORMATION

As the Green Star rating system for homes is still under development, the New Zealand government does also not have an agreed plan which can be introduced to finance an upgrade of the existing housing stock. Therefore, the challenge is now to encourage homeowners to include retrofit solutions that can help to improve the house performance as fast as possible rather than waiting and adding them later on. That way they are able to save money and to increase the value of their property which leads to a higher quality of their rental property as well. In order to reach this goal, it is necessary to make homeowners understand the implications of a poor performing house in terms of health, as well as high energy consumption and maintenance costs that have to be paid over the life span of a particular building (refer to figure 6.3).

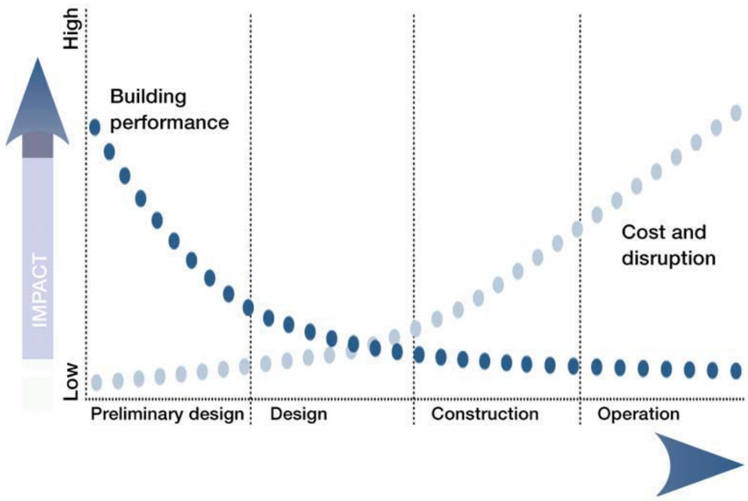

Figure 6.3
Early Integration
Homeowners can save money when they include building solutions right at the start of the design process than adding them later. This can help to improve the building performance.

Another problem that has to be solved; is that most home buyers and renovators in New Zealand do not usually know which retrofit solution can match up with their specific housing problem. Therefore, they are confused by a range of options and sustainable products that are available on the market. [34] Mostly, they do not have access to additional information which allows them to find the best combination of sustainable products in order to achieve a better performing home which is healthier, consumes less energy and, therefore, costs less to maintain. [35] The cause is a lack of information as renovators are not being presented by the industry with a targeted solution which contains the best combination package of

[33] Peter Isaac. “First ground up NZ green building”, *New Zealand Construction News*. Vol.2, Issue 3, May, 2007, p.13.
[34] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.25.
[35] New Zealand Business Council for Sustainable Development (NZBCSD), C-2008.

insulation, heat pump and heating, energy efficient kitchens or water efficient bathrooms for a house which is being renovated. There is not one overall solution that can fit into all building typologies because the existing housing stock of New Zealand contains a wide range of different housing typologies (refer to figure 6.4). [36]

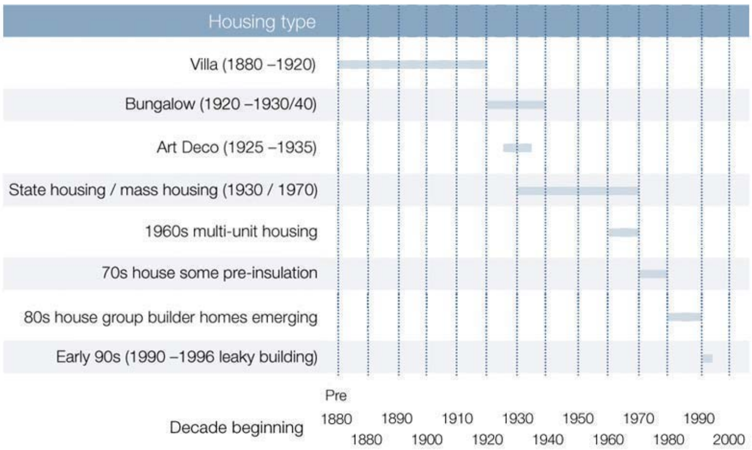

Figure 6.4
New Zealand Housing Typologies
There is a need for optimum retrofit packages for each housing type to improve both energy performance and IAQ.

Research is necessary to identify the best combination of different sustainable products and upgrade solutions to develop an optimum retrofit package for particular building types. Otherwise, ill-equipped off-the-shelf products will continue to be installed, requiring a building consent which can also limit the upgrade process and usually does not provide the best result to the fullest satisfaction of homeowners. [37] As Peter Neilson concluded:

> "This country does not have an agreed plan to upgrade our housing stock - what solutions are needed, which homes should go first, how it will be paid for and by when. […] We need that plan put in place by agreement between the government and building sector during the next year. It could easily form part of the economic stimulus package, as it has in the United Kingdom. The building, health and other sectors would welcome that. The investment is well worth making." [38]

An apparent solution seems to be to employ homeowner project managers who dominate the renovation market that is very fragmented and serviced by small businesses. However, most of these businesses lack experience in retrofitting houses in order to improve their energy and health performance. [39] Therefore, such partners are usually not in the position to advice people on the best product combination to meet their needs in solving their housing

[36] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.13.
[37] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.26.
[38] New Zealand Business Council for Sustainable Development (NZBCSD). *Media Release: $20 billion cost of fixing country's homes less than 4% of their value*. Auckland, New Zealand: NZBCSD, E-2008.
[39] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.25.

problems. [40] Also the skills and capacity of such small businesses are often limited which makes them unable to understand the potential of optimum retrofit packages developed to improve the building performance. They also do not have the financial resources to invest in market research. This, however, would be absolutely necessary to identify the best solutions that can be developed for particular buildings. After all, these businesses are usually not able to market such solutions packages and do not know the scale of resources that is required in order to integrate a large share of the potential market. [41] Therefore, it is necessary to train the renovation industry, as it undertakes more than 80,000 renovation projects per year to change the current situation of New Zealand's building stock (refer to figure 6.5). Such training can help to close the gap of knowledge and information on the renovator market and makes it possible to develop solutions which can improve the performance of existing and new homes instead of just offering individual products and building materials. [42]

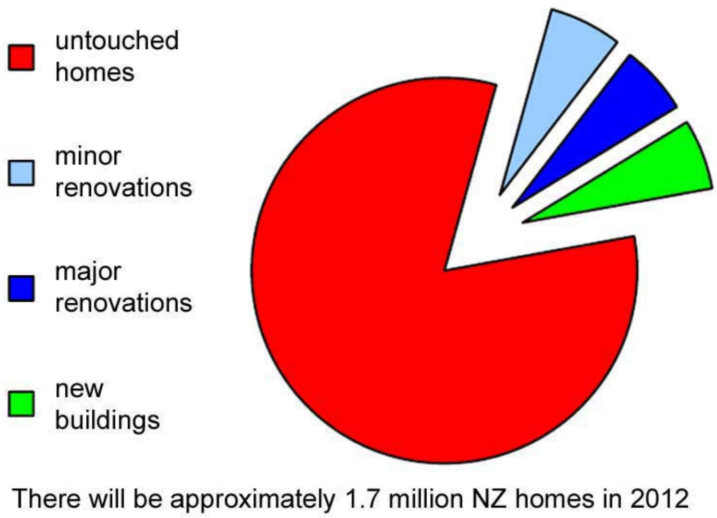

Figure 6.5
Untouched Homes
The current New Zealand housing stock consists of approximately 1.6 million homes which will rise to approximately 1.7 million in 2012.

In order to provide information that can help to develop optimum retrofit packages, research has already been done and carried on at the University of Auckland, School of Architecture. An outcome of this research is to map different house typologies in the Auckland Region which can be used now to develop optimum retrofit packages for each housing type. [43] An optimum retrofit package can improve the energy performance and health affects of homes in the Auckland Region, as well as nation wide. [44] Therefore, the grouping of building typologies in this thesis is based on these data to establish the potential of existing homes on retrofit opportunities. Furthermore, the thesis takes the results of the HomeSmart

[40] New Zealand Business Council for Sustainable Development (NZBCSD), C-2008.
[41] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.25.
[42] New Zealand Business Council for Sustainable Development (NZBCSD), C-2008.
[43] Derek Zhang. "Energy Efficiency Upgrade of Existing Homes in Auckland – A Housing Typology Analysis and Mapping". Auckland, New Zealand: Unpublished Master Thesis, School of Architecture and Planning, University of Auckland, 2009.
[44] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.13.

Renovations project, undertaken by Beacon Pathway into account. The HomeSmart Renovations project, formerly known as the Retrofit 1000 programme, is a large scale demonstration and research project which examines the retrofit of 1,000 New Zealand homes to meet Beacon's High Standard of Sustainability™ (Beacon HSS). Its benchmarks are focused on five key aspects of a performance for sustainable homes that include: [45]

- Energy and Water Consumption
- Indoor Environment Quality (IEQ)
- Waste Management
- Building Materials

6.5. DIFFERENT RETROFIT PACKAGES FOR DIFFERENT BUILDING TYPOLOGIES

The current condition of the existing housing stock can offer the opportunity to retrofit buildings at the same time as necessary maintenance has to be undertaken. Regarding this, research has been carried out by the NZBCSD. The goal of this research was to indicate the priority for developing housing retrofit packages for different building types and styles in New Zealand, built between 1950 and 1990 (refer to figure 6.6). During this time period, records show that a vast number of new residential buildings were built, which include four particular typologies: [46]

- State Housing between 1930 and 1970
- Multi Unit Housing and Private Development Houses in the 1960s
- 70's Houses, known as Pre-Insulation Houses between 1970 and 1978
- 80's Houses, known as Post-Insulation Houses between 1978 and 1989

Because of their prevalence, these 4 typologies represent a priority to develop a particular retrofit package for each of them. Therefore, these four typologies will now be explored further in order to develop such packages which can be presented to homeowners or renovator as a targeted solution. [47]

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[45] Lois Easton. "*Beacon's NOW Homes® - Building Momentum for Sustainable Homes, Symposium 2008: NOW Home Renovations: from 9 to 1000*". Auckland, New Zealand: Beacon Pathway Ltd, 2008, p.2.

[46] Verney Ryan. "Building Momentum for Sustainable Homes, Symposium 2008: Turning serial renovators into sensible retrofitters". Auckland, New Zealand: Beacon Pathway Ltd, 2008, p.3.

[47] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.13.

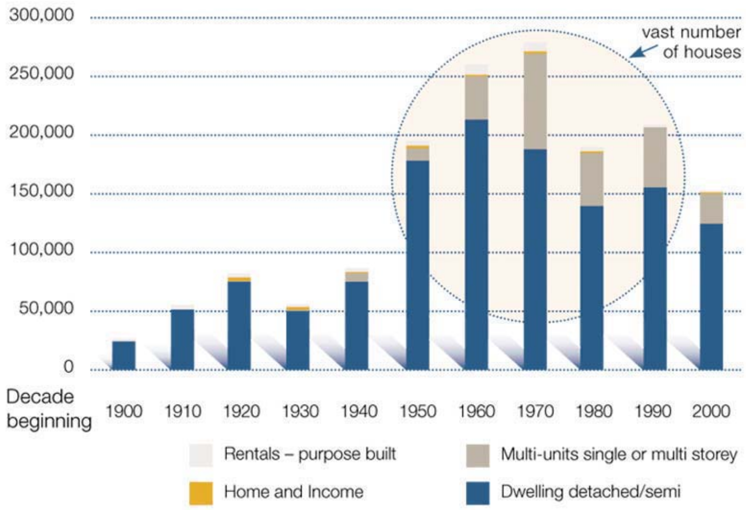

Figure 6.6
Housing Stock by Decade
Priority for developing housing retrofit packages for different building types in New Zealand have to be for houses that were built between 1950 and 1990.

6.5.1 LABOUR STATE HOUSING (1930 - 1970)

The first typology, labour state housing (1930 - 1970), was the result of a program of New Zealand's first labour government in order to deal with the massive scarcity of residential buildings, following the Great Depression in 1930. Therefore, the Department of Housing Construction (DHC) was formed and authorised as a branch of the State Advances Corporation in order to buy extensive areas of land. These areas were already provided with roads and other services, and the DHC began to sign contracts for housing construction. In order to insure that new suburbs created by the state were not seen by the public as low class communities with the impression of being typical "workers' dwellings", the Government established principles that allowed building adequate provision of new homes equal to the standards of typical homes of New Zealand citizens. The Government also assumed that an extant usage of one design could label the state houses as "Government mass-produced houses" by the public (refer to figure 6.7). Therefore, it was decided to develop different elevations for state houses that were in the same street area, but, nowadays, it can be said that this goal was clearly not reached. [48]

Generally, the housing program by the New Zealand Government was based on the Swedish housing program, resulting in a suburban-based municipal housing program that was suggested to be suitable to New Zealand conditions. The New Zealand housing program made it possible to create single dwellings that were based on the English cottage design. Considering that this design was the ideal type of accommodation for New Zealanders the

[48] Cedric Harold Firth. *State housing in New Zealand*. Wellington, New Zealand: Ministry of Works, 1949, p.6.

new state houses were set in individual suburban lots of land because typical blocks of flats were associated with working-class slums of Britain and, therefore, less favoured.[49]

Figure 6.7
Labour State Housing, 1930 - 1970
A typical example of state houses that were built around the 1950's.

The housing program raised the standard of housing in New Zealand during the 1930's and 1940's, but the escalation of building costs in the 1950's led the National government to lower the standard of new state housing. The outcome was that new state houses in 1950's were uniformly designed and were characterised by a lack of services and amenities.[50] Furthermore, the initial state house design did not include a garage due to the shortage of building material during the 1950's, but space was provided at the rear of the section to allow garages to be built in the future.[51] Because of all this, these new state houses were mostly occupied by poor households. As a consequence of this low-quality development, the construction of new state houses was redefined to take the change of living arrangements during the 1970's into account. Therefore, new areas of state houses e.g. were set in conjunction with private developments and closer to transport links, workplaces and other facilities.[52]

The layout of a state house varied depending on its scale, location and orientation, as dwellings were no longer facing straight on to the street in order to provide natural light as much as possible. Therefore, the position of the living room depended on the view while the east facing kitchen was designed to provide morning sun and the bedrooms were placed at

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[49] Ben Schrader. *We call it home: A history of state housing in New Zealand*. Auckland, New Zealand: Reed, 2005, p.36.

[50] New Zealand History Online. *State House style - State housing in New Zealand*. Ministry for Culture and Heritage, Wellington, New Zealand, Retrieved February 06, 2009 from the World Wide Web: http://www.nzhistory.net.nz/culture/we-call-it-home/state-house-style.

[51] Cedric Harold Firth, 1949, pp.12-13.

[52] New Zealand History Online, 2009 from the World Wide Web: http://www.nzhistory.net.nz/culture/we-call-it-home/state-house-style.

the west end of the house in order to provide afternoon sun. [53] The layout typically consisted of a hall, living room, kitchen, bathroom, toilet and laundry which were mostly all connected to the hall. Furthermore, it contained one or more bedrooms that were designed to accommodate two single beds in combination with built-in wardrobes. Compared to the bedrooms, the bathroom, laundry and toilet were usually kept as small as possible while the kitchen was created as a work place (refer to figure 6.8). The dining room was originally combined with the living room, but was added to the kitchen as a meal zone, during the 1950's. In terms of energy source, electricity became the main source for power and each state house was equipped with an individual electric hot water supply system. [54]

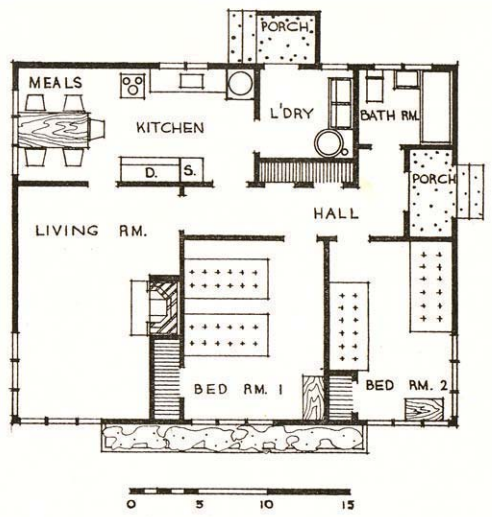

Figure 6.8
Ground Floor of a State House
A typical ground floor plan of a two bedroom labour state house during the 1950's.

The above buildings are characterised by steep pitched roofs, small eaves and windows which were generally three light high-sealed casements, more appropriate for the English climate than the New Zealand one. The house was designed as a timber frame construction which was prefabricated and included timber panels for framing. The timber frame construction then stood on a concrete slab that was made of precast concrete blocks with poured toping for the foundation. External panels were also prefabricated with standard size of 61 cm (2'0''), 122 cm (4'0'') or 244 cm (8'0'') wide with a continuous top plate around the building. They were normally covered with a variety of cladding materials such as weatherboards, asbestos cement sheets, brick veneer or concrete blocks. [55] Compared to the external walls, the internal walls were designed as non-load bearing walls and were usually lined with fibrous plaster and finished with wallpaper while the timber floor was carpeted. The ceilings were normally made of fibre board which were not attached to the nailed timber roof trusses. Furthermore, the roof was covered with concrete tiles or asbestos

[53] Cedric Harold Firth, 1949, p.31.
[54] Cedric Harold Firth, 1949, pp.31-32.
[55] Cedric Harold Firth, 1949, p.42.

cement sheets which came along with corrugated iron roofing. The standardisation of house parts was an important factor in terms of the maintenance costs. Therefore, the construction details of a typical state house were standardised, e.g. the window sizes were almost entirely restricted to two 1372 cm (4’6”) by 61 cm (2’0”) and 991 cm (3’3”) by 61 cm (2’0”), depending on the casement size. [56]

6.5.2 MULTI-UNIT HOUSING AND PRIVATE DEVELOPMENTS (1960’S)

In the 1960’s, the New Zealand government realised that their housing program, mainly based on single dwellings, had encouraged urban sprawl. Therefore, the government rose the development of new medium density state houses from the originally 20% to 30%, in 1957, and up to 50% in the following year. [57] Such medium density state houses were designed in a modern style to be in contrast to the original single dwellings that were based on the English cottage design. The duplex units, multi-unit rectangular blocks and star flats were the most common types of medium density state houses, known as multi-unit housing, during this time period (refer to figure 6.9).

Figure 6.9
Multi-Unit Housing, 1960’s
The multi-unit buildings, designed in a modern look to be a contrast to the English cottage design, partly influenced by the international style.

The duplex units were designed as a block of four dwellings which were placed on two levels, two up and two down. Its construction was usually made of wood or fibrolite and concrete stairs were placed in the middle. Each unit layout contained a family room which was the dining room in order to allow parents to supervise their kids while working in the kitchen. The multi-unit rectangular blocks were similar to the duplex units but their two-storey design was based on terrace housing which usually formed a block of 3 to 6 dwellings. The public area, which contained the living room and service areas were placed on the ground

[56] Cedric Harold Firth, 1949, pp.39-40.
[57] Ben Schrader, 2005, p.110.

floor while the private area, with the bedrooms were placed on the upper floor. When it was possible to build taller blocks these multi-unit rectangular blocks were built with further rows and units repeated above. The third common type of medium density state houses in the 1960's were the star flats (refer to figure 6.10). These blocks were designed as three-storey blocks which contained about up to 12 dwellings that were usually grouped around a central staircase.[58] Each dwelling was built with between one and three bedrooms and had a living room with sliding French doors. These doors could be opened to the external balcony in order to provide an indoor-outdoor living between the living room and the balcony.

Figure 6.10
Star Flats, 1960's
As the state housing suburbs were encouraging urban sprawl, the government began constructing more medium density housing, such as duplex units and star flats.

Influenced by the shortage of iron after the Second World War, asbestos cement sheets became a typical substitute in the New Zealand's building market which was used on roofs, typically designed as gable and hip roofs, together with corrugated iron and clay tiles. Asbestos cement sheets were also used for e.g. sprouting, downpipes or other external parts of a house, as well as cladding material. However, weatherboards were still used as a common cladding material, as well as brick veneer and roughcast. The construction of the multi-unit houses also included larger window units in order to allow a larger gain of natural light in the north facing areas of the houses.[59]

During the 1960's, brick and tile houses gained popularity as they were assumed to be of higher quality compared to houses which were clad with traditional building material, such as e.g. timber weatherboards (refer to figure 6.11). Wood was seen as flimsy and unreliable compared to brick which was seen as a strong building material. The result was that the low density state houses, known as the English cottage houses in New Zealand were clad with

[58] Ben Schrader, 2005, pp.111-112.
[59] Montague Burgoyne Cooke. *The age of houses illustrated, second edition*. Lincoln, New Zealand: Lincoln College, Department of Farm Management and Rural Valuation, 1975, p.159.

brick instead of using weatherboards from this time on. Also other external timber components that were made of wood, such as timber windows or door framings were avoided and replaced by e.g. aluminium joineries. Compared to the external timber components, the typical concrete foundation was not changed because concrete was considered as bricks to be a strong material with a long life time. Furthermore, wooden decks became unacceptable and, therefore, were built as concrete patios with a wrought iron railing which became characteristic for those houses, as well as the venetian blinds that were used to shade all windows. Overall, the State Advances Corporation, which merged with Housing Division of the Ministry of Works to become Housing Corporation of New Zealand in 1974, shared this view and it became very difficult to receive loans for low-cost private housing developments that were different to the conventional brick and tile house. As a result, this development led to the great number of such brick and tile buildings across New Zealand. [60]

Figure 6.11
Brick and Tile House, 1960's
Brick and tile houses gained popularity as they were assumed to be of higher quality compared to houses which were clad with traditional building material.

6.5.3 1970'S HOUSING - PRE-INSULATION (1970 - 1978)

The late 1960s lead to a change, as there was a need for new looks and more freedom in the design residential buildings. Apart from the conventional English cottage design, this movement led to a development of several new housing styles and forms, such as the rectangular style, split levels and flat roofs, in the 1970's. The rectangular style was partly constructed with walls made of concrete blocks which were often designed with large windows in the north facing walls. The end sections were also turned in order to form an angled house (refer to figure 6.12). The design of split level houses became very interesting for potential homeowners as it became possible to place a garage onto the ground floor (refer to figure 6.13). Therefore, one section of the building was raised up from the ground to

[60] Peter Shaw. *A history of New Zealand architecture*. Auckland, New Zealand: Hodder Moa Beckett, 2003, p.161.

the first floor in order to allow the placement of a garage and a laundry room underneath. This design was also popular with owners of sloped land lots as it supported the full use of the steep contour. The gradually lowered angle of the typical pitch roof led to a renaissance of the flat roof construction which was also very suitable to the new rectangular style of houses, during the 1970's. [61] The flat roofing materials ranged over a variety of different building materials, such as bitumen, asphalt, aluminium and galvanised iron. However, there were still a large number of low-cost private housing developments that were constructed beside other developments of single houses which were built before the mandatory insulation came into practice. Therefore, this period between 1970 and 1978 is well known as the pre-insulation period of the 1970's.

Figure 6.12
Rectangular Style House, 1970's
Based on the rectangular style, such houses were constructed partly with walls made use of concrete blocks. Mostly, they were designed with large windows in the north facing walls.

Figure 6.13
Split Level House, 1970's
The design of split level houses became very interesting for potential homeowners as it made it possible to place a garage onto the ground floor.

[61] Montague Burgoyne Cooke, 1975, p.221.

6.5.4 1980'S HOUSING - POST-INSULATION (1978 - 1989)

After 1978, the period of the post-insulation houses started by the introduction of the mandatory insulation practice. The minimum insulation level required a thermal resistance, known as the R-value for particular parts of a building construction, such as the floor (R 0.9), external walls (R 1.5) and the roof or ceiling (R 1.9). [62] Furthermore, as a response to the critic of the Commission of Inquiry in 1971, which basically criticised the conventional English cottage design as uniform and unattractive in its appearance, the New Zealand government did not longer encourage such housing developments. The Commission of Inquiry reviewed the development of multi-unit housing and came to the conclusion that especially the duplex units and rectangular blocks could be seen as negative. Their argument was that these housing types had a boring low cost appearance and did not provide any kind of private outdoor space and visual privacy in particular. [63]

Figure 6.14
Cluster Housing, 1980's
Housing Corporation attempted to build medium density housing and introduced the cluster housing development that better suited tenants' needs by including other features, such as private yards.

The result was the cluster housing development which was a series of small one to two stories high residential buildings that were built in medium density groups as private developments at individual sites (refer to figure 6.14). Each house in such cluster had its own outdoor space that was enclosed and also equipped with a carport. Through the involvement of different architects and developers it was possible that each cluster development became its own distinctive design which made it no longer distinguishable from buildings which were built for the private sector. [64] Following the cluster housing development, the infill housing development was introduced by the government in 1986, in order to build new state houses on the subdivided sections of existing state houses. These residential buildings were commonly known as plain boxes that were designed with low pitched steel gable roofs and

[62] I. McChesney, I. Cox-Smith, L. Amitrano. "Thermal insulation in New Zealand homes: A Status Report". Auckland, New Zealand: Beacon Pathway Ltd, 2007, p.8.
[63] Ben Schrader, 2005, pp.120-121.
[64] Ben Schrader, 2005, pp.122-123.

built of fibrolite (refer to figure 6.15). Generally, the quality of the construction was low and could be seen as a step backwards from the individual design to a low cost development. [65] However, the post-insulation period also covered other different types and styles of residential buildings, such as private single house developments which were built between 1978 and 1989.

Figure 6.15
Infill Housing, 1980's
Constructed of fibrolite and designed with low pitched steel gable roofs which gave them a look of plain boxes.

For each building typologies that have been described above it is now necessary to review the entire building construction and to examine the building details in order to identify particular housing problems and their specific causes. Therefore, the following chapters will explore existing building assembles and details of each of them to form a base that can be used to develop retrofit recommendations.

[65] Ben Schrader, 2005, pp.125-126.

7. HYGROTHERMAL PROCESSES IN BUILDING COMPONENTS

7.1. CALCULATION METHODS OF THERMAL AND HYGRIC PROCESSES

The balance of thermal conditions, moisture content and air quality are very important in residential buildings as an imbalance of these factors can have a significant influence of the building and its occupants. For example, high moisture content can damage the building structure and reduce the thermal comfort which can have significant health impacts. [1] In New Zealand practice there are currently no methods available to simulate the process of moisture transport within building components in relation to the indoor climate conditions of a particular building. Therefore, this master thesis will introduce two methods to investigate the thermal and hygric behaviour of particular building components:

- The "Glaser-method" as detailed in German standard DIN 4108
  (German: Glaser-Verfahren)
- The menu-driven computer program WUFI
  (German: Wärme und Feuchte instationär - Transient Heat and Moisture)

The Glaser-method can be used to calculate temperature and moisture conditions within an existing wall assemble in order to classify if such detail can be considered as "safe". In Germany, the Glaser-method is a detailed procedure described in the German standard DIN 4108 and is usually used by civil engineers and architects to evaluate the moisture performance of building envelopes. [2] If such evaluation of a particular wall component does not pass the standard Glaser assessment, alternative wall construction has to be developed in order to be able to obtain a building consent.

A simulation of realistic heat and moisture conditions can be produced with the WUFI Pro (Acronym of the German name: Wärme und Feuchte instationär meaning 'Transient Heat and Moisture'). This computer program has been developed to allow architects and engineers producing realistic and detailed simulations that present the behaviour of building components under natural conditions. [3] WUFI is based on the newest findings in terms of vapour diffusion and liquid transport in building materials and it can be used to address

[1] Kristin Lengsfeld and Andreas Holm. "Entwicklung und Validierung eines hygrothermischen Raumklimamodells - WUFI®-Plus". Holzkirchen, Germany: Fraunhofer Institute for Building Physics (IBP), 2008.

[2] Vydra, Vítězslav. "Degradation risk assessment of external envelopes: A practical engineering approach", *Building and Environment*, Volume 42, 2007, p.344.

[3] Robert Borsch-Laaks, "Im Blickpunkt: Bauen mit Massivholzelementen - Jenseits von Glaser", *Holzbau - die neue Quadriga*, Volume 5, 2003.

concerns in terms of damp housing. Compared to the simplified Glaser-method, WUFI is more complicated as it does not allow the employment of a strictly prescribed simple calculation scheme with explicitly tabulated input data. [4]

Therefore, in this thesis the Glaser-method is utilized as a simplified calculation method to determine the risk of interstitial condensation in existing wall components. [5] It is also assumed that the Glaser-method could allow practitioners in New Zealand to gain insight into the hygrothermal processes and the hygrothermal suitability of particular building components. Although it cannot be used as a simulation of reality the WUFI simulation software will be explored as well, in order to compare both tools and to develop best possible retrofit solutions in the following chapters.

7.2. THE GLASER-METHOD

The Glaser-method allows the assessment of the amount of interstitial condensation that is formed during winter and the amount of evaporable water in summer time. If the amount of condensation does not exceed specified limits calculated with the Glaser-method, and is also lower than the evaporable amount of water, the building assembly can be considered to be safe in terms of interstitial condensation problems. [6] The problem is that the method is not meant to produce a realistic simulation of heat and moisture conditions in a specific building component in relation to the weather conditions prevailing at its individual location. [7] Furthermore, the Glaser-method investigates only the condensation by vapour transport in winter, but there are also a large number of possible problems with other hygric processes, such as indoor air convection, precipitation and rising damp as well as the capillary moisture transport in a building component and its sorption capacity. [8] However, both the Glaser-method and the WUFI software need data input regarding climate conditions which are usually based on existing data records. [9] Currently, there are no complete sets of precise

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[4] Fraunhofer Institute for Building Physics (IBP). *Software / WUFI / Anwendung / Normen und Merkblätter / WTA-Merkblätter*. Holzkirchen, Germany, Retrieved February 18, 2009 from the World Wide Web: http://www.hoki.ibp.fhg.de/wufi/anw_wtamerkblaetter.html.

[5] Künzel, Hartwig M. "Moisture Risk Assessment of Roof Construction by Computer Simulation in comparison to the Standard Glaser-Method". Eindhoven, Germany: International Building Physics Conference, 2000, p.2.

[6] WUFI® Pro, 2D and Plus Software, 2009 from the World Wide Web: http://www.hoki.ibp.fhg.de/wufi/grundl_ueberblick_e.html.

[7] WUFI® Pro, 2D and Plus Software, 2009 from the World Wide Web: http://www.hoki.ibp.fhg.de/wufi/intro_e.html.

[8] WUFI® Pro, 2D and Plus Software. *Software for calculating the coupled heat and moisture transfer in building components*. Fraunhofer Institute for Building Physics (IBP), Holzkirchen, Germany, Retrieved February 10, 2009 from the World Wide Web: http://www.hoki.ibp.fhg.de/wufi/intro_e.html#Introduction.

[9] Klaus Sedlbauer. "Prediction of mould fungus formation on the surface of and inside building components". Holzkirchen, Germany: Fraunhofer Institute for Building Physics (IBP), 2001, p.96.

data available and, therefore, it will be necessary to explore New Zealand's climate conditions to create such climate data sets before using the Glaser-method.

7.2.1 NEW ZEALAND CLIMATE ZONES

Generally, the Glaser-method is based entirely on the diffusion theory and ignores any convection effect. It assumes steady-state conditions as a standard that allows calculating values, such as temperatures, at specific points within an external wall assemble. For example, the condensation period during winter is considered to be about 60 days long in Germany as a standard value in relation to an assumed outdoor climate of -10°C with 80% relative humidity (RH), and an indoor climate of 20°C with 50% RH. [10] When applying the Glaser-method in New Zealand it has to be realized that the climate in this country is much more complex and varies from warm subtropical in the far north to cool temperate climates in the far south, with severe alpine conditions in the mountainous areas. [11] Therefore, it is not possible to introduce one standard climate set for the entire country.

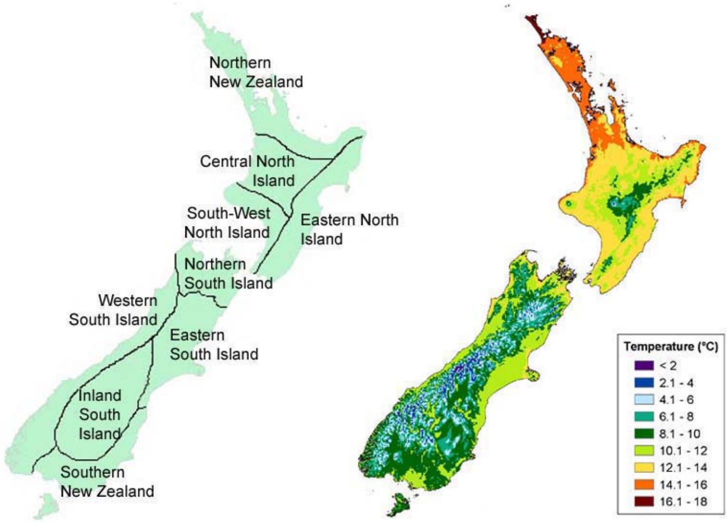

Figure 7.1
New Zealand Climate Zones
(Left) Selected locations throughout the country have been grouped into broad climate zones to summarize the climate of New Zealand. (Right) New Zealand's mean annual temperature (°C) 1971 to 2000.

The New Zealand National Institute of Water and Atmospheric Research (NIWA), selected locations throughout the country that have been grouped into broad climate zones (refer to figure 7.1). The available climate data sets of these zones consist of monthly averages for the period 1971 to 2000 for locations that have at least 5 years of complete data. For the purpose of this thesis only a specific climate set that refers to one specific climate zone in New Zealand is used in order to give an example of how to apply the method in this particular zone. The result can help to analyze interstitial condensation problems in different

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[10] Klaus Jürgen Schneider, *Bautabellen für Architekten - mit Entwurfshinweisen und Beispielen*. Düsseldorf, Germany: Werner Verlag, 2004, pp.10.38-10.43.

[11] New Zealand National Institute of Water and Atmospheric Research (NIWA), *Overview of New Zealand Climate*, Auckland, New Zealand, Retrieved November 20, 2008 from the World Wide Web: http://www.niwa.cri.nz/edu/resources/climate.

building components in relation to this specific climate zone. Generally, the intention of this thesis is to compare different building components within the same climate zone and later, by using different climate data sets, the Glaser-method could be easily applied to other climate zones in New Zealand as well. Regarding this, a possible future step will be to compare solutions in different climate zones.

In order to create a standard climate set that is suitable to the Auckland region, this thesis uses the Northern New Zealand climate zone. As known, this region has a sub-tropical climate with warm humid summers and mild winters. The typical daytime maximum air temperatures in this zone can range from 22°C to 26°C in summer time, but seldom exceed 30°C. During winter, the daytime maximum air temperatures are between 12°C to 17°C. The annual average of sunshine hours is about 2000 in many areas within the Northern New Zealand region and Tauranga can even be much sunnier with at least 2200 hours. However, the southwest winds prevail for much of the year and sea breezes occur on warm summer days quite often. In relation to the RH, the winter usually has more rain and is the most unsettled time of year compared to summer and autumn which have storms of tropical origin, and high winds as well as heavy rainfall from east or northeast. [12]

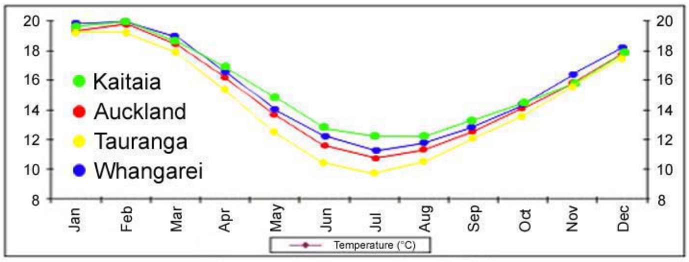


Figure 7.2

Northern NZ Climate Zone

The Northern New Zealand climate has a sub-tropical climate, with warm humid summers and mild winters with 2000 annual sunshine hours in many areas.

As mentioned before, NIWA provides monthly and annual data on rain, air temperature, sunshine hours, frost and wind for selected climate stations throughout New Zealand. In order to be able to produce a standard climate set for the Northern New Zealand region the climate data of the stations in Kaitaia, Whangarei, Auckland, Tauranga, Hamilton and Rotorua were selected. These stations provide data about the outdoor humidity and the average air temperatures during winter and summer (refer to table 7.1 and 7.2). According to

[12] NIWA, 2008 from the World Wide Web: http://www.niwa.cri.nz/edu/resources/climate/overview/map_north.

NIWA data, the summer time, also called the evaporation period in relation to the Glaser-method, is assumed to be 90 days long with an average air temperature of 19°C. The condensation period instead, during winter, is about 60 days long and has an outdoor average air temperature of 10°C (refer to table 7.1).

	Evapuration Period					Dew Period							
Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Kaitaia	19,7	20,0	18,6	16,9	14,8	12,7	12,2	12,1	13,1	14,5	15,8	17,9	15,7
Whangarei	19,9	20,0	19,0	16,5	14,0	12,2	11,2	11,7	12,9	14,3	16,4	18,2	15,5
Auckland	19,3	19,8	18,5	16,2	13,7	11,6	10,8	11,3	12,6	14,1	15,8	17,8	15,1
Tauranga	19,2	19,2	17,9	15,4	12,5	10,4	9,7	10,5	12,1	13,6	15,6	17,5	14,5
Hamilton	18,3	18,7	17,1	14,5	11,6	9,4	8,7	9,8	11,4	13,1	15,0	16,8	13,7
Rotorua	17,8	17,9	16,4	13,5	10,5	8,4	7,6	8,7	10,4	12,3	14,3	16,1	12,8
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
	19,0	19,3	17,9			10,8	10,0						
	AverageE 19 °C					Average 10 °C							

Based on data from National Institute of Water & Atmospheric Research (NIWA), see: http://www.niwa.cri.nz/edu/resources/climate

Table 7.1

Monthly Air Temperature (°C)

The selected stations of the Northern New Zealand climate zone provide monthly data with which the average air temperature during winter and summer time can be calculated.

Another factor that is important in relation to the Glaser-method is the RH (φ_e). NIWA also provides this set of data which shows that the average relative outdoor humidity is about 80% during the evaporation period and 90% during the dew period (refer to table 7.2). [13] Compared to the relative outdoor humidity, the relative indoor humidity in is almost always above 65% during winter. [14]

			Evapuration Period - 90 Days			Dew Period - 60 Days		
Location	Year	Stats_Code	Jan	Feb	Mar	Jun	Jul	Annual
-----	-----	-----	-----	-----	-----	-----	-----	-----
Kaitaia	2007	64	82,3	83,5	83,9	90,6	92,7	84.3
Whangarei	2007	64	77,9	82	82,9	88,3	89,3	82.0
Auckland	2007	64	77,8	78,1	80,1	83,3	88,2	81.7
Tauranga	2007	64	78,8	76,3	79,6	80,9	86,1	78.9
Hamilton	2007	64	83,1	84,1	88,9	90,6	91,7	86.7
Rotorua	2007	64	82,6	77,5	83,6	86,1	87,3	82.9
-----	-----	-----	-----	-----	-----	-----	-----	-----
			80,42	80,25	83,17	86,63	89,22	
			Average RH = 80 %			Average RH = 90 %		

Based on data from National Institute of Water & Atmospheric Research (NIWA), see: http://www.niwa.cri.nz/edu/resources/climate

Table 7.2

Monthly Relative Humidity (%)

The selected stations of the Northern New Zealand climate zone provide monthly data with which the typical relative humidity (RH) during winter and summer time can be calculated.

[13] NIWA, 2008 from the World Wide Web: http://www.niwa.cri.nz/edu/resources/climate.

[14] Kerstin Rosemeier. *News about energy efficiency: Comfortable Homes*. NZ Passive House, Auckland, New Zealand, Retrieved February 18, 2009 from the World Wide Web: http://www.passivehouse.org.nz/?id=newsmanager&s=passive&news=1845239e4d&lang=en.

Taking all these data of average outdoor temperatures and the relative indoor humidity, as well as the relative outdoor humidity into account, it is possible now to state a “norm-climate” for the Northern New Zealand climate zone (refer to table 7.3) which is necessary before the Glaser-method can be applied.

		Temperature	Relative Humidity	
Dew period 1440 Hours (60 Days)	Outdoor Climate	θ_e = +10.0 °C	φ_e = 90%	Wintertime
	Indoor Climate	θ_i = +16.0 °C	φ_i = 65%	
Evaporation Period 2160 Hours (90 Days)	Outdoor Climate	θ_e = +19.0 °C	φ_e = 80%	Summertime
	Indoor Climate	θ_i = +19.0 °C	φ_i = 80%	

Table 7.3
Norm-Climate of the Northern New Zealand Climate Zone
Taking the average climate data of table 6.1 and 6.2, as well as a relative indoor humidity of 65% and an average indoor air temperature of +16°C into account, it is possible to state a “norm-climate” for the Northern New Zealand climate zone.

7.2.2 THE GLASER CALCULATION

The Glaser-method is based on five fundamental assumptions namely (a) an independent thermal and moisture transport, (b) a moisture transport that is purely based on vapour diffusion according to Fick's law of diffusion and (c) a thermal energy transport by thermal conduction according to Fourier’s law of heat conduction. Furthermore, the Glaser-method does not assume (d) any sorption or desorption of liquid water in a building component. Because of this, it is assumed that (e) liquid water in an external wall is due to condensation of water vapour that takes place on interstitial surfaces where the water vapour pressure has to be equal or higher in relation to the saturated vapour pressure. [15] Besides, boundary conditions for the purpose of this thesis must be defined: air temperature inside the building envelope will be about +16°C in winter (refer to table 1.1). [16] Furthermore, the application of the Glaser-method to determine the risk of interstitial condensation requires the input of the physical values for indoor and outdoor during the dew and evaporation period as follows:

- The surface temperature (θ_i and θ_e) and specific RH (φ_e and φ_i) that is stated by the norm climate for the Northern New Zealand region.
- The saturated vapour pressure (p_{sei} and p_{se}) which is given in relation to the surface temperature in table 10.37, is attached in the appendix.[17]
- The vapour pressure (p_i and p_e) that has to be calculated as it occurs in relation to the air temperature and the RH (refer to table 7.4). [18]

[15] Vydra, Vítězslav, 2007, p.345.
[16] Refer to chapter 1, p.7.
[17] Refer to appendix, table 11.10, p.159.

Symbol	Name	Unit	Data Source	
θ_i	Air Temperature (Indoor)	°C	Dew Period: WHO	Evapuration Period: NIWA
θ_e	Air Temperature (Outdoor)	°C	Dew Period: NIWA	
p_{si}	Saturated Vapour Pressure (Indoor)	Pa	Dew and Evapuration Period: Refer to Schneider, K.J. Table 10.37	
p_{se}	Saturated Vapour Pressure (Outdoor)	Pa		
φ_i	Relative Humidity (Indoor)	%	Dew Period: Rosemeier, K. [18]	Evapuration Period: NIWA
φ_e	Relative Humidity (Outdoor)	%	Dew Period: NIWA	
p_i	Vapour Pressure (Indoor)	Pa	Formula: $pi = p_{si} \cdot \varphi_i$	
p_e	Vapour Pressure (Outdoor)	Pa	Formula: $pe = p_{se} \cdot \varphi_e$	

Table 7.4

Nomenclature and Data Source

The nomenclature that is necessary to determine the surface temperature and RH.

After the internal and external surface temperature and RH were stated, it is possible to calculate temperatures within particular external wall components. First of all, it is necessary to examine the different layers of materials of the particular wall construction, from the inside to the outside. This will determine the specific thermal resistance of each material (R), as the air temperature depends on the R-value (R_r) and has an influence on the saturation vapour pressure within a wall. If the saturation vapour pressure (p_s) is below the calculated vapour pressure (p) at a specific point within a wall, interstitial condensation occurs. Such condensation mostly occurs on the warm inside surface of cladding material, but the actual location is not always obvious as multiple locations are also possible. Therefore, the calculation of the R-value (R_r) of a wall component is an integral part of the Glaser-method. The R-value depends on the specific thermal resistance of each material (R) and the internal and external air-films (R_{si} and R_{se}) that can be found on each side of an external wall. The values of R_{si} and R_{se} describe air that does not constantly move on a material surface in form of a thin air-film but the external air-film can easily be washed from the surface due to wind or a constant air stream (refer to table 7.6).

	Internal				External			
Position	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	θ_i °C	p_{si} Pa	φ_i %	p_i (2)•(3) = (4) Pa	θ_e °C	p_{se} Pa	φ_e %	p_e (6)•(7) = (8) Pa
Dew Period (60 Days)	+16	1818	65	1182	+10	1228	90	1105
Evapuration Period (90 Days)	+19	2197	80	1758	+19	2197	80	1758

Table 7.5

Necessary Surface Temperature and RH

Internal: air temperature (1), saturation vapour pressure (2), RH (3) and Vapour Pressure (4)

External: air temperature (5), saturation vapour pressure (6), RH (7) and Vapour Pressure (8)

[18] Klaus Jürgen Schneider, *Bautabellen für Architekten - mit Entwurfshinweisen und Beispielen*. Düsseldorf, Germany: Werner Verlag, 2004, Table 10.39.

[19] Kerstin Rosemeier, 2009 from the World Wide Web: http://www.passivehouse.org.nz/?id=newsmanager&s=passive&news=1845239e4d&lang=en.

Wind Speed m/s	R_{se} m²•K/W
1	0.08
2	0.06
3	0.05
4	0.04
5	0.04
7	0.03
10	0.02

Table 7.6

R_{se}- External Air-film

The thermal resistance of R_{se} that describe the external air-film depends on the wind speed.

Therefore, the indoor air-film (R_{si}) is normally more important in relation to the thermal resistance of a wall construction than the external air-film (R_{se}) that is usually buffeted by wind. [20] Air provides the highest thermal resistance as it has the lowest thermal conductivity (λ). The thermal conductivity (W/m·K) specifies the rate of heat transfer in any homogenous material. If a building material has e.g. a thermal conductivity of 1, it means that a cube of one cubic metres of this material can transfer heat at a rate of 1 Watt for each degree of temperature difference between the opposite material surfaces. Therefore, the lower this value is, the less is the amount of heat which the material is able to transfer. Insulation materials consist of trapped air which is stop from moving, such as rockwool, fibreglass or polystyrene that provide a thermal conductivity usually between 0,035 W/(m·K) and 0,050 W/(m·K). [21] Without such insulation material inside the wall construction, the air would be in constant motion and the R-value (R_r) would usually be too low, leading to a high overall heat transfer coefficient (U-value). Generally, a high U-value indicates a building envelope with low quality of thermal insulation, compared to a high R-value which usually indicates high quality of thermal insulation.

Symbol	Name	Unit	Data Source
d	Thickness	m	Layerthickness of each particular building material
λ	Thermal Conductivity	W/(m•K)	Refer to Schneider, K.J. Table 10.20, 10.24 - 10.25
R	Thermal Resistance	m²•K/W	Formula: $R = R_r - R_{si} - R_{se}$
R_r	Thermal Resistance (Building Material)	m²•K/W	Formula: $R_r = d/\lambda$
R_{si}	Thermal Resistance (Air-fim Internal)	m²•K/W	Refer to Schneider, K.J. Table 10.42
R_{se}	Thermal Resistance (Air-fim External)	m²•K/W	Refer to Schneider, K.J. Table 10.42
U	Overall heat transfer coefficient	W/(m²•K)	Formula: $U = 1/R_r$
q	Heat Flow	W/m²	Formula: $q = U \bullet (\theta_i - \theta_e)$
Δθ	Drop in Air Temperature	K	Formula: $\Delta\theta = q \bullet d/\lambda$
θ	Air Temperature	°C	Refer to NIWA and WHO
p_s	Saturated Vapour Pressure	Pa	Refer to Schneider, K.J. Table 10.37
μ	Diffusion Resistance Coefficients	1	Refer to Schneider, K.J. Table 10.20, 10.24 - 10.25
S_d	Diffusion-Equivalent Air Layer Thickness	m	Formula: $S_d = \mu \bullet d$

Table 7.7

Nomenclature

Physical values and formulas that are necessary in order to be able to do the calculation of the Glaser assessment for different external wall components

[20] William B. Rose, *Water in buildings: an architect's guide to moisture management and mould*. Hoboken, New Jersey, USA: John Wiley & Sons, c2005, p.77.

[21] Klaus Jürgen Schneider, 2004, Table 10.20, 10.24 - 10.25.

Also related to thermal resistance is the heat flow factor, known as q (W/m²). The heat flow value is based on the overall heat transfer coefficient (U-value) and the difference of the internal and external air temperature. Generally, heat flow is used to calculate the specific difference of air temperature across each particular building material which is called the drop in air temperature ($\Delta\theta$). Another important factor is the diffusion resistance coefficient (μ) which depends both on the porosity of the material and on its structural characteristics, particularly on the opening of the pores. Therefore, it has a high influence on the transfer of water vapour through a building material and is used in relation to the material thickness to calculate the so called diffusion-equivalent air layer thickness (S_d). This value will be used along with the saturated vapour pressure, as well as the vapour pressure to produce the graphs of the dew and evaporation period.

7.3. EXAMPLE - LABOUR STATE HOUSE CONSTRUCTION

The Glaser-method will now be used to identify the possibility of interstitial condensation problems within an existing wall component, as well as to indicate a change of the physical behaviour after a retrofitting. As an example, this chapter will review the construction details of the first building typology, previous mentioned, resulted from the labour state housing program (1930-1970). The typical structure of such buildings was designed as a timber frame construction. The external panels were usually 61 cm (2'0''), 122 cm (4'0'') or 244 cm (8'0'') wide with a continuous top plate around the building and covered with (a) weatherboards, (b) asbestos cement sheets or (c) brick veneer. Internally, the surface was lined with fibrous plaster and finished with wallpaper. [22]

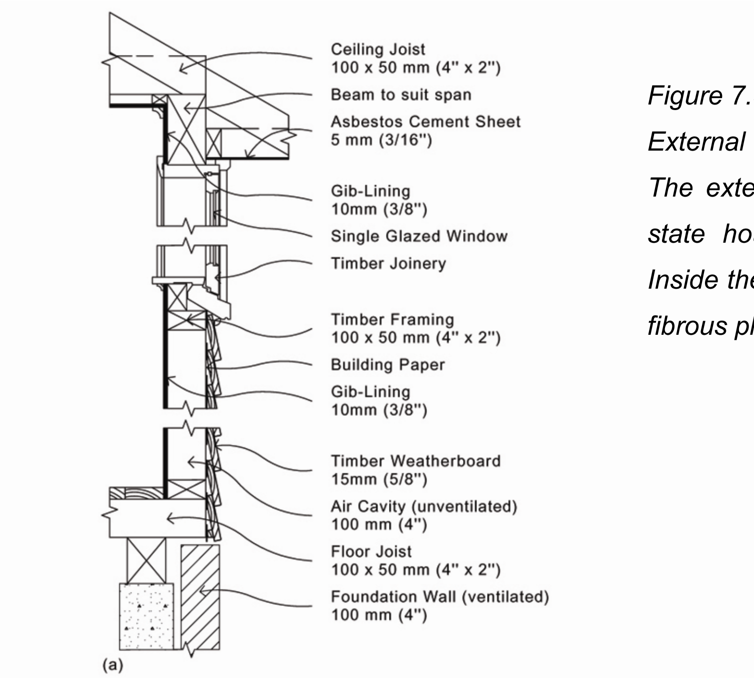


Figure 7.3
External Wall of a Labour State House
The external wall of this example of a labour state house is covered with weatherboards. Inside the house, the wall is normally lined with fibrous plaster and finished with wallpaper.

[22] Cedric Harold Firth, 1949, p.42.

Figure 7.3 shows a typical wall construction covered with weatherboards. The external wall constructions consists of a standard construction support wall that is designed as a 4 inch (100 mm) timber frame wall without any kind of insulation, as it was not required by the New Zealand Building Code (NZBC) till 1978. [23] The frame is covered with 3/8 inch (10 mm) gib lining on the inside and covered with weatherboard 5/8 inch (15 mm) to the outside. In order to verify this construction by the Glaser-method it is necessary to input specific physical values, such as the particular thermal conductivity (λ) of each material layer. Currently, not all New Zealand building material suppliers publish these values of their products. Therefore, it is necessary to close such gaps with values of similar building products that are available on the European market. Regarding this, this thesis is using data that are published in *Bautabellen für Architekten - mit Entwurfshinweisen und Beispielen* (English: Building Spreadsheets for Architects - with plan details and examples) by Klaus J. Schneider in 2004 (refer to table 7.8 and 7.12).

Type	Building Material	d m	λ W/(m•K)	µ	Notice
(a)	Gib-Lining	0.010	0.25	8	Refer to Schneider, K.J. Table 10.20
	Timber Frame with Air Cavities (unventilated)	0.100	0.18	1	Refer to Table 7.9
	Building Paper	0.001	2.3	0.1	Refer to WUFI-Database
	Timber Weatherboard	0.015	0.13	50	Refer to Schneider, K.J. Table 10.25

Table 7.8

Physical Values of the Existing Building Materials

Physical values of particular building materials and similar building products that are currently available on the European market.

Air Cavity (unventilated)	Direction of the Heat Flow		
[mm]	m²•K/W		
	Upwards	Horizontal	Downwards
0	0.00	0.00	0.00
5	0.11	0.11	0.11
7	0.13	0.13	0.13
10	0.15	0.15	0.15
15	0.16	0.17	0.17
25	0.16	0.18	0.19
50	0.16	0.18	0.21
100	0.16	**0.18**	0.22
300	0.16	0.18	0.23

Table 7.9

Unventilated Air Cavities

The thermal resistance of unventilated Air cavities depends on the heat flow direction.

Furthermore, it is necessary to consider the direction of the thermal heat flow through an unventilated air cavity, from the inside to the outside. Such unventilated air cavities can be found within the timber framing wall of all existing wall component. The following Glaser calculation considers a horizontal heat flow through an air cavity of 100 mm that has a thermal resistance value of 0.18 m²·K/W (refer to table 7.9). Known all the mentioned values it is then possible to apply the Glaser-method (refer to table 7.10). Based on the results it is

[23] Refer to chapter 6, p.77.

possible to create two graphs which will show the thermal and hygric behaviour of the external wall during the dew and evaporation period.

Wall Component	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Labour State Housing (a)	d Tab 7.8	λ Tab 7.8	d / λ (1)/(2)=(3)	Δθ q * (3) = (4)	θ (5)-(4)=(5n)	p_s 10.32 *	μ Tab 7.8	S_d (7)•(1)=(8)
inside to outside	m	W/(m•K)	m²•K/W	K	°C	Pa	1	m
R_{si}	-	-	0,13	0,88	16,00	1818	-	-
					15,11	1717		
Gib-Lining	0,010	0,25	0,04	0,27	14,84	1684	8	0,08
Air Cavity (unventilated)	0,100	0,18	0,56	3,78	11,06	1321	1	0,10
Building Paper	0,001	2,3	0,00	0,00	11,06	1321	0,1	0,00
Timber Weatherboard	0,015	0,13	0,12	0,79	10,28	1254	50	0,75
R_{se}	-	-	0,04	0,27	10,00	1228	-	-
* Refer to Schneider, K.J. Table 10.32			$\theta_i - \theta_e = \Sigma\, \Delta\theta$ =	6,00			$\Sigma\, S_d$ =	0,93

$R_r = \Sigma(3) =$ 0,88 m²•K/W U = $1/R_r$ = 1,13 W/(m•K)

$R = R_r - R_{si} - R_{se} =$ 0,71 m²•K/W q = $U\cdot(\theta_i - \theta_e)$ = 6,81 W/m²

Table 7.10

Glaser Calculation: Existing Wall of a Labour State House [24]

The Glaser calculation gives information about the overall heat transfer coefficient (U-value), the temperature (°C) and moisture conditions within the specific wall assemble.

The values of the saturated vapour pressure (p_s) calculated by the Glaser-method (refer to table 7.10, column 6), as well as the vapour pressure (p_i and p_e) that is presented in table 7.5 are used to create the graph of the dew period (refer to figure 7.4). The second graph, refers to the evaporation period (refer to figure 7.5), considers the saturated vapour pressure (p_{se}) as well as the vapour pressure (p_e), also presented in table 7.5. The graphs assess the amount of interstitial condensation which is formed during the dew period. The graphs show that such condensation does not occur because the vapour pressure (red) is lower than the saturated vapour pressure (blue) in the building component. Therefore, it is assumed that interstitial condensation problems cannot occur within this external wall component.

Based on the outcome of the Glaser calculation, this example of a wall component can be considered “safe”, according to the German standard DIN 4108. Nevertheless, the Glaser calculation also indicates the U and R-value. Both give evidence that the thermal comfort inside the residential building can be considered as low as this thesis assumes that a low R-value in New Zealand climate corresponds to low housing performance. According to the recommendation of the World Health Organization (WHO), the average indoor air temperature of 16°C in New Zealand homes is generally assumed to be unacceptable as it has significant impacts on human health. [25] Therefore, it is necessary to improve the thermal properties of this wall component by upgrading the wall with thermal insulation materials.

[24] Refer to figure 7.3, p.87.
[25] Refer to chapter 1, p.7.

Such improvements can help to guarantee an indoor air temperature of 20°C as recommended by the WHO and can lower the assumed health impacts of New Zealand homes. Nevertheless, an upgrade such as this can also change the physical behaviour of the building component. Therefore it is necessary to explore if such change will generate new and unexpected problems in terms of interstitial condensation and moisture.

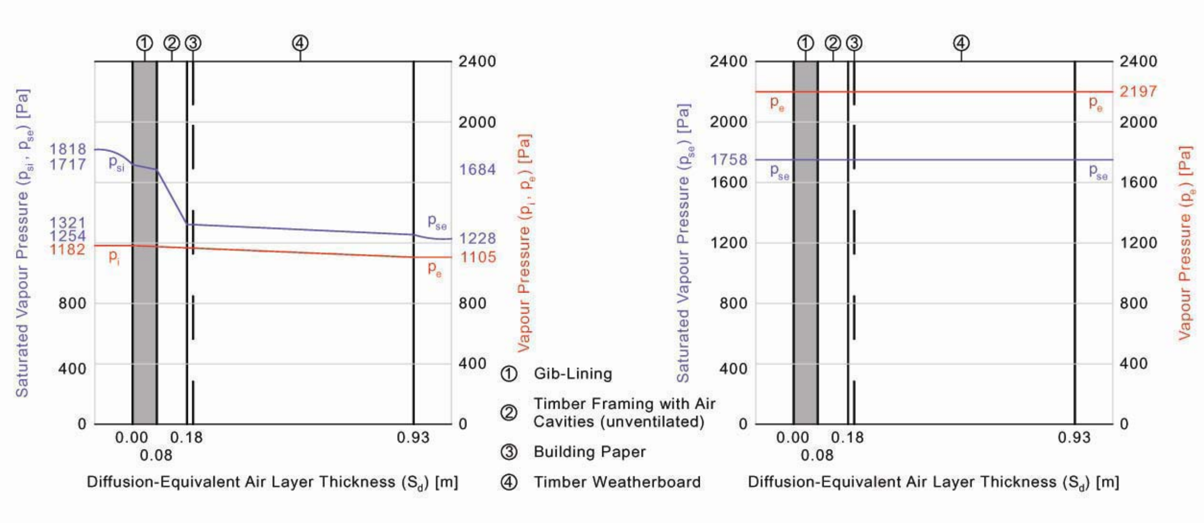


Figure 7.4

Graph: Dew Period

Saturated vapour pressure is not reached.

Figure 7.5

Graph: Evaporation Period

No interstitial condensation is present.

7.4. RETROFIT SOLUTION - LABOUR STATE HOUSE CONSTRUCTION

Since October 2008, the New Zealand Standard NZS 4218:2004 requires that all new homes throughout New Zealand have to meet new thermal insulation requirements. These rules apply to light frame timber houses, as well as solid wall construction such as buildings made of concrete blocks (refer to table 7.11), but regard most buildings with a floor area of less than 300 m², as well as all major extensions. The new R-values of the updated NZS 4218:2004 can be used as minimum targets to achieve an acceptable thermal comfort in relation to each particular climate zone in New Zealand. Generally, different insulation materials can be used to improve the thermal resistance of the existing building envelope of a labour state house (refer to figure 7.6). The roof construction of the labour state house is usually accessible and ventilated, which makes it possible to retrofit the roof space with an insulation layer of 120 mm cellulose fibre insulation material. Cellulose fibres are usually made of shredded newspapers with fire-retardant chemical. Through its hygroscopic ability, this material is capable to deal with moisture by up to 17% of its mass before it has a detrimental effect on its insulation quality. When moisture below this level occurs, the cellulose fibres are able to absorb and to transfer it to drier areas where it can be dissipated through evaporation. [26] Such improvement for the roof is able to provide an acceptable R-value of minimum 2.9 m²·K/W. In terms of the floor construction, this thesis recommends to install 60 mm of expanded polystyrene (EPS) underneath the accessible and ventilated floor construction. EPS is known as a lightweight cellular plastics material and usually to 100% recyclable. The insulation material consists of small spherical shaped particles that contain about 98% air providing a thermal conductivity of 0.04 W/(m·K). This improvement is able to provide a minimum R-value of 1.3 m²·K/W.

Building Component	Minimum Thermal Resistance Value for Construction [m²•K/W]		
	Climate Zone 1: Northland, Auckland and the Coromandel Peninsula	Climate Zone 2: Rest of the North Island other than the Central Plateau	Climate Zone 3: Central Plateau of the North Island and the South Island
Light Frame Timber Houses			
Roof (Ceilings)	R 2.9	R 2.9	R 3.3
External Wall	R 1.9	R 1.9	R 2.0
Floor	R 1.3	R 1.3	R 1.3
Solid Wall Construction			
Roof (Ceilings)	R 3.5	R 3.5	R 3.5
External Wall	R 0.8	R 1.0	R 1.2
Floor	R 1.5	R 1.5	R 1.5

Table 7.11

Changes to Building Code Clause H1

Since October 2008, new homes have to meet new thermal insulation requirements.

In case of the external wall construction it is common practise to fill the existing frame cavities with thermal insulation material. The absence of a ventilated gap between the weatherboards and the timber frame can improve the insulation ability of the external wall on the one hand, but can also force the risks of moisture on the other. [27] Therefore, this thesis assumes that moisture problems within the wall component may occur, resulting into an unacceptable level of moisture content within the wall construction. Without a ventilation gap it is also difficult to use mineral wool insulation, such as rockwool or glass fibre insulation that does not allow moisture to escape.

Type	Building Material	d m	λ W/(m•K)	μ	Notice
(a)	Mineral Wool Insulation	0.100	0.04	1.5	Refer to WUFI-Database

Table 7.12

Physical Values of the Mineral Wool Insulation

The physical values of the mineral wool insulation material are based on the WUFI database.

[26] Paul Hymers. *Converting to an Eco-friendly Home: The Complete Handbook*. London, UK: New Holland, 2006, p.99.

[27] John Oliver, *John Oliver's Brick Book: A guide for designing and building in bricks – Second Edition*. Auckland, New Zealand: Lifetime Books, 2006, p.94.

However, in order to prove that such retrofit solution is not acceptable and to provide a result that allows comparing both the Glaser-method and the WUFI software, this thesis explores the behaviour of such retrofitted wall. Produced as batts, the insulation material can be placed into the cavities in combination with a new layer of building paper after the existing gib lining has been removed (refer to figure 7.6). This retrofit solution can improve to component to an acceptable R-value of minimum 1.9 m²·K/W.

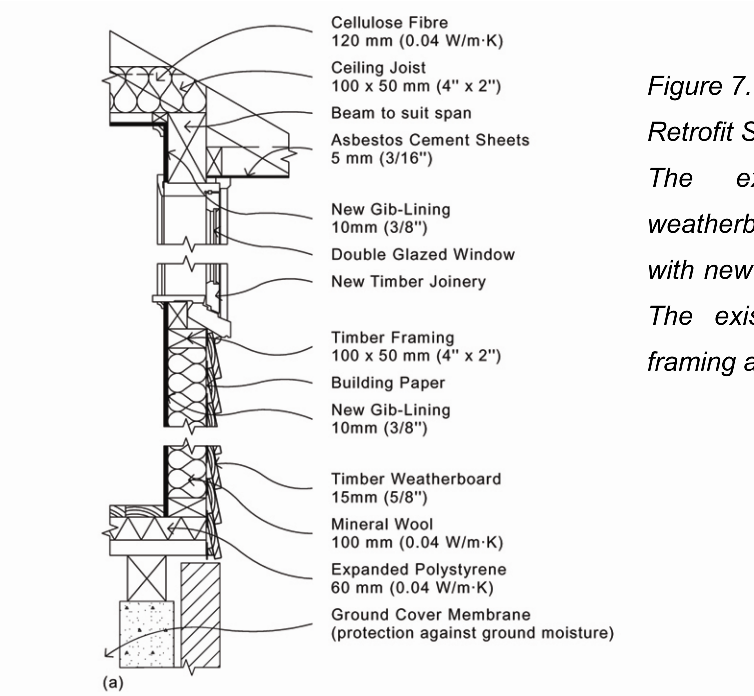


Figure 7.6
Retrofit Solution of a Labour State House
The external wall is covered with weatherboards on the outside, and finished with new gib lining and wallpaper to the inside. The existing air cavities within the timber framing are filled with mineral wool insulation.

The following Glaser calculation is used to assess the discussed upgrade solution but with an improved indoor air temperature of 20°C which has a direct influence on the internal vapour pressure (refer to table 7.13). Furthermore, the calculation takes the properties of the existing building materials into account, as well as the new of the mineral wool batt insulation material (refer to table 7.8 and 7.12). The goal of this calculation is to prove if interstitial condensation caused by a change of the physical behaviour can occur in this proposed retrofit solution (refer to table 7.14).

	Internal				External			
Position	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	θ_i °C	p_{si} Pa	φ_i %	p_i (2) * (3) = (4) Pa	θ_e °C	p_{se} Pa	φ_e %	p_e (6) * (7) = (8) Pa
Dew Period (60 Days)	+20	2340	65	1521	+10	1228	90	1105
Evapuration Period (90 Days)	+19	2197	80	1758	+19	2197	80	1758

Table 7.13
Necessary Surface Temperature and RH
The internal air temperature is changed from e 16°C up to 20°C.

Wall Component	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Labour State Housing (a)	d Tab 7.8	λ Tab 7.8	d / λ (1) / (2) = (3)	Δθ q * (3) = (4)	θ (5) - (4) = (5_n)	p_s 10.32 *	μ Tab 7.8	S_d (7) * (1) = (8)
inside to outside	m	W/(m•K)	m²•K/W	K	°C	Pa	1	m
					20,00	2340		
R_{si}	-	-	0,13	0,46	19,54	2268	-	-
Gib-Lining	0,010	0,25	0,04	0,14	19,40	2254	8	0,08
Mineral Wool	0,100	0,04	2,50	8,85	10,55	1279	1,5	0,15
Building Paper	0,001	2,3	0,00	0,00	10,55	1279	0,1	0,00
Timber Weatherboard	0,015	0,13	0,12	0,41	10,14	1237	50	0,75
R_{se}	-	-	0,04	0,14	10,00	1228	-	-
* Refer to Schneider, K.J. Table 10.32			$\theta_i - \theta_e = \Sigma\Delta\theta =$	10,00			$\Sigma S_d =$	0,98

$R_r = \Sigma$ (3) = 2,83 m²•K/W U = 1 / R_r = 0,35 W/(m•K)

$R = R_r - R_{si} - R_{se}$ = 2,66 m²•K/W q = U * ($\theta_i - \theta_e$) = 3,54 W/m²

Table 7.14

Glaser Calculation: Retrofit Solution of a Labour State House

Compared to the existing wall construction, the Glaser method proves that the retrofit solution changes the physical behaviour of the wall. The graphs show that interstitial condensation occurs as the vapour pressure (red) is higher as the saturated vapour pressure (blue) in the building component for a period of time. Therefore, this thesis assumes that moisture problems can occur within the wall component.

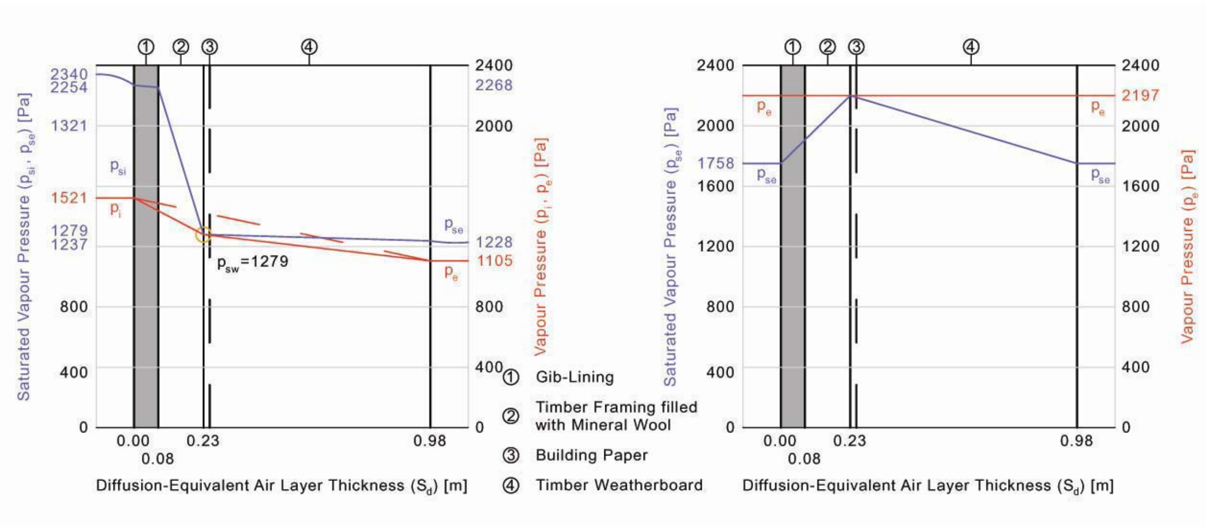


Figure 7.7

Graph: Dew Period

Saturated vapour pressure is reached.

Figure 7.8

Graph: Evaporation Period

Interstitial condensation is present.

In order to determine the water content that can occur within the external wall component (i_i) it is necessary to calculate the amount of water that can also leave again by evaporation (i_e) during the dew and evaporation period (refer to table 7.12). Such calculation takes the thickness of each material layer (ΣS_{di}) and (ΣS_{de}), the internal and external vapour pressure

(p_i and p_e), as well as the specific saturation vapour pressure (p_{sw}) at the dew point into account (refer to figure 7.7).[28]

$$i_i = \frac{p_i - p_{sw}}{1500 \cdot \Sigma S_{di}} = \frac{1521 - 1279}{1500 \cdot (0{,}08 + 0{,}15)} = 0{,}39 \quad g/(m^2 \cdot h)$$

$$i_e = \frac{p_{sw} - p_e}{1500 \cdot \Sigma S_{de}} = \frac{1279 - 1105}{1500 \cdot 0{,}75} = 0{,}15 \quad g/(m^2 \cdot h)$$

The result shows that 0.39 $g/(m^2 \cdot h)$ of interstitial condensation occurs inside the external wall component and 0.15 $g/(m^2 \cdot h)$ is leaving the wall by evaporation again. That means that the 0.24 $g/(m^2 \cdot h)$ of water can occur every hour inside the external wall assemble. This amount multiplied by 1440 hours (60 days) gives the result of the total content of water that is caused by interstitial condensation during the dew period.

$$W_T = 60 \text{ days} \cdot (i_i - i_e) = 1440 \cdot (0{,}39 - 0{,}15) = 201{,}60 \quad g/m^2$$

The same calculation is done for the evaporation period. Therefore, the amount of water is determined that leaves the wall component per hour by evaporation to the inside (i_i) of the house, as well as to the outside (i_e). The sum of the evaporated water multiplied by 2160 hours (90 days) shows the total amount of evaporable water that leaves the wall ensemble during the evaporation period.

$$i_i = \frac{p_{si} - p_i}{1500 \cdot \Sigma S_{di}} = \frac{2197 - 1758}{1500 \cdot (0{,}08 + 0{,}15)} = 1{,}27 \quad g/(m^2 \cdot h)$$

$$i_e = \frac{p_{se} - p_e}{1500 \cdot \Sigma S_{de}} = \frac{2197 - 1758}{1500 \cdot 0{,}75} = 0{,}39 \quad g/(m^2 \cdot h)$$

$$W_V = 90 \text{ days} \cdot (i_i + i_e) = 2160 \cdot (1{,}27 + 0{,}39) = 3585{,}60 \quad g/m^2$$

The outcome allows for a comparison between the amount of 201.60 g/m^2 of water that occurs during the dew period inside the wall component and the amount of 3585.60 g/m^2 of water that can leave again during the evaporation period. The calculation above demonstrates that the total sum of interstitial condensation does not exceed the specified limit of condensation which is about 3585.60 g/m^2 or 3.59 liters/m^2 of liquid water.

$$W_V = 3585{,}60 \ g/m^2 \ > \ W_T = 201{,}60 \ g/m^2$$

Finally, this retrofit solution can be considered as "safe" in terms of interstitial condensation, according to German standard DIN 4108DIN. The Glaser-method though is not meant to

[28] Klaus Jürgen Schneider, 2004, Table 10.39.

produce a simulation of realistic heat and moisture conditions in a building component. [29] Therefore, this thesis will also introduce the WUFI simulation software in the following chapter to be able to compare the outcomes of both, the Glaser and the WUFI calculation. Finally, the outcome will check if the example of the retrofit solution has any negative effects on the physical behaviour of a particular wall component. Furthermore, the WUFI software can be used to prove if the Glaser-method can be recommended as a general tool to determine the risk of interstitial condensation in New Zealand homes.

[29] WUFI® Pro, 2D and Plus Software, 2009 from the World Wide Web: http://www.hoki.ibp.fhg.de/wufi/intro_e.html.

8. WUFI : TRANSIENT HEAT AND MOISTURE TRANSPORT

8.1. A REALISTIC SIMULATION OF HYGRIC PROCESSES IN WALL COMPONENT

The Fraunhofer Institute for Building Physics (IBP) has developed a software program called “WUFI Pro” (Acronym of the German name: Wärme und Feuchte instationär - Transient Heat and Moisture). The WUFI program is a non-steady simulation software that is menu-driven for the use on a personal computer. This program can provide e.g. customized solutions to moisture engineering and damage assessment problems for various building envelope systems. Therefore, it is directed at manufacturers and suppliers of building products, consultants, designers, engineers, architects and experts in the field of hygrothermics.

Compared to the WUFI software, the Glaser-method considers steady-state transport under simplified boundary conditions which cannot be used to reproduce individual short-term events. For the purpose of this thesis it is assumed that such an outcome does not give enough evidence to indicate if a wall component can be considered as “safe” in particular but it provides a general assessment of the hygrothermal suitability of a particular building component. Other hygric processes are not taken into account by the Glaser-method are e.g. the convection of indoor air, precipitation or rising damp. The method also does not consider capillary moisture transport in the building material or sorption capacity, which e.g. can reduce the risk of moisture caused by condensation. [1] Furthermore, Glaser does not consider the initial water content of each particular building material, known as the built-in moisture, as well as the construction moisture which can cause significant damages on a building construction. Especially in context to today's typical deadline pressures during the building design and construction phases the Glaser-method as a simplified calculation method can become questionable as these pressures can cause an increasing number of moisture damage cases.

Facing these problems, this thesis introduces the WUFI software to be able to pass on to a realistic simulation of hygric processes in each external wall component. With this tool it is possible to model individual walls and roofs, enabling the user to select climate data referring

[1] WUFI® Pro, 2D and Plus Software. *Software for calculating the coupled heat and moisture transfer in building components*. Fraunhofer-Institut für Bauphysik (IBP), Holzkirchen, Germany, Retrieved February 10, 2009 from the World Wide Web: http://www.hoki.ibp.fhg.de/wufi/grundl_ueberblick_e.html.

to the specific building location in order to estimate the hygrothermal behaviour of an external building component. The software can be used to calculate: [2]

- the drying time of a solid masonry wall with built-in moisture;
- the risk of interstitial condensation, (Glaser-method);
- the influence of driving rain on exterior building components;
- the effect of repair and retrofit measures;
- the hygrothermal performance of the roof and wall assemblies.

Such calculations can show if the moisture content within a particular wall component increases permanently and can, finally, result in moisture damages that will lead to hygienic problems and health risks due to mould growth. Furthermore, it shows the interrelation between the thermal and hygric behaviour of a building component as high moisture content favours e.g. heat losses, affecting thermal conditions. Therefore, thermal properties of a particular wall component and their impact on heat losses are important, but the hygric behaviour has to be considered as well. The WUFI software is able to produce a simulation of realistic heat and moisture conditions like this by reproducing the complex effects that are caused by natural weather at its individual location. That enables the user e.g. to calculate the transient heat and moisture transport in their mutual interdependence in a particular building component. [3]

8.1.1 THE IMPLEMENTATION OF AUCKLAND'S CLIMATE DATA

Based on the newest findings regarding vapour diffusion and liquid transport in building materials, the WUFI program uses data that are derived from outdoor and laboratory tests. These data allow a realistic calculation of the transient hygrothermal behaviour of multi-layer external building components that are exposed to natural climate conditions. [4] Furthermore, the software uses measured climate data such as test reference years (TRY) of the German National Weather service (DWD) which have currently been pre-registered, [5] as well as climate data from other sources. Such data can also include driving rain and solar radiation as boundary conditions which allow a realistic investigation on the behaviour of the wall

[2] WUFI® Pro, 2D and Plus Software, 2009 from the World Wide Web: http://www.hoki.ibp.fhg.de/wufi/grundl_ueberblick_e.html.
[3] WUFI® Pro, 2D and Plus Software, 2009 from the World Wide Web: http://www.hoki.ibp.fhg.de/wufi/validierung_e.html.
[4] WUFI® Pro, 2D and Plus Software, 2009 from the World Wide Web: http://www.hoki.ibp.fhg.de/wufi/grundl_ueberblick_e.html.
[5] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, *WUFI® Pro - Manual*. Holzkirchen, Germany: Fraunhofer Institute for Building Physics (IBP), 2009, p.30.

component under natural conditions. [6] Regarding the Auckland climate data it is necessary to implement a *.TRY file as a weather hourly data standard. A *.TRY file has been generated for this thesis with the Meteonorm 6.1 software and contains the following climate data: [7]

- Global Radiation Horizontal (Gh)
- Air Temperature (Ta)
- Wind Speed (FF)
- Wind Direction (DD)
- Precipitation (RR)
- Sunshine Duration, Mean Values (Sd)
- Dewpoint Temperature (Td)
- Days with Precipitation >0.1 mm, Mean Values (Rd)

In order to use a user-defined *.TRY file such as this, which has to be read from another source, it is necessary to provide an additional file specifying the geographical coordinates, height above sea level and time zone of the weather station in addition to the climate file itself. Such a file must be purchased by the user and copied into the same database as the *.TRY file (refer to table 8.1).

```
Additional Geographic Data
Showing data for Auckland NZ
Longitude, Latitude [°] (East,North is negative)
Height AMSL [m]
Time Zone [hours from UTC]

[WUFI]
Longitude=174.60
Latitude=-36.92
HeightAMSL=32
TimeZone=12
```

Table 8.1

Additional Geographical Data

*Example of an *,AGD file that needs to be implemented into the WUFI database to address the Auckland region.*

Geographical data of Auckland are, in this case, generated as an additional geographic data file (AGD) which contains the longitude and latitude of Auckland (Long. 174.60 °E; Lat. 37.92 °S), its height above the mean sea level (AMSL +32.00 m) and the coordinated universal time of the particular location (UTC +12 h). Both, the *.AGD and *.TRY file then have to be copied into the WUFI climate database to be applied. When implemented, the program is able to display a plot of the temperatures and relative humidity values (refer to figure 8.1). [8]

---

[6] WUFI® Pro, 2D and Plus Software, 2009 from the World Wide Web: http://www.hoki.ibp.fhg.de/wufi/grundl_ueberblick_e.html.
[7] Refer to Appendix, pp.162-163.
[8] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, pp.30-31.

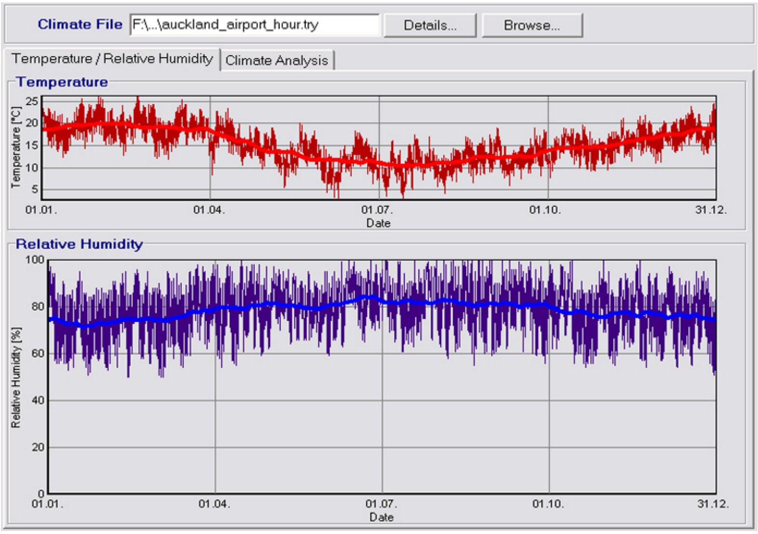


Figure 8.1

Auckland Climate Data

The thin curves show the hourly data read from the selected climate data, the bold curves represent the centred moving monthly means for a clear overview.

Additionally to the climate module, WUFI also allows a more detailed analysis of the climate file in order to provide temperature statistics and humidity and rain statistics. Such an analysis can show e.g. the minimum, maximum and mean values of temperature and relative humidity (RH), as well as the yearly amount of rain, the directional distribution of solar radiation and driving rain. Referring to figure 8.2, the rose of sun radiation presents e.g. the yearly sum of solar radiation for different orientations and inclinations of a building component. Therefore, low values are displayed in dark red, medium values in yellow and high values in light blue. This makes it possible to see if a particular location obtains high or low radiation intensity. Compared to the rise of sun radiation, the rise of driving rain shows the yearly sum of driving rain on a vertical surface for different orientations. The scale of this diagram is adapted to accommodate the maximum driving rain load occurring at this particular location which indicates the amount of driving rain in mm per year (mm/a). [9]

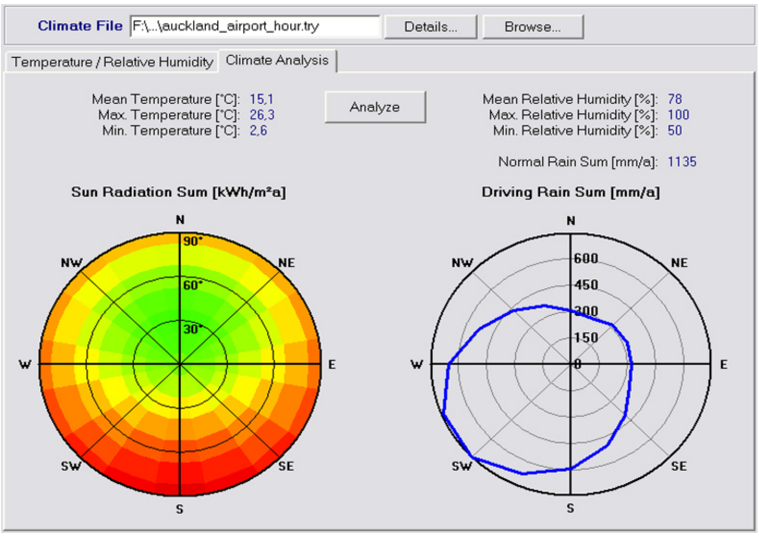


Figure 8.2

Analysis of the Climate Data

It displays the minimum, maximum and mean values of temperature and RH, as well as data about rain and solar radiation.

[9] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.31.

8.1.2 AVERAGE INDOOR CLIMATE OF NEW ZEALAND HOMES

Generally, WUFI allows using measured climate data which are already integrated into the WUFI software as well as other implemented climate data from other sources to define the indoor climate. Additionally, it is also possible to use arbitrary user-defined data. These can be e.g. exterior, interior or artificial laboratory climates, indoor climates derived from outdoor climates and constant or sine-wave shaped temperatures and RH values. [10] Therefore, WUFI allows the use of four kinds of different options to model the indoor climate: the European Standard EN13788, European Provisional Standard prEN15026, ASHRAE Standard 160P and User-defined Sine Curves.

The European Standard EN13788 and the European Provisional Standard prEN15026 cannot be applied for New Zealand conditions. The EN13788 suggests a constant indoor temperature of 20°C throughout the year. Such indoor temperature is simply not given in New Zealand homes and, therefore, this standard cannot be used without changing the constant indoor air temperature of 20°C. Furthermore, the prEN 15026 derivates the indoor climate from outdoor conditions which means that the indoor temperature and humidity depend on the outdoor temperature. [11] The problem is that the outdoor temperature used by this standard does not meet the typical New Zealand climate conditions. Therefore, the prEN 15026 also cannot be applied to create typical indoor conditions for New Zealand homes. The ASHRAE Standard 160P, "Criteria for Moisture Control Design Analysis in Buildings", by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) derives the interior climate from an exterior climate by using a specified algorithm. Generally, this standard provides performance-based procedures to analyse a building component on moisture and sets criteria for moisture design loads, moisture analysis methods and building performances. [12] This standard can be used for New Zealand houses but only if the following data are available:

- the number of bedrooms;
- the type of air conditioning system;
- the air exchange rate;
- the building volume.

Compared to the European Standard EN13788 and the European Provisional Standard prEN15026, the user-defined sine curve parameters describe an indoor climate as a one-

[10] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.29.
[11] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.34.
[12] Anton TenWolde. "*ASHRAE Standard 160P: Criteria for Moisture Control Design Analysis in Buildings*", ASHRAE Transactions, Volume 114, 2008, p.171.

year period for temperature and relative humidity. It specifies the mean value, amplitude and day of maximum by using maximum values in summer and minimum values in winter. In this context, it is also possible to select constant values for the indoor temperature and indoor humidity. Predefined sine curves for different exterior and interior climates with low, medium or high moisture loads are provided by the software. These different moisture loads are based on the recommendation 6-2-01/E "Simulation of Heat and Moisture Transfer" that specifies hygrothermal simulations as an alternative to the Glaser-method by the International Association for Science and Technology of Building Maintenance and Monuments Preservation (WTA). However, for most cases the given default values are related to an average European indoor climate: medium moisture load, temperature 21°C with 1°C amplitude. [13] Therefore, it is always necessary to review the given default values in order to meet average New Zealand conditions of existing uninsulated homes: moisture load 65%, temperature 16°C with 1°C amplitude (refer to figure 8.3). [14]

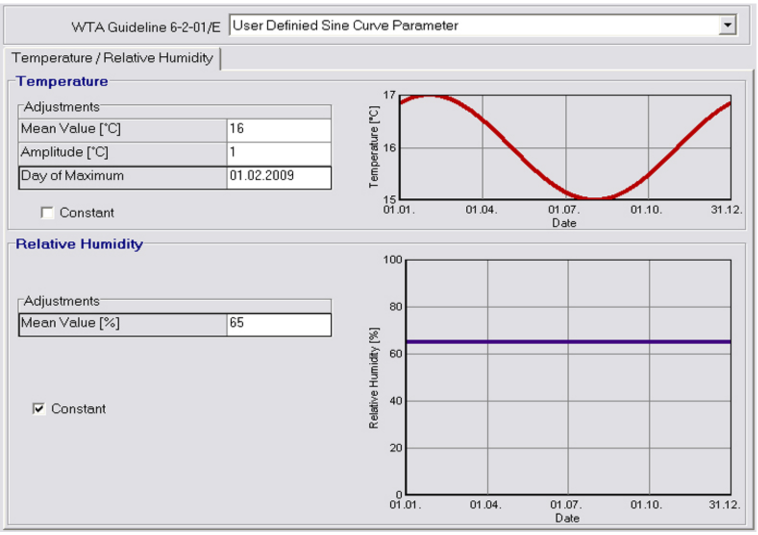


Figure 8.3

New Zealand Indoor Climate

Typical indoor climate conditions in New Zealand homes, according to the norm-climate as stated before in chapter seven.

8.1.3 LOCATION, BUILDING MATERIALS AND THE EFFECT OF BUILT-IN MOISTURE

After the outdoor and indoor conditions have been stated, the orientation of the exterior surface has to be specified. For example, an exterior surface which is facing South-West in New Zealand will have the most impacts in terms of rain, compared to an exterior surface which is facing North-East (refer to figure 8.2). Also important in this case is the Inclination that describes the angle at which the surface is tilted in relation to the horizontal, as well as the height above the surrounding ground of the building component (refer to figure 8.4).

[13] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, pp.32-33.
[14] Refer to chapter 1, table 1.1, p.7.

These inputs are necessary as they allow calculating the rain and radiation loads incident on the surface. [15]

Afterwards, the construction component and its different layers of building materials with the desired material properties have to be specified. WUFI allows assigning material property values from its database but it is also possible to add user-defined materials or properties by hand. This is quite important as most building material suppliers in New Zealand do not publish the properties of their building products, such as the bulk density (ρ), porosity (Φ), thermal conductivity (λ) and diffusion resistance coefficients (μ). According to Kevin Hartigan, Technical Advisor of Monier Bricks, some building material manufacturers and suppliers simply do not even know the properties of their product. [16] Therefore, it can be necessary to fill such gaps of information with values of a similar product that are available on the European market, as already done for the Glaser-method. [17] When these data are assigned into the program, all inputs will be shown immediately in a graphical diagram.

Regarding this, the sequence of layer in the wall component can be freely chosen, as the exterior and interior conditions can be assigned to any side of the graphical diagramm. However, the effect of rain and solar radiation can be taken into account only on the left and therefore, the left is usually considered to be the exterior side (refer to figure 8.5). WUFI also allows placing several monitoring positions at any point of interest within the building component. Compared to such user-defined monitoring positions, the exterior and interior surface are automatically preselected as monitoring positions to record the change of temperature and RH. [18]

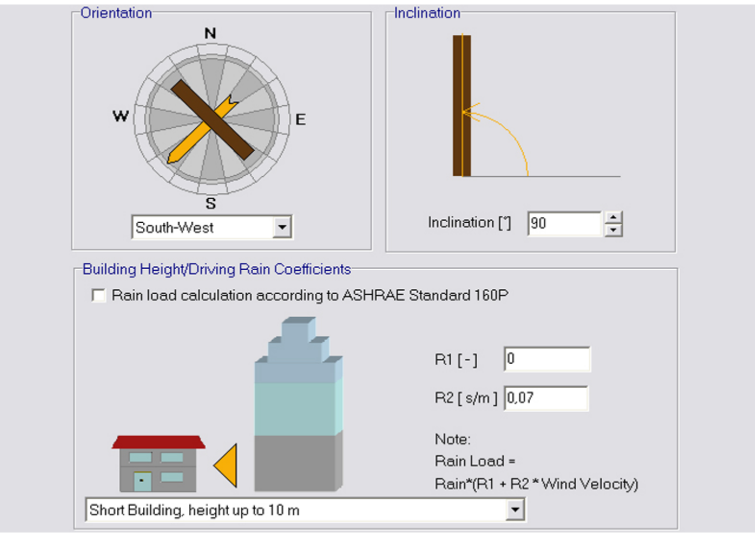


Figure 8.4
Orientation, Inclination and Height
External wall components facing South-West are usually affected by moisture and dampness problems in New Zealand.

[15] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.24.
[16] Kevin Hartigan, "Thermal Properties" Office Communication, 21st November 2008.
[17] Refer to chapter 7, p.88.
[18] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, pp.16-19.

Another important part is the initial distributions of built-in moisture and temperature to be able to determine how long a construction will need to reach a dynamic state. [19] Building components which definitely contain built-in moisture are usually constructions with materials that contain manufacturing moisture, such as plaster, concrete and masonry walls with mortar joints, as well as building materials that have not been sheltered against rain during construction. The WUFI database offers some typical built-in moisture contents for building materials, but some values of typical New Zealand building materials, such as values for masonry may have to be found in the literature. Compared to new timber frame constructions and materials with manufacturing moisture, existing components have usually reached a dynamic equilibrium after several years of use. [20] Based on that and the fact that the long-term water content does not change from year to year, a specified calculation period should be at least two years long. For this thesis a general calculation period of three years is used for all WUFI calculations with a default time step of one hour.

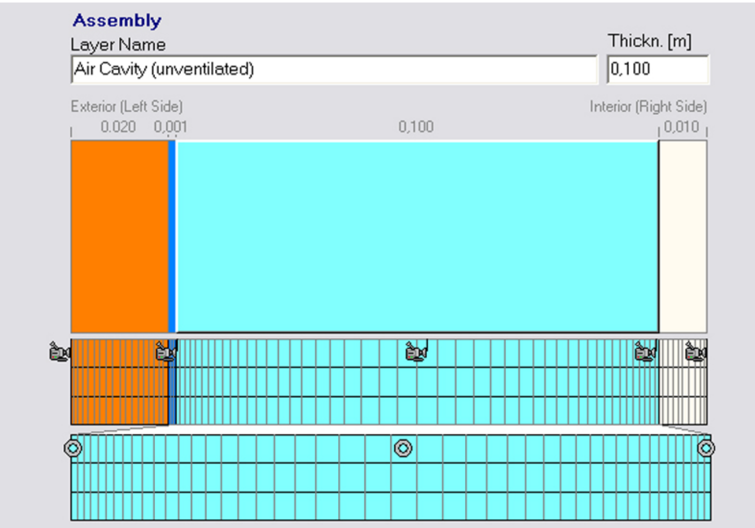


Figure 8.5

Graphical Diagram

All inputs will be shown immediately in a graphical diagram which usually considers the left as the exterior side.

8.1.4 RESULTS AND PROBLEMS OF A WUFI CALCULATION

The results of the WUFI calculation can be displayed either in a short brief overview or as result graphs. The overview contains quick graphs which give a first assessment to compare different cases but are limited in terms of formatting. For example, the quick graphs can be used to show statistics on the liquid water content in different layers of a component in order to determine whether moisture has accumulated or dried out during the investigated period (refer to figure 8.6). Slower, but more flexible in terms of editing and formatting are the result graphs which contain already formatted and printable courses and profiles. [21]

[19] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.11.
[20] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.26.
[21] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, pp.36-37.

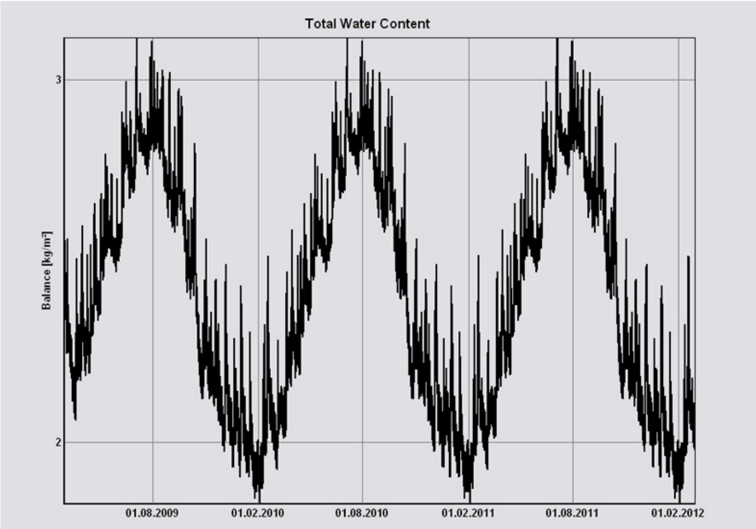


Figure 8.6

Total Water Content

The graph shows that the total water content has reached dynamic equilibrium but it does not mean that each layer did it as well. Therefore, it is necessary to verify that also all individual layers have reached dynamic equilibrium.

Generally, the quick graphs allow assessing the total water content within each material to foresee possible consequences. For example, when a timber frame construction exceeds 20 mass-percent for a longer period of time it can lead to mould growth. Furthermore, insulation material which is possibly placed inside the frame cavities can be affected, losing its insulation efficiency through the intake of moisture. [22] Especially in regions of New Zealand's South Island, cladding materials might become susceptible to frost damages if the water content is too high. Therefore, the water contents that are described as mass-percent have to be known for each particular material to determine e.g. the risk of frost damages. Currently, this seams to be a problem as material suppliers in New Zealand are mostly not able to provide such information which can be used to identify possible limits that should not exceeded.

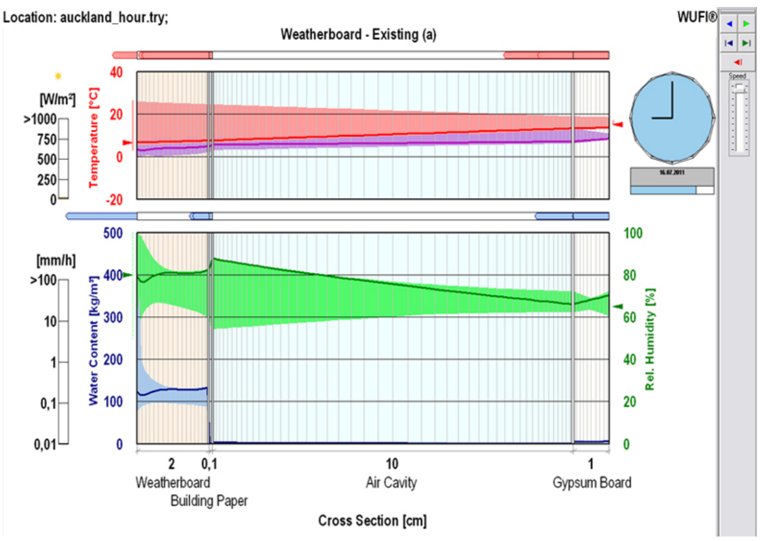


Figure 8.7

WUFI Animation

The dark curves present the current profiles while the light coloured areas show the range swept by the profiles. Temperature is shown in red, dew point in purple, RH in green and the water content in blue.

[22] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.39.

Beside the short overview and result graphs, WUFI also present the results in form of a movie to illustrate the thermal and hygric processes in a building component by an animation. This animation simply shows the progress in time in relation to the temperature, dew point, RH and actual water content. It shows the reactions in different material layers that are directly linked to specific changes of climate conditions (refer to figure 8.7). For example, the seasonal migration of moisture is immediately evident and the animation shows which parts of the construction component may be critical. [23] A complete report of the input data which includes a summary of the calculation itself is also available to illustrate the basis of the animation.

8.2. THE WUFI CALCULATION

The general target for a possible retrofit solution is to achieve an indoor air temperature of an average of 20°C in order to be able to control dampness problems and to lower health impacts in New Zealand homes. So far in the context of this thesis, moisture transport in building materials was explored in relation to vapour diffusion, dewpoint with the Glaser-method as described in the German standard DIN 4108 in the previous chapter. [24] According to DIN 4108, a particular external wall component can be classified as "safe" after passing the standard Glaser assessment. Only if the standard Glaser assessment is not passed or unexpected moisture damage occurs, alternative assessment methods have to be introduced. For example, the Glaser calculation of the existing labour state house construction has shown that interstitial condensation does not occur on the one hand, but also indicated that the R-value of the wall component is not acceptable on the other hand. [25] Furthermore, condensation by vapour transport is only one of many possibilities in terms of moisture problems in building components: a positive assessment according to the German standard DIN 4108 can indicate a moisture safety in terms of condensation problems that might not really exist. [26] In order to prove if the Glaser-method can be recommended as a general tool to apply in New Zealand context, it is necessary to review and to evaluate the outcome of the previous Glaser calculations by using WUFI before classifying a possible retrofit package as "safe". If the outcome of the WUFI program proves that an unacceptable level of moisture is present within the particular wall component the retrofit package has to be reviewed and optimised until the thermal comfort and performance is satisfactory.

[23] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.42.
[24] Refer to chapter 7, p.79.
[25] Refer to chapter 7, p.87-90.
[26] WUFI® Pro, 2D and Plus Software. *Software for calculating the coupled heat and moisture transfer in building components*. Fraunhofer-Institut für Bauphysik (IBP), Holzkirchen, Germany, Retrieved February 10, 2009 from the World Wide Web: http://www.hoki.ibp.fhg.de/wufi/intro_e.html#Introduction.

8.2.1 RETROFIT SOLUTION - LABOUR STATE HOUSE CONSTRUCTION

The previous example of a typical labour state house construction is also taken as an example for the following WUFI calculation to compare both outcomes. [27] As described before, the accessible and ventilated roof is retrofitted with 120 mm cellulose fibre insulation material that is blown dry into the roof space. The floor is also insulated with expanded polystyrene (EPS) underneath the accessible and ventilated floor construction (60 mm) and the unventilated existing frame cavities of the wall component are filled with mineral wool batts (refer to figure 7.6). [28] The outcome of the Glaser-method showed that interstitial condensation does not occur within the original external wall construction of the labour state house. When the retrofit solution is applied, the Glaser calculation showed that interstitial condensation can occur but the water content did not exceed the specified limit of 3.6 kg/m² (3,585.60 g/m²) of liquid water. [29]

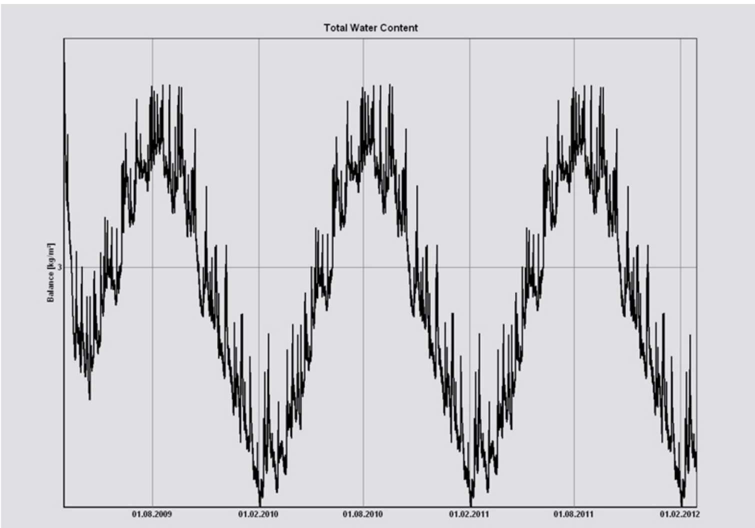


Figure 8.8
Total Water Content
The total water content is approximately about 2.2 kg/m² in summer and 3.7 kg/m² in winter. The graph shows that the external wall is able reaches its dynamic steady state as the water content only repeats minor variations due to seasonal climatic changes.

In order to determine the risk of this moisture content within the wall component after the retrofit solution has been applied, it is necessary to identify the content of water within each material layer. Therefore, the dimensions and properties of all building materials that already have been used for the Glaser calculation are integrated into the WUFI calculation to reflect the behaviour of the wall construction under the applied climatic conditions of Auckland. The outcome shows that the total water content within the wall component is approximately about 2.2 kg/m² during summer and 3.7 kg/m² during winter due to seasonal climatic changes and remains constant over the years. This proves that the component is able to reach its dynamic steady state (refer to figure 8.8). [30]

[27] Refer to chapter 7, pp.90-95.
[28] Refer to chapter 7, p.92.
[29] Refer to chapter 7, p.94.
[30] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.38.

Compared with the outcome of the Glaser calculation the total content of water caused by interstitial condensation during winter should be only about 0.2 kg/m² (201.60 g/m²). [31] Regarding this outcome, the WUFI calculation proves that the total content of water within the insulation layer reaches a higher level which may also be caused by other hygrothermal processes, such as capillary moisture transport in the building material or its sorption capacity. Furthermore, the amount of 3.7 kg/m² of water is above the specified limit of 3.6 kg/m² (3,585.60 g/m²) stated by the Glaser calculation. Therefore, this thesis assumes that moisture problems within the wall component will occur. Nevertheless, the numerical value of the total content of water within the wall assemble is relatively irrelevant because it does not indicate the content of water content within each layer material. The numerical value defines only the sum of water in all layers which depends on the thickness of the construction and the applied building materials. Therefore, the total content of water over a long-term is the basis for any assessment but it only proves if a wall construction is able to reach its dynamic steady state. [32]

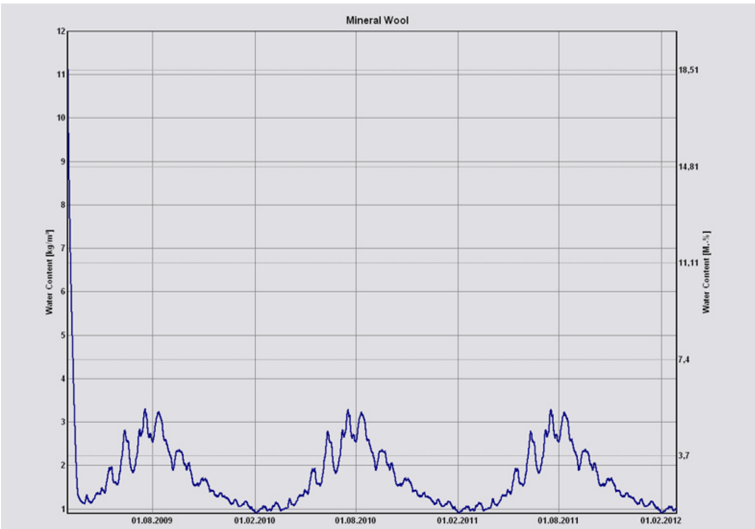


Figure 8.9

Water Content of the Mineral Wool

The water content within the mineral wool is about 1.0 kg/m³ during summer. In winter, it raises up to more than 3.5 kg/m³ which can have negative effects on the wall construction.

The graph of the content of water within the insulation material layer of the external wall shows that the minimum moisture content is about 1.0 kg/m³ during summer, but raises up to more than 3.5 kg/m³ during winter (refer to figure 8.9). In addition, the WUFI animation shows that interstitial condensation is evident and might be the cause for the high moisture content within the mineral wool insulation layer. Referring to figure 8.10, the animation shows that the RH (green curve) reaches 100% (top of the scale) during the calculation period of three years and, therefore, interstitial condensation occurs. In result, the outcome of the WUFI calculation does not recommend filling mineral wool insulation batts into the existing frame cavities without additional construction changes as this will cause a content of moisture

[31] Refer to chapter 7, p.94.
[32] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.38.

during winter that is not acceptable. Following this, problems can be initial mould growth within the timber construction which is able to destroy the entire structure of the external wall.

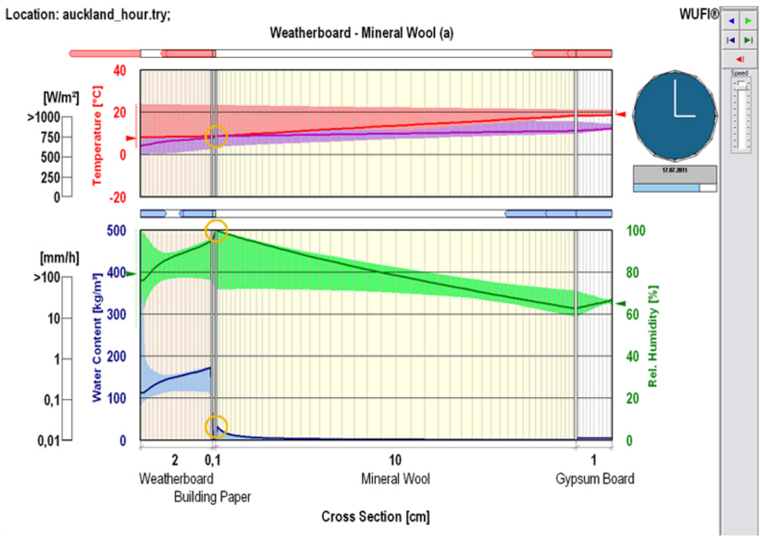


Figure 8.10
WUFI Animation
The light green area, presenting the RH within the wall component proves that 100% RH is reached during the calculation period which leads to liquid water within the wall component (yellow circle).

8.2.2 ALTERNATIVE RETROFIT SOLUTION - LABOUR STATE HOUSE CONSTRUCTION

In order to ensure that the cellulose fibre batts do not absorb too much water and harm the original timber framing, two different options can be introduced: The first option would include a minimum 20 mm ventilated air cavity between the weatherboards and the building paper to control the content of water within the external wall component. The second and preferred option in this thesis is the combination of a vapour barrier and a new layer of building paper. The new building paper will be installed between the insulation layer and the weatherboards to avoid direct contact between these two material layers. The vapour barrier will be installed between the new internal gib lining and the mineral wool batts to create an airtight layer.

A vapour barrier acts as a vapour control layer that covers the insulation layer that impedes the transfer of warm and moisture laden air from the internal living space into the wall component by means of convection. Convection usually results in undesirable heat losses and high levels of moisture that can occur within the insulation layer. Therefore, the vapour barrier should not be interrupted and is covered with a new gib lining (refer to figure 8.11). [33] This solution presents the potential to insulate the wall component with mineral wool batts, providing an acceptable R-value above the required minimum standard of 1.9 m²·K/W. Furthermore, without the need of a ventilated air cavity it does not require changes to the original thickness of the external walls which would also affects the interior planning e.g. doors and window frames. However, further testing is recommended to investigate the full extent of effectiveness and success of this approach.

[33] Clemens Richarz, Christina Schulz, Friedmann Zeitler, *Detail Practice: Energy-Efficiency Upgrades - Principles, Details and Examples*. Basel, Switzerland: Birkhäuser, 2007, pp.26-27.

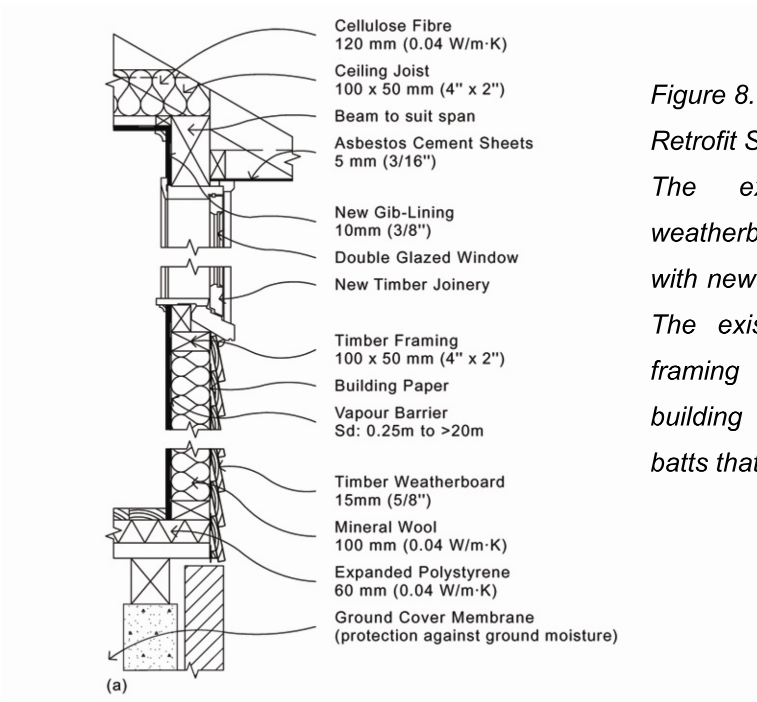


Figure 8.11
Retrofit Solution of a Labour State House
The external wall is covered with weatherboards on the outside, and finished with new gib lining and wallpaper to the inside. The existing air cavities within the timber framing are covered with a new layer of building paper and filled with cellulose fibre batts that are covered with a vapour barrier.

The outcome of the WUFI calculation shows a decreasing content of water in the first two month within the wall component (refer to figure 8.12). This behaviour is known as the dry out phase as the moisture content decreases below the initial conditions. Generally, it is necessary to extend the calculation period until the wall component has reached its dynamic steady state. [34] In this case, the calculation period of three years is long enough to provide an assessment of the long-term moisture level. The graph shows that the total content of water is approximately about 2.2 kg/m² in winter and 3.2 kg/m² during summer after the dry out phase. These variations can be linked to seasonal climatic changes over the calculated period and prove that the wall construction is able to reach its dynamic steady state which allows proceeding to analyze the individual building material layers.

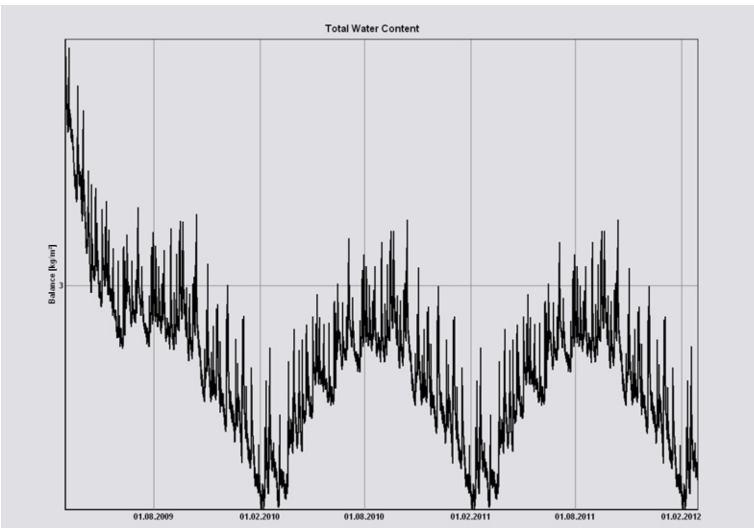


Figure 8.12
Total Water Content
The total water content is approximately about 2.2 kg/m² in summer and 3.2 kg/m² in winter. The graph shows that the external wall is able reaches its dynamic steady state as the water content only repeats minor variations due to seasonal climatic changes.

[34] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.38.

The analysis of the individual layers with the WUFI program shows that the moisture level within each material is acceptable and does not indicate any kind of moisture problems. For example, the content of moisture within the mineral wool is about 1.0 kg/m³ during summer and 1.4 kg/m³ during winter. Such level is acceptable and does not having an effect on the timber frame construction (refer to figure 8.13). Therefore, the WUFI calculation proves that the moisture content within the retrofitted wall will not exceed limits that support mould growth or having an effect on the materials that could damage the existing structure. In combination with new double glazed windows and timber joinery, it is also recommended to install a mechanical ventilation system to provide fresh air and to control the indoor humidity in combination with the air pollutant levels. This in combination with a new airtight layer, thermal insulation and tightly sealed windows will improve the indoor air quality (IAQ). [35] Overall, the alternative retrofit solution including the installation of a vapour barrier can be recommended to improve the thermal comfort and to reduce housing costs.

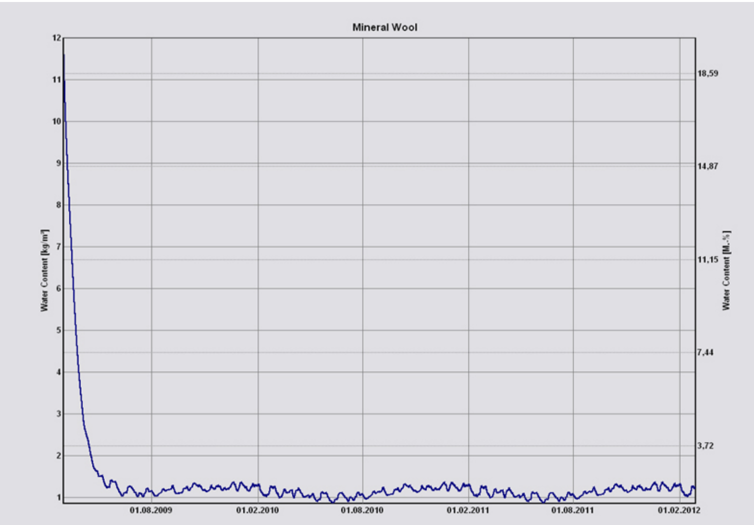


Figure 8.13
Water Content of the Mineral Wool
The mass-percentage of moisture within the mineral wool is about 1.0 kg/m³ during summer and about 1.4 kg/m³ during winter. Such level of moisture does not indicate any moisture problems.

The comparison of both, the Glaser-method and the WUFI programme show that it is necessary to explore more than only the risk of interstitial condensation within a building component. The WUFI program allows determining the problem of moisture within a wall component more detailed than the Glaser-method can do, but it also needs much more information in terms of material properties. The fact that most New Zealand manufactures and building material suppliers currently are not able to provide all these information make it questionable if WUFI can be used properly. It is already necessary to use data of similar building products that are currently available on the European market to apply the Glaser-method. When it comes to the WUFI software, this gap of information is even bigger and the result may become imprecisely. Therefore, the thesis recommends the Glaser-method as an

[35] Clemens Richarz, Christina Schulz, Friedmann Zeitler, 2007, p.14.

alternative that can be used to provide a general assessment of the hygrothermal suitability of a wall component. Nevertheless, the WUFI program should be introduced if possible as it allows understanding the complexity of the hygrothermal processes within a building component.

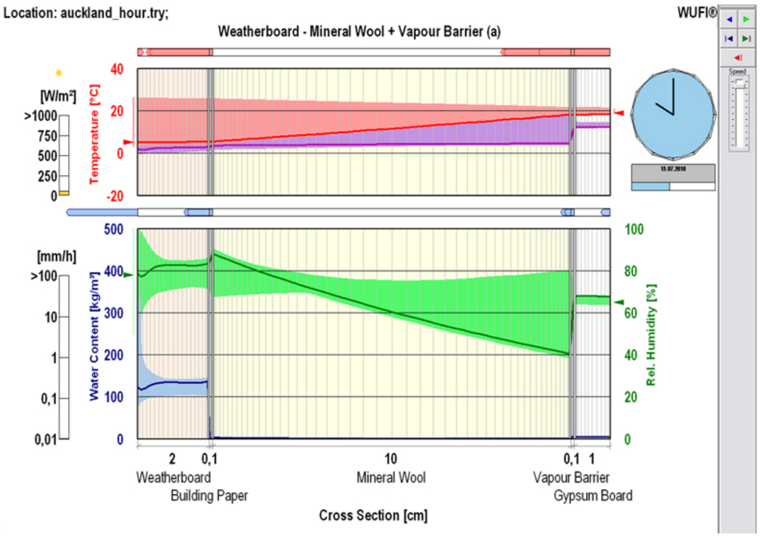


Figure 8.14
WUFI Animation
The light green area, presenting the RH within the wall component proves that 100% RH is not reached during the calculation period of three years.

An important factor which both, the Glaser-method and the WUFI software do not take into account is the human factor. A healthy indoor environment cannot be achieved without considering the human factor which usually includes various aspects such as cooking, lifestyle or other cultural needs. Thus, before starting to improve the building construction, it is necessary to review the lifestyle of the occupants, as their behaviour can have a significant influence on the amount of moisture that is available inside the house. Where a lifestyle is thought to be influential, it is necessary to face the problem and the occupiers need to be aware that their own actions have a negative effect on the indoor environment. [36] The implementation of the human factor is currently missing in both the Glaser-method and the WUFI software. Therefore, this master thesis proposes that this factor has to be applied in order to determine the human effect and, if possible, to make this factor visible to the occupiers.

[36] Ralph Burkinshaw, Mike Parrett, *Diagnosing Damp*. Coventry, UK: RICS Business Services, c2003, pp.32-34.

9. INTERVENTIONS AND REFURBISHMENT

9.1. PRACTICAL RECOMMENDATION FOR A REFURBISHMENT

The basic key elements of all retrofit packages or particular combinations for a building type are retrofitted insulation in the external walls, ceiling and underfloor, as well as installing double glazed windows. Indeed, when uninsulated or under-insulated, these building components have a significant affect on the thermal comfort. For example, 30 to 35% of the internal heat energy can be lost through the ceiling, 12 to 14% through the floor construction and up to 18 to 25% through external walls. Also single glazed windows dissipate the thermal energy and, therefore, affect thermal comfort within a house, by up to 21 to 31%. [1] These amounts of heat loss through the building envelope can be reduced by improving the insulation layer and installing double glazed low emissivity (low-e) windows with thermal breaks. Such improvement will lead to higher thermal comfort and can also help to control problems of condensation and noise. Apart from this, it is also necessary to review the lifestyle and behaviour of the occupants, commonly known as the human factor. As already considered in relation to the WUFI software, healthy housing cannot be achieved without considering occupants and their influence on the indoor environment. Therefore, changing a lifestyle can also produce improvements in terms of the indoor air quality (IAQ). [2]

This combination of retrofit solutions and change of human behaviours appear to be the most effective solution in order to improve thermal comfort in existing homes, while producing greatest benefits on a national scale. [3] Only a clear understanding of damp housing allows recommending effective remedies, by identifying moisture sources that can cause a high indoor humidity. [4] For a full result, a retrofit package could also include e.g. to install mechanical devices such as extraction fans to control the indoor humidity, reducing it to the level of 40 to 60%. [5] Such improvement can also be combined with a mechanical ventilation and heating system in order to provide an adequate ventilation rate, [6] which would help improving the IAQ by avoiding problems such as house dust mites (HDM) or high levels of airborne pollutants. [7] As proposed in the context of this thesis retrofit solutions for external

[1] New Zealand Business Council for Sustainable Development (NZBCSD). *Better Performing Homes for New Zealanders: Making it Happen*. Auckland, New Zealand: NZBCSD, A-2008, p.15.
[2] Ralph Burkinshaw, Mike Parrett, *Diagnosing Damp*. Coventry, UK: RICS Business Services, c2003, pp.32-34.
[3] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.14.
[4] Ralph Burkinshaw, Mike Parrett, c2003, p.32.
[5] Refer to chapter 3, p.21.
[6] Refer to chapter 4, p.38.
[7] National Institute of Public Health. *Indoor Environment and Health: A book for everyone who cares about a healthy indoor environment*. Trelleborg., Sweden: Berlings Skogs, 1999, p.67.

wall components of different house typologies can only improve housing condition in terms of IAQ and comfort when realized in combination with:

- roof insulation
- underfloor space insulation
- double glazed windows with thermal break joinery
- acceptable ventilation rate / system
- heating system

This combination can guarantee a higher thermal comfort within these houses besides IAQ improvement and a higher building energy performance. Additionally, when combined with a mandatory rating system for existing residential buildings, such retrofitted homes may also have a premium value in the market place which will be reflected in the value of homes at on sale or rental. [8] Therefore, this thesis will now provide practical recommendation and retrofit solutions for refurbishments of specific building typologies, built between 1950 and 1980's.

9.2. LABOUR STATE HOUSES (1930 - 1970)

According to Beacon, the labour state housing typology can be rated as a good candidate for retrofit packages but most occupants are still of the lower income group with large families. [9] Therefore, maintenance and renovation options in the past and present are restricted by the financial ability of the homeowners or a leak of public founding from the government. These circumstances lead to the current situation that many labour state houses suffer under dampness and mould growth which may require e.g. to remove and to replace the internal gib lining. Regarding this, it is necessary to assess the extension of damage before introducing a retrofit package.

The design of the labour state house can allow upgrading the construction relatively easy (refer to figure 9.1). For example, the steep roof of the English cottage style design is usually built with maintenance holes that are placed in the ceiling panels. These make the existing roof space accessible for insulation addition. Furthermore, when the house is located on a slope site, the underfloor space is mostly accessible and offers the opportunity to be insulated from the outside. When located on a flat site, the house is usually built with a ventilated foundation wall which can limit the access to the floor construction from the outside. In this case, it is necessary to create a small access point in the foundation wall to be able to retrofit the ventilated underfloor area with insulation material. Apart from the roof

[8] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.39.

[9] Verney Ryan. "Building Momentum for Sustainable Homes, Symposium 2008: Turning serial renovators into sensible retrofitters". Auckland, New Zealand: Beacon Pathway Ltd, 2008, p.6.

and floor construction, also the standard window units which were used for the original labour state house design offer now a high flexibility to replace the existing windows with double glazed units, including new framing. Regarding this, it is recommended to install double glazed windows with timber frames combined with aluminium protective profiles on the outside. Interventions on different external wall construction of labour state houses appear instead more complicated. Generally, a retrofit package has to be suitable to the existing cladding system, regarding the labour state house design which made use of three different cladding systems: (a) weatherboards, (b) asbestos cement sheets or (c) brick veneer. [10]

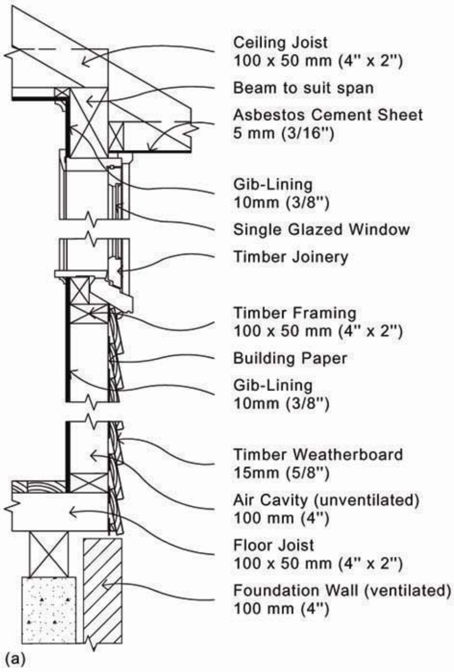
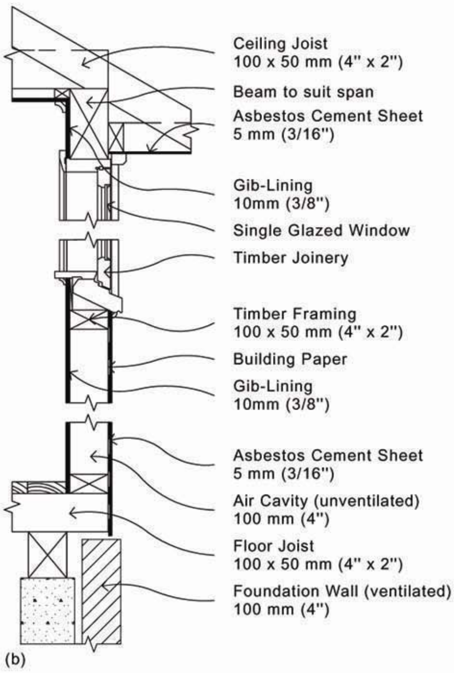
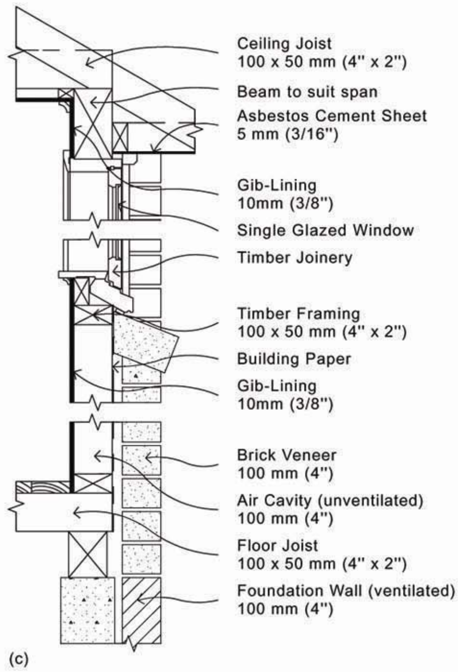


Figure 9.1
External Wall of the Labour State Houses
The external wall of the labour state houses are typically covered with (a) weatherboards, (b) asbestos cement sheets or (c) brick veneer. Inside the house, the walls are normally lined with fibrous plaster and finished with wallpaper. Therefore, different retrofit packages will be proposed and tested for each cladding system.





[10] Refer to chapter 6, pp.70-73.

9.2.1 WEATHERBOARD CLADDING SYSTEM (A)

The weatherboard cladding system has already been explored in the previous chapters to explain the Glaser-method [11] and WUFI simulation software. [12] The outcomes of both methods were compared and used to identify a suitable retrofit package for the weatherboard system. For example, most non-practitioners may assume that the easiest retrofit solution might be to install insulation material into the existing timber frame cavities to improve the thermal layer. But the WUFI calculation proved that such retrofit solution will lead to a serious level of moisture content within the timber framing and insulation material that can support initial mould growth. Therefore, the results lead to the recommendation to combine the insulation layer with a vapour control layer between the new internal gib lining and the installed mineral wool insulation batts (refer to figure 9.2). The WUFI software proved that this improvement does not lead to unacceptable moisture levels within the wall component. In combination with an insulated roof and underfloor space this retrofit solution can be recommended to improve thermal comfort and IAQ. [13]

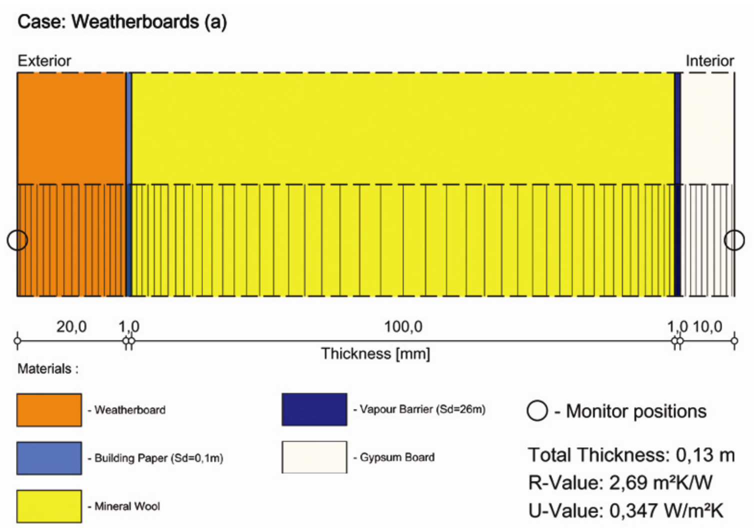


Figure 9.2
WUFI: Weatherboards
The WUFI calculation considers a wall component that exists of a timber frame construction which is retrofitted with 100 mm mineral wool insulation batts, covered with a new vapour barrier and gib lining.

9.2.2 ASBESTOS CEMENT SHEET CLADDING SYSTEM (B)

Compared to the weatherboard cladding system which can experience moisture problems, the asbestos cement sheet cladding system can also be a potential hazard to occupant health if the material becomes damaged. [14] Generally, when the asbestos is not damaged, there are no serious problems, as the asbestos fibres cannot be released into the environment. It means that, leaving the building material untouched the escape of asbestos fibres is prevented. Therefore, it is necessary to check the current conditions of the asbestos

[11] Refer to chapter 7, pp.87-95.
[12] Refer to chapter 8, pp.106-111.
[13] Refer to chapter 8, pp.106-111.
[14] Refer to chapter 2, pp.18-19.

cement sheets before considering the possibility of asbestos decontamination. When the asbestos cement sheets are not damaged, they do not have to be removed and it is recommended to introduce the same retrofit solution that has already been developed for the weatherboard cladding system (refer to figure 9.3). Considering the same internal structure, it is recommended to remove the existing gib lining in order to install 100 mm mineral wool insulation batts into the existing wall cavities. Afterwards, a vapour barrier is installed to cover the insulation layer which is finished than with a new gib lining.

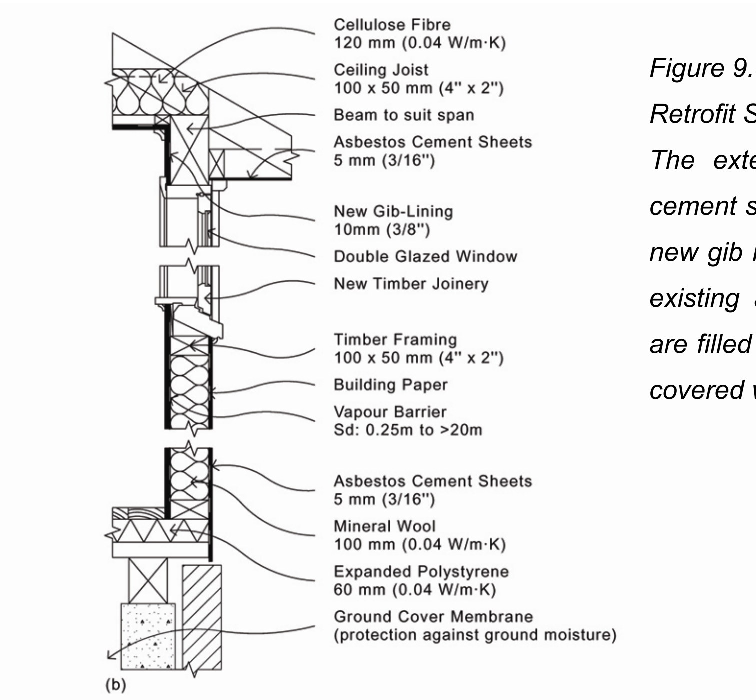


Figure 9.3
Retrofit Solution: Asbestos Cement Sheets
The external wall is covered with asbestos cement sheets on the outside and finished with new gib lining and wallpaper to the inside. The existing air cavities within the timber framing are filled with mineral wool insulation batts and covered with a new vapour barrier.

Asbestos decontamination has to be carried out when the asbestos building material is damaged and can become a potential hazard to occupant health but the removal of asbestos can also cause an increase of the indoor airborne asbestos fibre levels that can remain for a year or even longer. [15] Therefore, demolishing the building might be another opportunity. However, if an asbestos decontamination has to be undertaken it can also offer the opportunity to retrofit such particular building at the same time. In this case, it is recommended to remove the entire cladding layer in order to replace it with a new cement sheet cladding system on battens. But before constructing the new cladding layer, the existing timber frame cavities can be insulated from the outside with mineral wool insulation batts which will keep disruption to the interior to a minimum. The new cement sheets cladding is separated with vertical battens and building paper from the existing wall construction by a minimum 20 mm cavity to provide an adequate mount of air flow for moisture removal (refer to figure 9.4). If possible, this thesis also recommends combining this

[15] Refer to chapter 2, p.19.

retrofit solution with a vapour barrier to achieve best possible thermal comfort. Therefore, the internal gib lining has to be removed as well to install the vapour barrier.

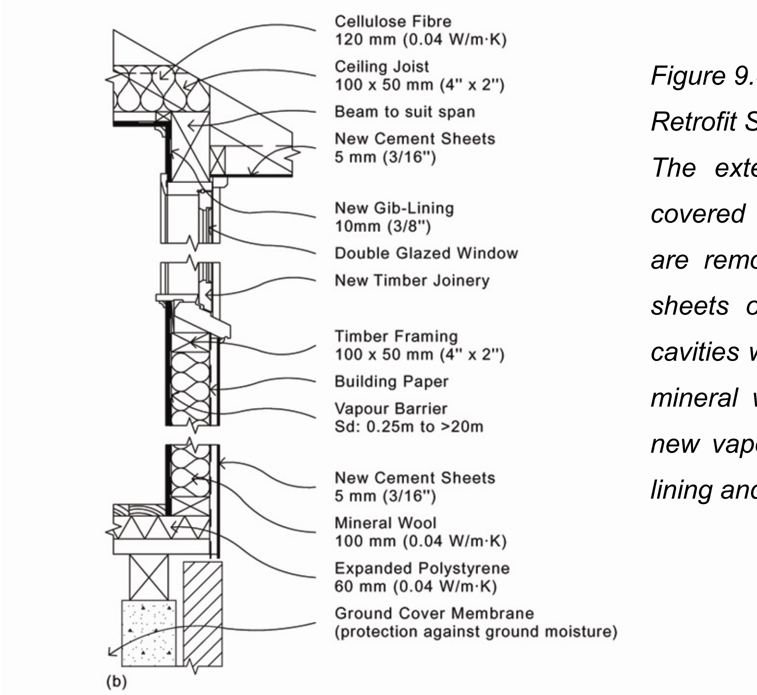


Figure 9.4

Retrofit Solution: New Cement Sheets

The external wall component was originally covered with asbestos cement sheets which are removed and replaced with new cement sheets on 20 mm battens. The existing air cavities within the timber framing are filled with mineral wool insulation batts, covered with a new vapour barrier and finished with new gib lining and wallpaper to the inside.

The outcome of the WUFI calculation shows that when the retrofit solution is applied the external wall construction can be considered as "safe" in terms of moisture problems (refer to figure 9.5). Indeed, the WUFI calculation proves that the total water content within the wall component only follows minor variations due to seasonal climatic changes and remains constant over the years under the applied climatic conditions of Auckland. This result shows that the wall component is able to reach its state of equilibrium forming the basis for the following assessment of the content of water within each material layer.

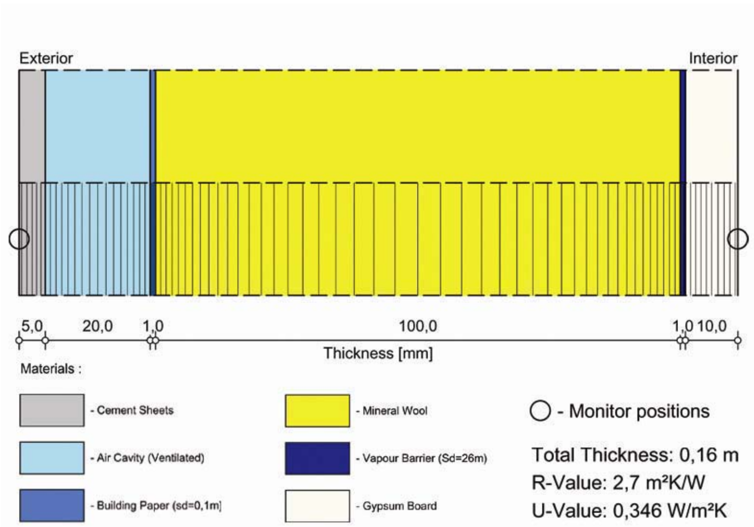


Figure 9.5

WUFI: New Cement Sheets

The WUFI calculation considers 100 mm mineral wool insulation batts, covered with a new vapour barrier. The calculation proves that the retrofit solution does not lead to moisture problems within the wall component.

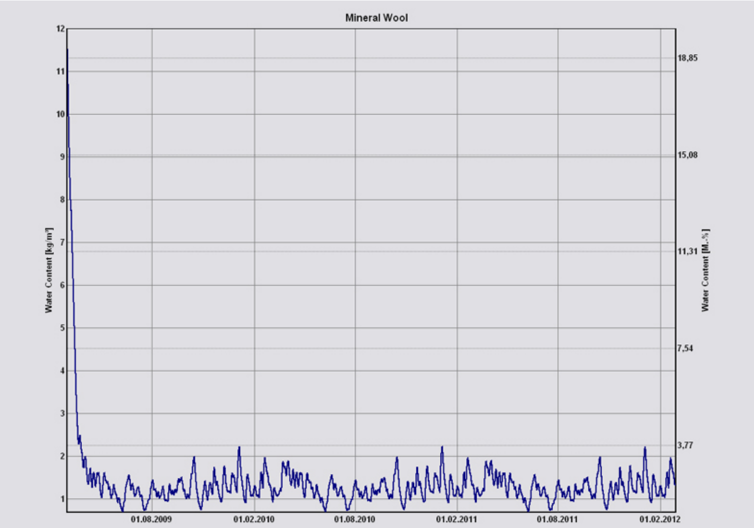


Figure 9.6

Water Content of the Mineral Wool

The content of moisture within the mineral wool insulation is usually between 0.6 kg/m³ in summer and 2.3 kg/m³ in winter.

The graph, shown in figure 9.6, illustrates the content of water within the insulation material layer and shows that the minimum moisture content is about 0.6 kg/m³ during summer and rises up to 2.3 kg/m³ during winter. Furthermore, the WUFI animation shows that the RH within the wall component stays below 100% and interstitial condensation does not occur during the calculation period of three years (refer to figure 9.7). Therefore, this thesis recommends installing mineral wool insulation batts into the existing frame cavities in combination with a ventilated air cavity of 20 mm and a vapour barrier to improve the thermal comfort of the house.

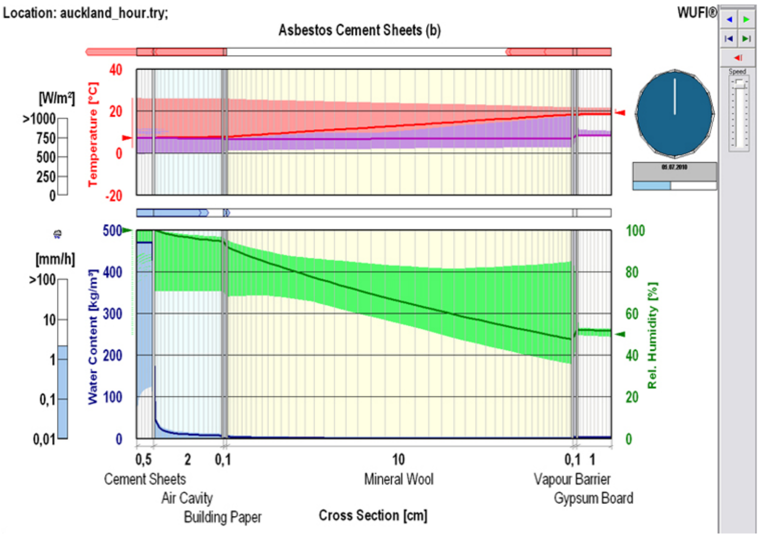


Figure 9.7

WUFI Animation

The light green area, presenting the RH within the wall component proves that 100% RH is not reached during the calculation period of three years.

9.2.3 BRICK VENEER SYSTEM (C)

Compared to the previous examples of weatherboard and asbestos cement sheet systems, brick veneer systems are not directly connected to the timber frame construction. Therefore, a brick veneer system is different from most other cladding systems that are originally used for labour state houses (refer to figure 9.1).[16] Generally, brick veneer consists of brick stones and mortar which is hard, leaves hairline cracking at head joints and has the ability to absorb rainwater. Some head joints are left open to allow rainwater that has entered the cavity behind the brick to weep through these holes and to be able to leave it again. Weep-holes should normally be found every third head joint which is commonly known as the weep-hole strategy. For example, when rainwater strikes the surface of brick veneer, the capillarity effect carries the water thought the cracked head joints but stops when the crack begins to widen at the back side. Air pressure can also support this effect as it can suck the water through the opening into the cavity that separates the brick veneer from the timber frame construction. Mostly, this air pressure is created by wind pressure, mechanical pressure in the building or even by buoyancy pressures in the brick cavity itself. However, after the water has entered the cavity it should not stay in there but unfortunately though, the water does not leave the air cavity through the weep-holes as mentioned. There is just too much mortar that is able to absorb the liquid water again and, therefore, the water has to evaporate in order to leave the air cavity through the openings of the ventilated air cavity.[17] It is necessary that the air cavity between the timber frame and brick veneer is properly sized to provide an adequate mount of air flow for moisture removal. The minimum width of a ventilated air cavity that is currently required by the New Zealand Building Code (NZBC) is about 40 mm but some New Zealand based building material suppliers such as Monier Bricks recommend a width of 50 mm.

Regarding this, it is considered that a labour state house that is built with brick veneer systems provides a better basis for upgrades then those which are built with weatherboards or asbestos cements sheets. For example, the present ventilated air cavity can also be used now to provide the air flow for moisture removal that can be caused by interstitial condensation. Nevertheless, it is necessary to undertake an inspection to ensure that the original construction is still intact before a retrofit solution can be applied (refer to figure 9.8). In order to improve the thermal comfort within the house the existing gib lining has to be removed to be able to install mineral wool insulation batts into the existing frame cavities without opening or demolishing the existing brick veneer. When the original building paper is damaged or needs to be replaced a new building paper has to be installed as well. Afterwards, a vapour barrier is installed to control the vapour movement from living spaces into the external wall envelope, covering the timber framing before finished with a new gib lining and wall paper.

[16] John Oliver, *John Oliver's Brick Book: A guide for designing and building in bricks – Second Edition*. Auckland, New Zealand: Lifetime Books, 2006, p.94.

[17] William B. Rose, *Water in buildings: an architect's guide to moisture management and mould*. Hoboken, New Jersey, USA: John Wiley & Sons, c2005, pp.126-127.

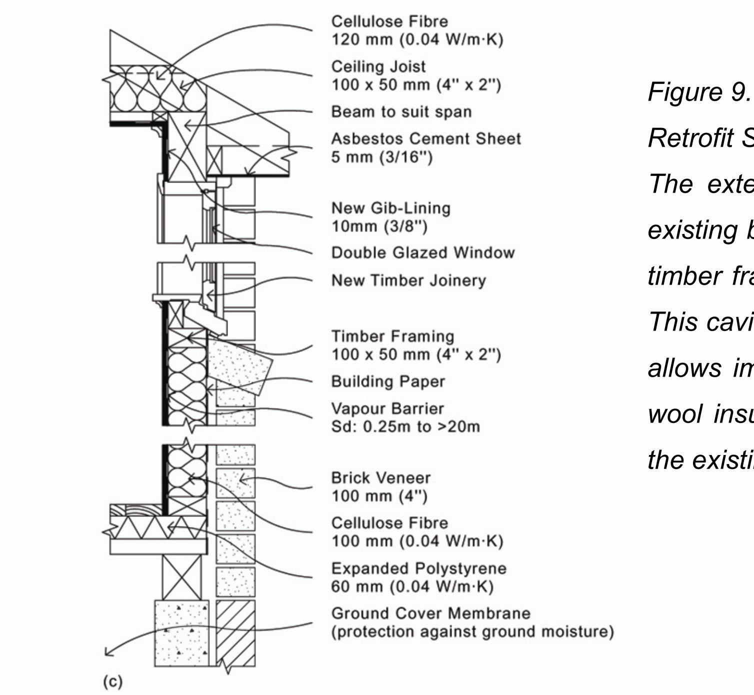


Figure 9.8

Retrofit Solution: Brick Veneer

The external wall component is covered with existing brick veneer that is separated from the timber frame by a 50 mm ventilated air cavity. This cavity in combination with a vapour barrier allows improving the construction with mineral wool insulation batts that can be installed into the existing frame cavities.

In order to determine the risk of moisture problems and to examine possible changes of the physical behaviour within the retrofitted wall component, the WUFI calculation considers the same timber frame construction as used for the previous examples of labour state houses. The difference is the combination of a ventilated air cavity and a vapour barrier that is installed underneath the new internal gib lining (refer to figure 9.9). Externally, the brick veneer system is still separated from the timber framing with a ventilated air cavity of approximately 50 mm (2''). That means that the brick veneer might lose much of its insulation ability, but it also has a significant influence on the physical behaviour of the wall assemble as mentioned before in terms of the content of water vapour.

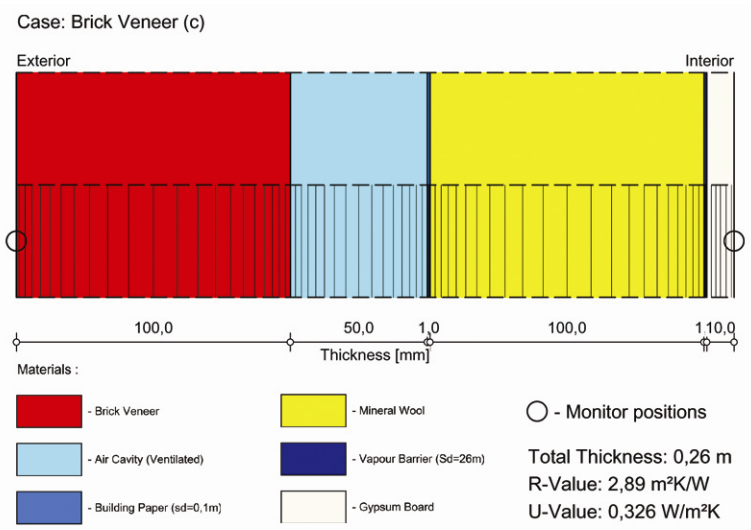


Figure 9.9

WUFI: Brick Veneer

The WUFI calculation considers a wall component that exists of a timber frame construction which is retrofitted with mineral wool insulation batts, a vapour barrier and is externally clad with brick veneer.

In this case, the WUFI simulation shows that the total water content within the wall component decreases below the initial conditions after cellulose fibre batts have been installed. That indicates that the wall component dries out before it reaches its state of equilibrium and only follows minor variations due to seasonal climatic changes (refer to figure 9.10). On this basis, it is possible to proceed with analyzing the individual material layers. If the total water content does not reach its dynamic steady state after a calculation period of three years it is necessary to extend the period until state of equilibrium has been reached. Afterwards, a definite assessment of a long-term moisture level can be given. [18]

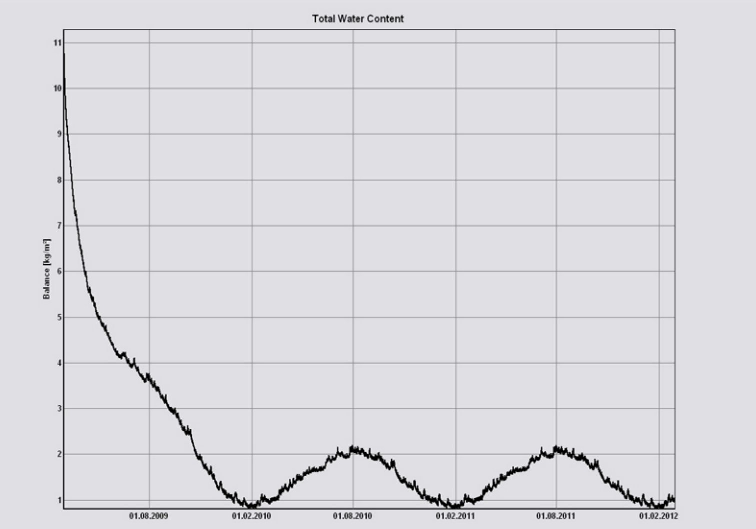


Figure 9.10
Total Water Content
The total water content decreases below the initial conditions which means that the construction dries out. Afterwards, it reaches its state of equilibrium.

The outcome in terms of the particular material layer shows that the water content within the mineral wool insulation layer increases for a short period of time by up to 1.8 kg/m³ above the initial conditions before decreasing again and finally reaching its dynamic steady state. Afterwards, the water content only follows minor variations due to seasonal climatic changes which are up to 1.3 kg/m³ during winter and 0.7 kg/m³ during summer (refer to figure 9.11). Based on these values, this retrofit solution can be recommended as the moisture levels within the wall component can be considered as "safe".

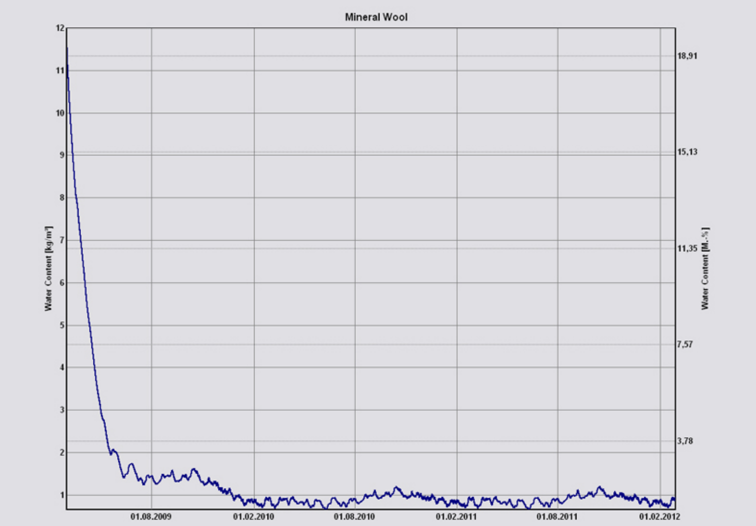


Figure 9.11
Water Content of the Mineral Wool
The content of moisture within the mineral wool insulation differs between 0.7 kg/m³ during summer and 1.3 kg/m³ during winter when it has reached its state of equilibrium.

[18] Zirkelbach, D. Schmidt, Th. Kehrer, M. Künzel, H.M. *WUFI® Pro - Manual*. Holzkirchen, Germany: Fraunhofer Institute for Building Physics (IBP), 2009, p.38.

9.3. MULTI-UNIT AND PRIVATE DEVELOPMENT HOUSES (1960'S)

During the 1960's, the medium density state houses followed the labour state house typology. Known as multi-unit housing, this typology includes the star flats, the duplex units and the multi-unit rectangular blocks that are designed in a modern style in order to be in contrast to the previous labour state houses. Generally, the construction of the duplex unit and the multi-unit rectangular block are similar and made of wood or fibrolite. The cladding options range from asbestos cement sheets, manufactured timber, stucco, concrete, plastics or weatherboard. For the assessment case, asbestos cement sheets are used for cladding as it became a common building material in New Zealand during the 1960's. [19] Compared to the multi-unit that is normally designed as a two-storey block, the flat star is build as a three-storey block and also includes larger window units than the previous labour state house typology (refer to figure 9.12). The structure of the star flat usually consists of a combination of concrete blocks and timber framing which is covered with profiled metal sheets. [20]

Generally, the multi-unit houses have the advantage to retrofit (e.g. 6) different units at once but a problem can be the typical skillion roofs. As mentioned at the beginning of this chapter, the greatest heat loss is through the roof and, therefore, ceiling insulation is highly recommended. If the ceiling space is accessible, insulation material such as polyester fibre can be fitted between and over the existing ceiling joists. If it is partially accessible, loose fill insulation such as cellulose fibre can be blown into the construction. But a closed skillion roof, usually made of one continuous piece of steel, does not offer such retrofit possibilities. In this case, it is possible to install insulation material in a suspended or dropped ceiling underneath the existing one. Alternatively, battens can be fitted under the existing ceiling and the insulation material will be placed between these before covered with a vapour barrier and a new ceiling lining. These two options can improve the thermal comfort but are relatively expensive and the performance is limited by the thickness of the insulation material that can be installed. Therefore, the best and most cost-effective solution is to upgrade the level of insulation when the interior linings or the external cladding material of the skillion roof has to be replaced. [21] This will give the advantage to maximise the level of insulation within the skillion roof construction and to ensure the optimum protection for the insulation against moisture from outside. But when the existing construction is not deep enough for the required thickness of insulation it might be necessary to install an extra frame on the outside. This can

[19] Verney Ryan, 2008, p.8.
[20] Refer to chapter 6, pp.73-75.
[21] Level. *Insulation: Insulation Options for Existing Homes*. Level - BRANZ Ltd, Porirua, New Zealand, Retrieved January 30, 2009 from the World Wide Web: http://www.level.org.nz/passive-design/insulation/insulation-options-for-existing-homes.

be a disadvantage as it leads to a change of the building appearance and might need a building authority approval.

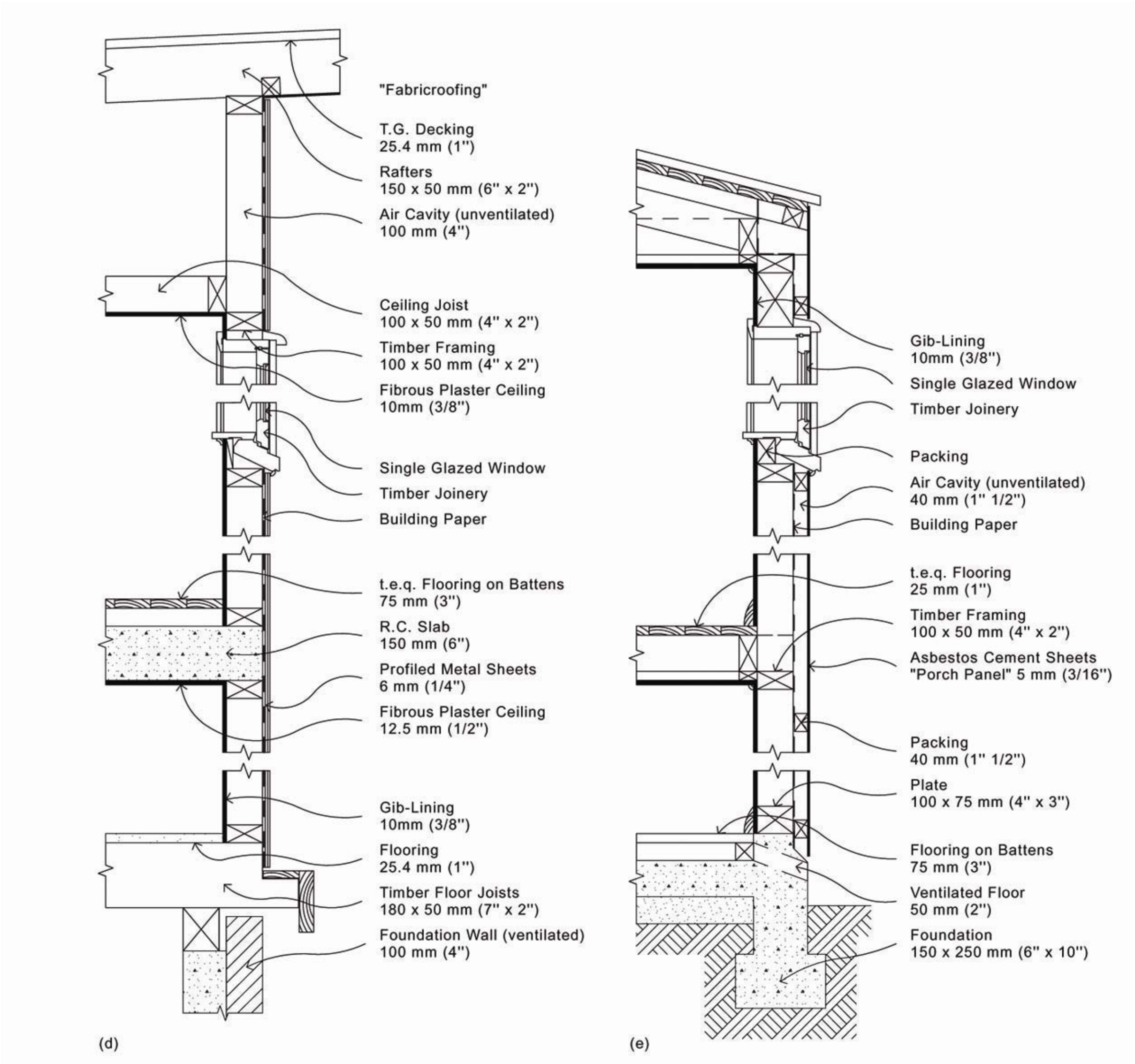


Figure 9.12

External Wall of the Star Flat and Multi-Unit

The existing external wall construction of the star flat (d) partly covered with profile metal sheets. The multi-unit (e) including the duplex unit and multi-unit rectangular block covered with asbestos cement sheets on timber framing as shown above, or made of fibrolite.

The following retrofit solutions are developed for two typical medium density state houses: the star flat (d) and the multi-unit (e). Both constructions consider an existing standard construction support wall that is designed as a 100 mm (4'') timber frame wall and covered with 10 mm (3/8'') gib lining internally. Externally, the timber frame of the star flat is covered with a profiled metal sheet cladding system while the multi-unit which is covered with an asbestos cement sheet cladding system. Furthermore, both star flat and multi-unit house constructions do not have insulation material within the wall component as it was still not required to insulate such residential buildings till 1978. [22] Regarding the problem of missing material information by New Zealand building material suppliers, this thesis is using data that are published in *Bautabellen für Architekten - mit Entwurfshinweisen und Beispielen* (English: Building Spreadsheets for Architects - with plan details and examples) by Klaus J. Schneider in 2004 (refer to table 9.1). [23]

Type	Building Material	d [m]	λ [W / (m * K)]	μ	Notice
(d)	Profiled Metal Sheets	0.006	160	*	Refer to Schneider, K.J. Table 10.26

** The diffusion resistance coefficient is not given as the metal is vapour proof*

Table 9.1
Physical Values of similar Profiled Metal Sheets (d)

9.3.1 PROFILED METAL SHEET CLADDING SYSTEM (d)

The existing star flat construction offers a high level of thermal mass combined with large single glazed windows. These windows can guarantee high solar gain but acting as a thermal bridge as well which leads to unacceptable indoor temperatures during winter. This problem can be addressed by replacing these single glazed windows with double glazed windows with timber frames and aluminium protective profiles on the outside. Additional shading devices can prevent that blinds might be closed during the day and to reduce the problem of overheating. The construction of the ground floor is originally designed as a timber construction which is ventilated and partially accessible from the outside. That allows retrofitting the ventilated underfloor space with 60 mm of expanded polystyrene (EPS). [24]

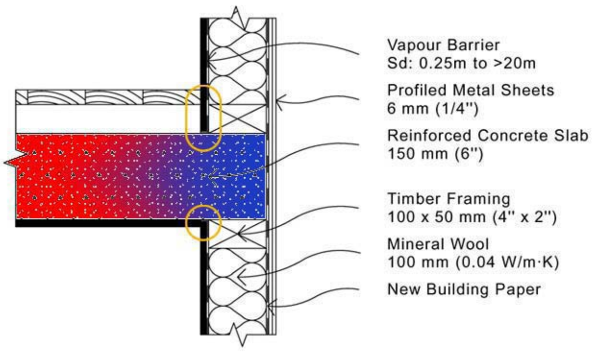


Figure 9.13
Thermal Bridging
Mineral wool insulation batts installed into the existing wall cavities can lead to condensation problems (yellow circles).

Compared to the construction of the ground floor, the ceiling construction is originally designed as a 150 mm (6’’) reinforced concrete (R.C.) slab with fibrous plaster underneath

[22] Clemens Richarz, Christina Schulz, Friedmann Zeitler, *Detail Practice: Energy-Efficiency Upgrades - Principles, Details and Examples*. Basel, Switzerland: Birkhäuser, 2007, p.28.
[23] Refer to chapter 7, p.88.
[24] Refer to chapter 7, p.92.

and flooring on battens above. It is obvious that the R.C. slab provides a thermal bridge from the inside to the outside which makes it difficult to keep the internal temperature on an acceptable level during winter (refer to figure 9.13). Regarding this problem of thermal bridging, it is not recommended to install mineral wool insulation batts within the existing wall cavities as this improvement will not minimise the thermal heat loss due existing thermal bridges and, much more important, will encourage condensation problems. In order to improve the thermal comfort inside the house and to insulate the reinforced concrete slab to avoid thermal bridging it is necessary to create a new thermal insulation layer on the external surface of the existing wall component. Therefore, this thesis recommends removing the entire profiled metal sheets to be able to construct a new layer of EPS insulation (60 mm) placed between vertical battens (80 mm). In this case, EPS insulation is chosen for its high flexural strength to weight ratio and proven dimensional stability as the external wall construction of the star flat is usually three-storey high. Furthermore, the ventilated air cavity between the battens (20 mm) separates the new insulation layer from the replaced profiled metal sheets and allows an air flow for moisture removal (refer to figure 9.14).

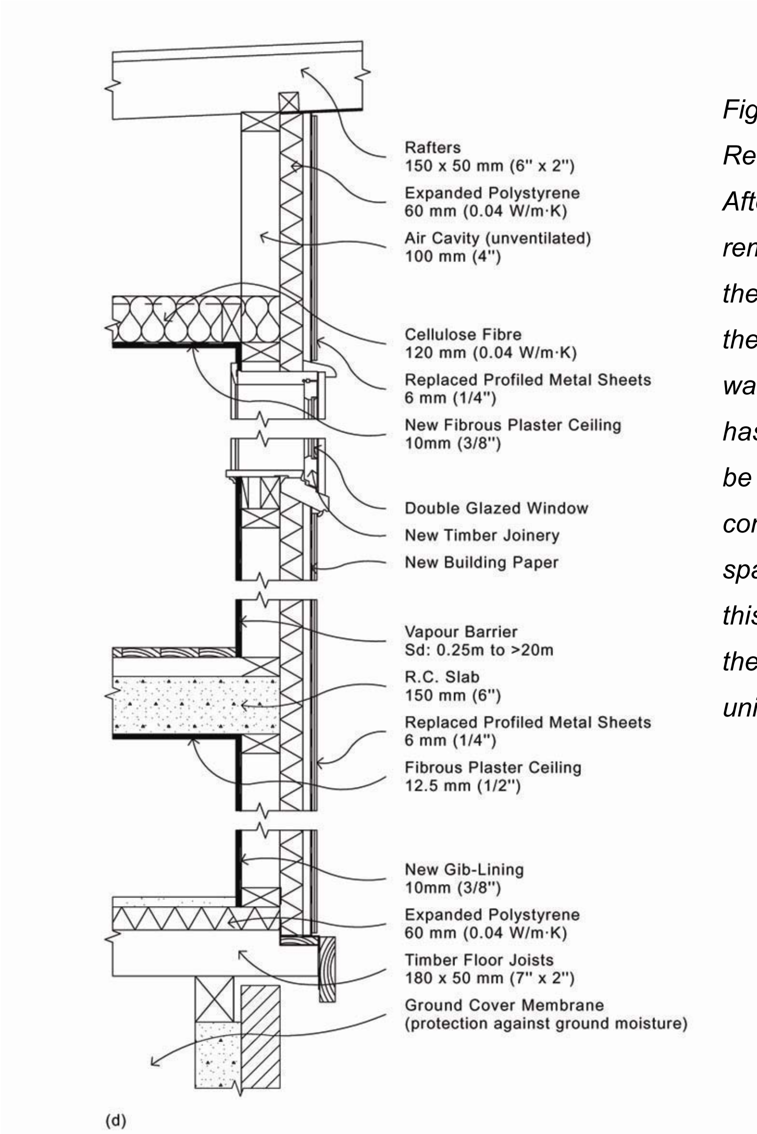


Figure 9.14

Retrofit Solution: Star Flat

After the profiled metal sheets have been removed, it is possible to install EPS on the external surface to improve the thermal insulation layer of the existing wall component. The existing gib-lining has been replaced by a new gib-lining to be able to install a vapour barrier. In combination with roof and under floor space insulation, as well as ventilation this retrofit solution allows to control the thermal energy loss due to the uninsulated reinforced concrete slab.

Regarding the WUFI calculation, this retrofit solution will lead to an R-value of 2.2 m²·K/W for the external wall component which meets the minimum requirements for thermal resistance values for climate zone one, two and three (refer to table 7.11). [25] Furthermore, the calculation proves that the component is able to reach its state of equilibrium and only repeats minor variations due to seasonal climatic changes within the different material layers (refer to figure 9.15). Therefore, this thesis suggests that this retrofit solution in combination with roof and underfloor space insulation, as well as new double gazed windows with thermal break joinery can highly improve the thermal comfort and IAQ.

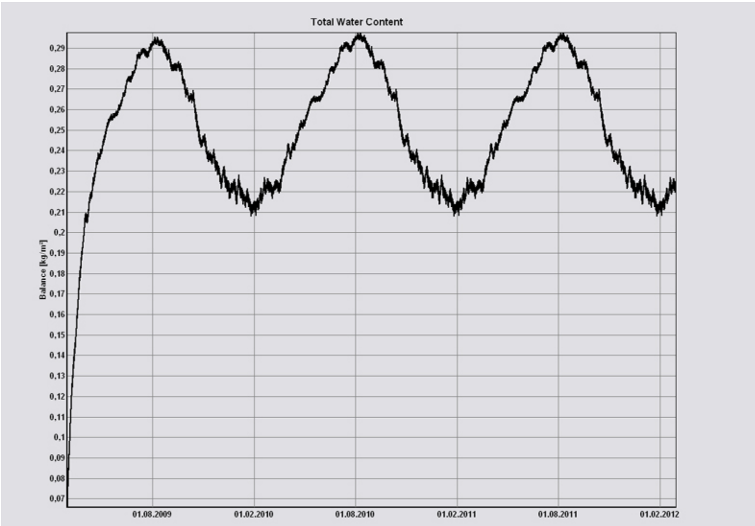


Figure 9.15
Total Water Content
The wall component reaches its state of equilibrium after the total water content remains constant over the years and only repeats minor variations related to seasonal climatic changes.

9.3.2 ASBESTOS CEMENT SHEET CLADDING SYSTEM (e)

Compared to the star flat, the multi-unit is usually designed with an uninsulated R.C. slab which cannot be insulated underneath due to the lack of a floor access. On the top of the R.C. slab is timber flooring on 50 mm battens with small openings to the outside to provide ventilation underneath. The existing 40 mm horizontal air cavity separates the asbestos cement sheets and the timber framing but it does not have the same affect on the wall component as a vertically ventilated air cavity. In this case, the cavity cannot provide a constant air flow that is necessary for moisture removal and, therefore, cannot lower the risk of interstitial condensation problems within the building component. Due to conditions, this example of a multi-unit can be considered as a possible demolition case. However, if the asbestos cladding material is not damaged and, therefore, an asbestos decontamination is not necessary it may be possible to introduce an affordable retrofit solution. In this case, a retrofit solution has to be developed for an existing multi-unit construction that consists of a timber framing wall that is externally covered with 5 mm asbestos cement sheets on 40 mm battens and internally lined with gib board and finished with wall paper (refer to figure 9.12).

[25] Refer to chapter 7, p.91.

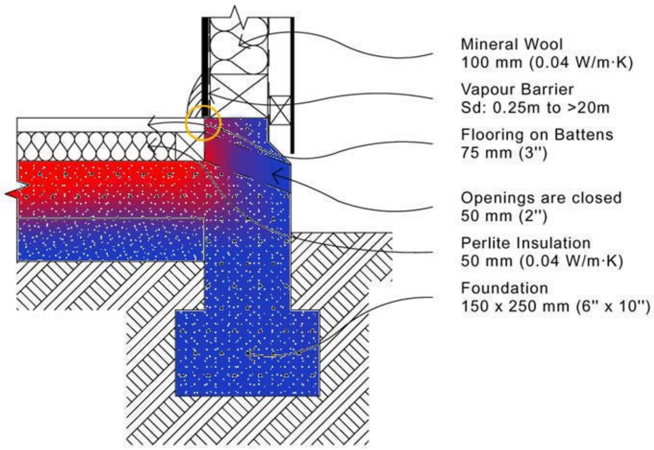


Figure 9.16
Thermal Bridging
Mineral wool insulation batts installed within the existing wall cavities can lead to condensation problems at the corners of the timber floor (yellow circles) due to the uninsulated R.C. slab.

In order to insulate the existing timber floor it is possible to blow loose fill perlite insulation into the 50 mm cavity underneath the timber flooring. Perlite is an inert volcanic glass material that is expanded by a special heat process. The resultant lightweight insulation material is a white granular that is inorganic and, therefore, mould, rot, and vermin resistant. For underfloor insulation, it is recommended to use a water repellent, dust suppressed perlite which is specially produced for this purpose (λ = 0.04 W/(m·K)). Furthermore, this insulation material can be filled into the underfloor space through openings without removing the entire exiting timber floor as it provides flow ability. [26] This new thermal insulation layer of 50 mm height is able to provide an R-value of approximately 1.4 m²·K/W. Of course, this R-value does not meet the current thermal insulation requirements of the New Zealand Building Code (NZBC) for solid constructions but it will already improve the thermal comfort of the existing house (refer to figure 7.11).

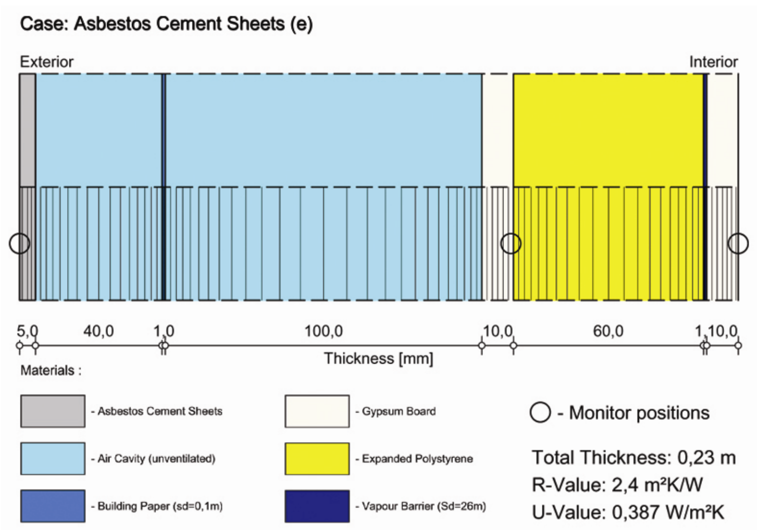
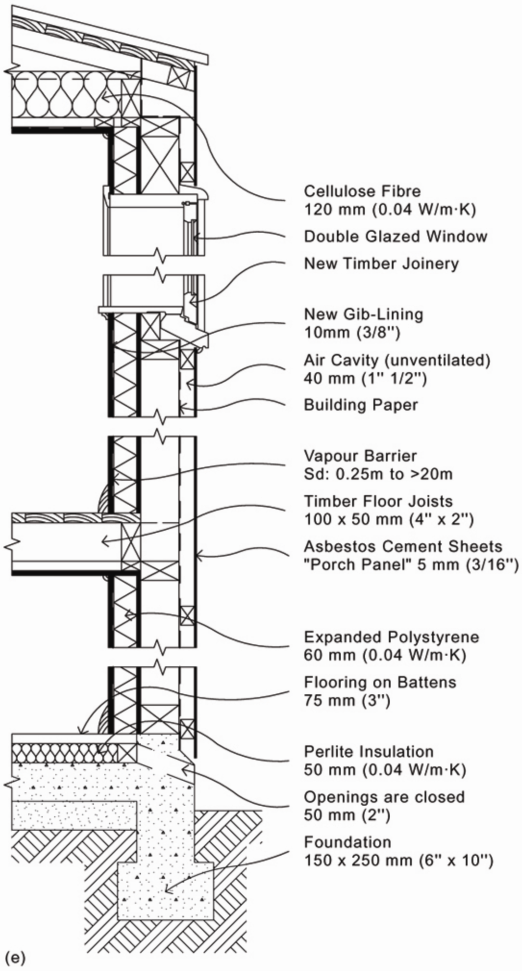


Figure 9.17
WUFI: Asbestos Cement Sheets
The WUFI calculation proves that the retrofit solution does not lead to moisture problems within the wall component. The result shows an R-value of 2.4 m²·K/W which will meet the thermal insulation requirements of the NZBC.

[26] Industrial Processors Ltd. (INPRO). *Insulation Material: Perlite*. Perlite Institute, Auckland, New Zealand, Retrieved April 20, 2009 from the World Wide Web: http://www.perlite.co.nz/loose-fill-insulation.htm.

In order to insulate the timber fame wall it may be possible to install mineral wool insulation batts into the exiting timber frame cavities but such improvement will not lead to the best results. A thermal bridge will be present as the uninsulated R.C. slab provides an increased heat transmission underneath the uninsulated timber plate and therefore, a thermal bridge which can lead to condensation problems (refer to figure 9.16). Generally, the most frequent parts with thermal bridges are the foundations, ring beams, lintels, parapets and reinforced concrete pillars as well as window sills. It is necessary to prevent the development of such thermal bridges in order to avoid condensation, surface damages or active mould growth. Regarding the thermal bridge between the timber plate and the uninsulated R.C. slab it is recommend covering the existing fibrous plaster with a new 60 mm layer of EPS insulation between battens in combination with a vapour barrier (refer to figure 9.18). Regarding the WUFI calculation, such improvement in combination with roof space insulation with cellulose fibre, as well as underfloor space insulation with perlite will improve the thermal comfort within the house (refer to figure 9.17).



(e)

Figure 9.18

Retrofit Solution: Multi-Unit

Internally, the existing gib-lining of the external wall component is covered with a new 60 mm layer of EPS between 60 mm battens which is covered with a vapour barrier and finished with new gib-lining. This retrofit solution can avoid thermal bridges between the timber plate and the uninsulated reinforced concrete slab.

9.4. PRE-INSULATION HOUSES (1970 - 1978)

The next building typology considers residential buildings that can be identified as pre-insulation houses and were built in a large scale across the country. This typology consists of several new housing styles and forms of the 1970's, such as rectangular style, split levels and flat roofs. [27] Most of these houses are private low cost developments in less affluent areas and there is not much interest in upgrading these homes. Built before thermal insulation was required by the NZBC, these homes are often constructed with a skillion roof and mostly designed as single homes with a garage underneath. Such design can lead to difficulties in terms of a missing attic space to install thermal insulation. [28] A suspended or dropped ceiling underneath the existing ceiling in combination with insulation can be an alternative solution but may not provide the best results. Therefore, it is recommended to upgrade the insulation level when the external cladding material of the skillion roof has to be replaced to install an extra frame on the outside in order to maximise the level of insulation.

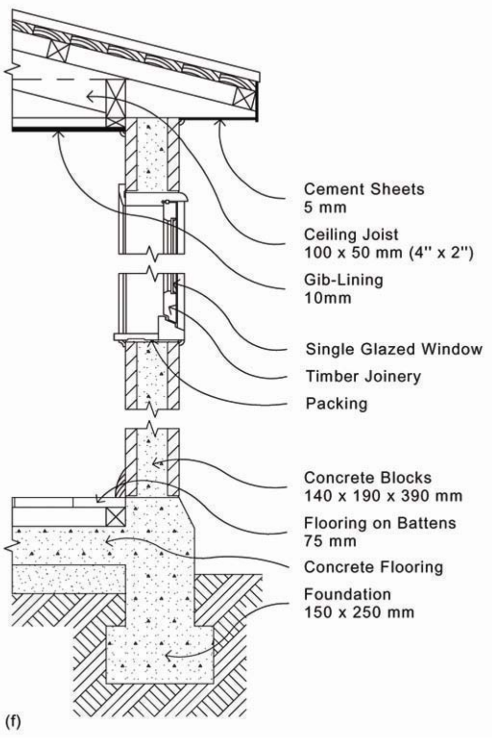


Figure 9.19

External Wall of the Rectangular Style House

The external wall construction of the rectangular style house was built with concrete blocks and timber frame construction. Other private developments also include split level and flat roof constructions during the pre-insulation period.

9.4.1 CONCRETE BLOCK WORKS (F)

The example of a pre-insulation rectangular house shows an external wall construction which is made of concrete blocks. The rectangular house is designed with a typical lowered angled pitch roof, covered with concrete tiles and an uninsulated reinforced concrete floor that is not accessible from the outside (refer to figure 9.19). The existing building structure consists of concrete blocks fair faced to the internal and painted with weather coating to the external.

[27] Refer to chapter 6, pp.75-76.
[28] Verney Ryan, 2008, p.8.

Furthermore, the concrete block wall is solid filled with grout and expansive additive which includes reinforced bars. The ceiling is covered with gib board underneath the roof joists. In order to perform the WUFI calculation, it is necessary to know the physical values of the concrete blocks which are currently not available from New Zealand building material suppliers. Therefore, this gap of information is closed with suitable values of a similar building product that are published again in *Bautabellen für Architekten - mit Entwurfshinweisen und Beispielen* (English: Building Spreadsheets for Architects - with plan details and examples) by Klaus J. Schneider in 2004 (refer to table 9.2). [29]

Type	Building Material	d [m]	λ [W / (m * K)]	μ	Notice
(f)	Weather Coating	0.001	-	2700	http://www.einza.com "Wetterschicht"
	Concrete Blocks	0.140	0,7	150	Refer to Schneider, K.J. Table 10.19

Table 9.2
Physical Values of similar Concrete Blocks and Weather Coating (f)

The WUFI calculation of the existing wall indicates an R-value about 0.2 m²·K/W which is significantly low and not acceptable, considering that the NZS 4218:2004 requires an R-value for masonry that differs between 0.8 and 1.2 m²·K/W and is specified over the climate zones one, two and three. The calculation period shows that the water content increases over several years (refer to figure 9.20). An explanation can be that the WUFI calculation uses low initial water content and is trying to reach its normal and harmless water content. But in this case, the thesis assumes that the construction may have a design flaw that allows accumulating unacceptable water content. [30] By using a longer calculation period of 6 years the calculation is able to determine that the state of equilibrium will be reached at a moisture level of approximately 7.0 kg/m² during winter und 6.6 kg/m² during summer.

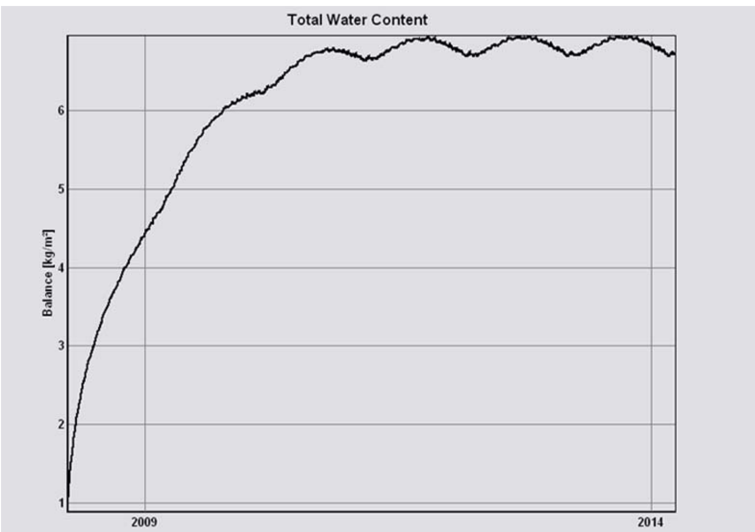


Figure 9.20
Total Water Content
The existing wall component reaches its state of equilibrium after the total water content increases over several years. Afterwards it remains constant and only repeats minor variations.

[29] Refer to chapter 7, p.88.
[30] D. Zirkelbach, Th. Schmidt, M. Kehrer, H.M. Künzel, 2009, p.38.

The intake of such high amount of moisture can reduce the insulation efficiency of the concrete blocks which can also become susceptible to frost damages, especially in regions of New Zealand's South Island. [31] Therefore, this thesis highly recommends considering an upgrade to improve the house performance.

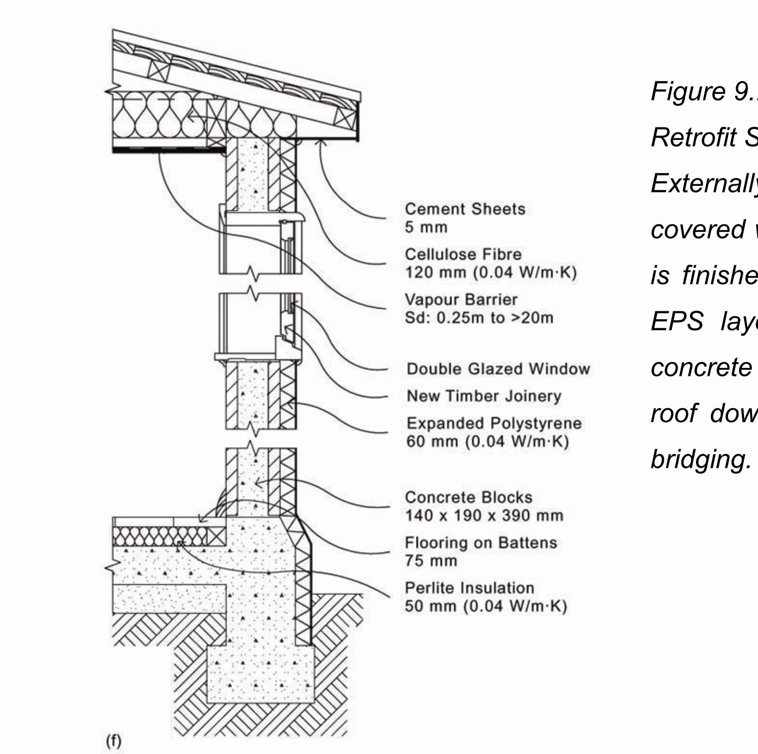


Figure 9.21
Retrofit Solution: Pre-Insulation House
Externally, the existing concrete blocks are covered with a new 40 mm layer of EPS which is finished with an acrylic stucco plaster. The EPS layer spans on the outer layer of the concrete blocks, spanning from underneath the roof down to the foundation to avoid thermal bridging.

Normally, it is possible to create an insulation layer on the internal face of the concrete blocks but that will lead to the loss of the thermal storage benefits. In order to make usage of the thermal storage capability of the solid wall and to improve the thermal comfort within the house the insulation layer will be constructed on the exterior face of the concrete blocks. The insulation layer, made of 40 mm of EPS will be finished with an acrylic stucco plaster to protect it from the outside and to provide an acceptable R-value of 1.2 m²·K/W. [32] In order to insulate the underfloor space, it is also advisable to introduce the same solution as recommended for the multi-unit house. Perlite can be blown into the existing cavities forming a thermal insulation layer of approx 50 mm to achieve an R-value of 1.4 m²·K/W. These solutions in combination with afore mentioned roof or ceiling space insulation will improve the thermal comfort within the pre-insulation house example (refer to figure 9.21).

[31] Refer to chapter 3, p.35.
[32] Firth Industries. *Masonry Insulation Solutions Brochure*. Auckland, New Zealand: National Support Office, July, 2008.

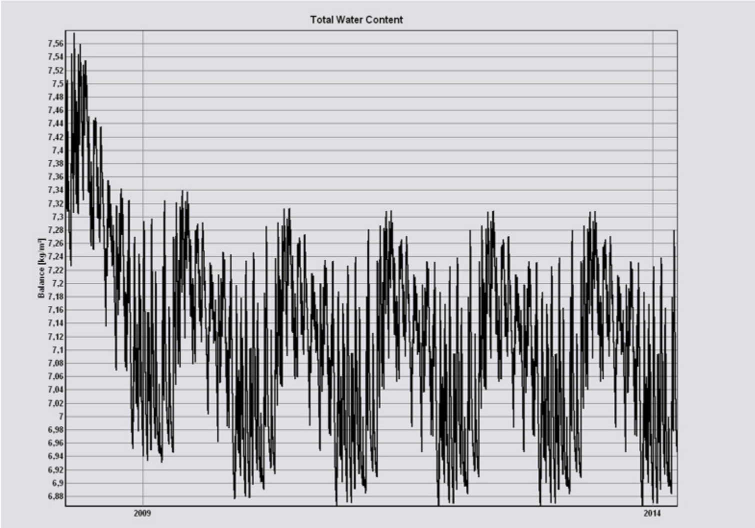


Figure 9.22
Total Water Content
The retrofitted wall component reaches its state of equilibrium after the total water content increases over a short period of time during the calculation period before it remains constant and only repeats minor variations.

The WUFI calculation of the retrofitted wall component shows that the total moisture content decreases after the retrofit solution is applied. That indicates that the wall component is able to dry out before it reaches its state of equilibrium and only repeats minor variations due to seasonal climatic changes again (refer to figure 9.22). This outcome allows proceeding with analyzing the outcomes of the individual material layers. According to these results and the improved and acceptable R-value about 1.2 m²·K/W (refer to figure 9.23), this thesis assumes that moisture problems within the wall component will not occur and the retrofit package for the pre-insulation house can be considered as “safe” and recommended.

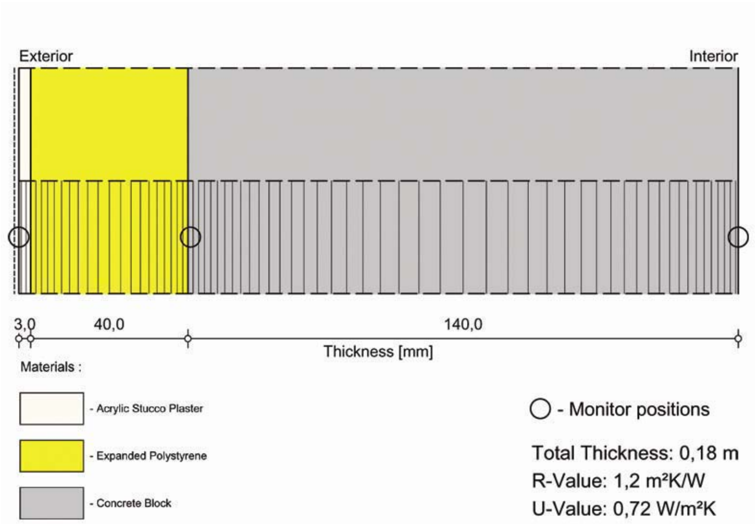


Figure 9.23
WUFI: Concrete Blocks
The WUFI calculation proves that the retrofit solution does not lead to moisture problems within the wall component. The result shows an R-value of 1.2 m²·K/W which will meet the thermal insulation requirements of the NZBC.

9.5. POST-INSULATION HOUSES (1978 - 1989)

After 1978, the period of post-insulation houses began by the introduction of the mandatory insulation practice. This practice applied nationally and required minimum insulation level for roofing (R 1.9), flooring (R 0.9) and external wall (R 1.5) constructions (refer to table 9.3). As mentioned before, the post-insulation period covers different types and styles of residential buildings which include e.g. private single house developments, as well as state house developments, known as cluster developments. [33] Generally, these houses can vary in design, form and planning and make it difficult to develop guidelines for retrofitting. However, in order to meet the insulation requirements of the NZBC in 1978, these houses are already insulated with insulation material within the external wall component. Furthermore, a limited number of these houses are constructed with double glazed window units, compared to the majority which are still designed with single glazed windows and aluminium frames. These aluminium frames provide a high level of draught proofing on the one site but also do not have thermal breaks on the other. Therefore, the aluminum frames causing heat loss through thermal bridging which means that valuable thermal energy generated in winter can be lost.

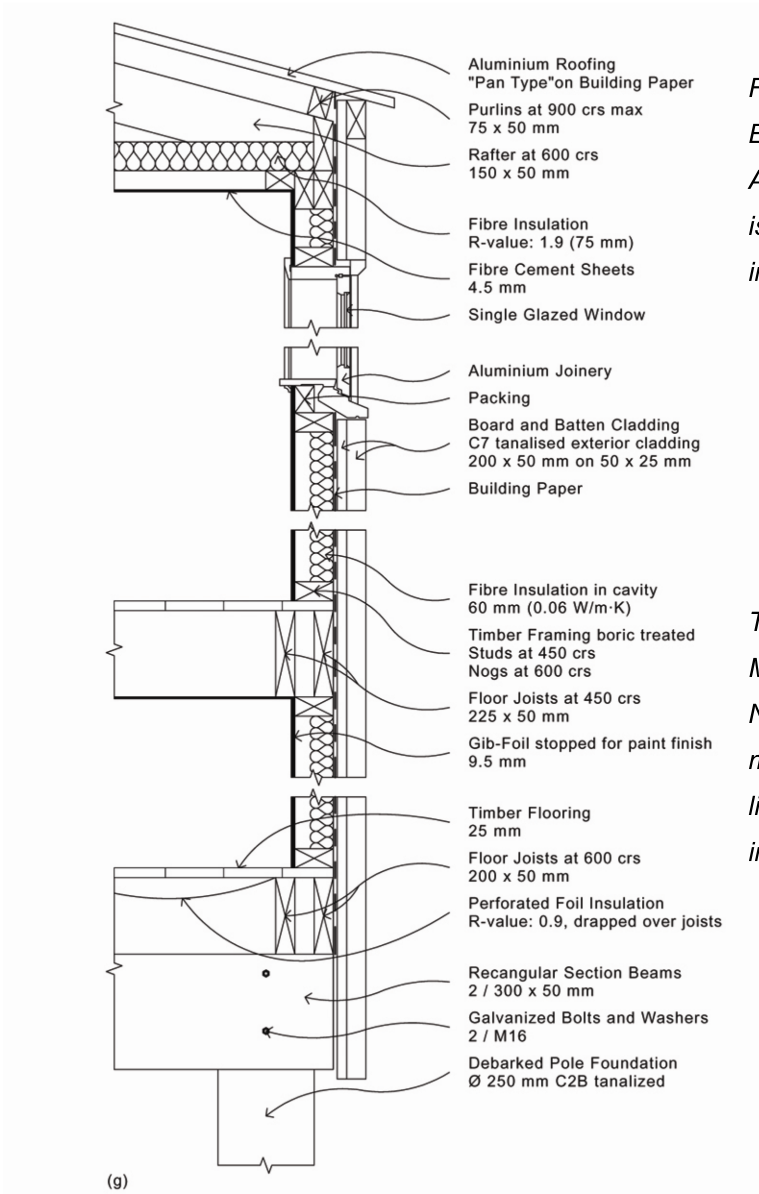


Figure 9.24
External Wall of a Private Development
A two storey high private development is taken as an example of the post-insulation period.

Table 9.3
Minimum R-value for Construction
New Zealand Building Code (NZBC) minimum insulation requirements for light timber frame houses, introduced in 1978 (Post-Insulation Period).

Minimum thermal resistance value for construction	
Component	R-Value
	m²•K/W
Roof	1.9
Wall	1.5
Floor	0.9

[33] Refer to chapter 6.pp.77-78.

9.5.1 POST-INSULATION WALL CONSTRUCTION (G)

The following example of a wall component does not address the infill housing development which was introduced by the government in 1986 and is considered as a demolition case in this thesis. Because of its low quality in terms of design and construction, as well as internal layout, any performance improvements would not be efficient in terms of cost benefits. [34] Nevertheless, the two storey high private development that is explored below was built during the post-insulation period (refer to figure 9.24). Compared to the infill housing development, the layout and design of this residential building is of higher quality and therefore, a retrofit package is considered to be efficient. Located within climate zone 2, it had to meet the minimum thermal insulation requirements of this zone as stated by the NZBC for light timber frame houses. Therefore, this construction is the only example among different building typologies that contains insulation material within the building envelope.

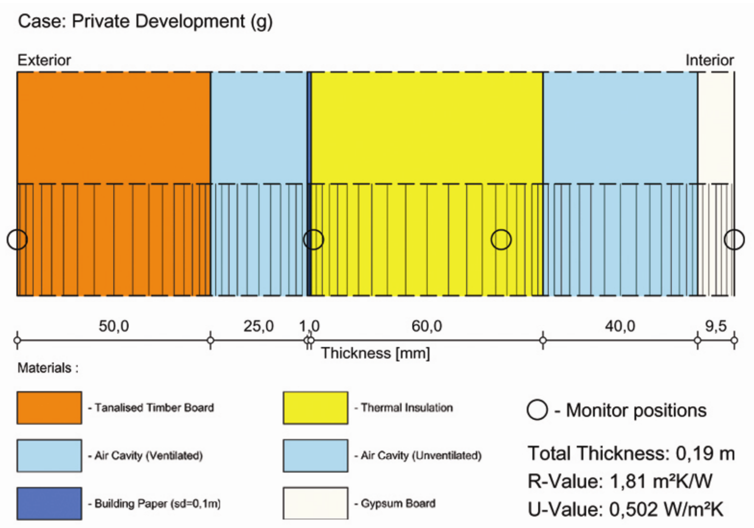


Figure 9.25
WUFI: Private Development
The WUFI calculation of the existing wall component indicates the current R-value. It shows that an upgrade might not be as urgent as for the previous examples but to meet new insulation standards of nowadays it is recommended to upgrade this building component.

The existing external wall construction is made of 9.5 mm gib-foil and finished with paint. According to Thomas van Raamsdonk, Technical Director of Pro Clima New Zealand, gib-foil was introduced during the post-insulation period to control the vapour movement from living spaces into the external wall envelope. This indicates that the problem of vapour movement was identified although the answer was not correct as gib-foil does not allow moisture evaporation toward inside in summer. Therefore, the build-in moisture within the wall construction is held and can leads to construction damages and mould which is usually out of sight. [35] Because of that, New Zealand building manufactures and suppliers stopped to produce and to sell gib-foil in the 1990's. Externally, the existing wall construction is covered with tanalised timber board cladding that is separated from the timber framing by a 25 mm ventilated air cavity. This cavity can help to keep the moisture content within the wall

[34] Refer to chapter 6.pp.77-78.
[35] Thomas van Raamsdonk, "Vapour Control Layer" Office Communication, 20th May 2009.

component under control but might also reduce much of the insulation ability of the timber board. Beside this, the wall component also includes 60 mm of thermal insulation that is placed within the air cavities of the timber framing (refer to figure 9.25). The existing floor is insulated with a perforated insulation foil that is able to reflect thermal heat back into the house. Furthermore, the underfloor space is accessible from the outside which can be important as it may reduce the costs and time to install a retrofit solution. The roof space is insulated with 75 mm of thermal insulation material that is placed between the purlins and covered with aluminium roofing on building paper.

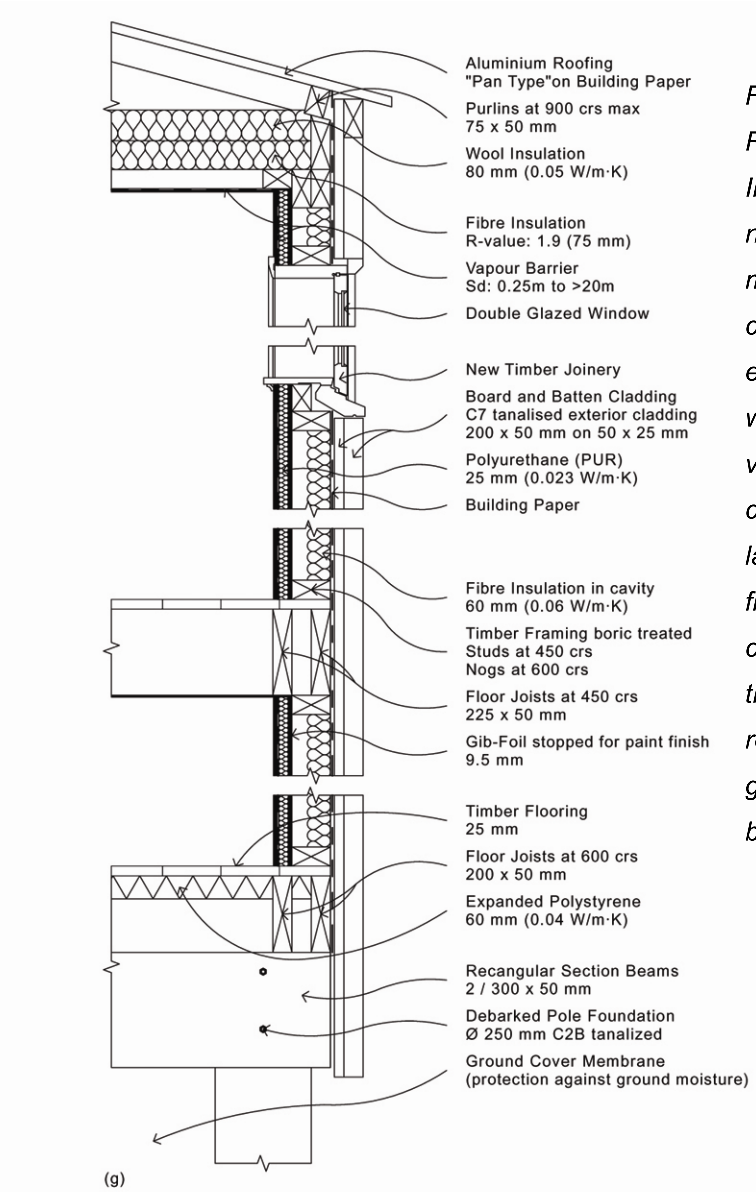


Figure 9.26

Retrofit Solution: Post-Insulation House

Internally, the wall is covered with a new layer of polyurethane insulation material and a vapour barrier that is combined. The insulation of the existing ceiling is combined with new wool blankets and covered with a vapour barrier underneath. The floor construction is insulated with a new layer of EPS insulation between the floor joists to improve the thermal comfort within the house. Furthermore, the existing single glazed windows are replaced with timber framed double glazed windows to avoid thermal bridging.

The current R-value of the roof is approximately about 1.9 m²·K/W. In order to improve this R-value and to meet the current insulation requirements of the NZBC it is recommend installing additional wool insulation blankets within the ceiling space in combination with a vapour barrier underneath the insulation layer (refer to figure 9.26). Wool insulation is made of natural recycled sheep wool that can be an alternative to synthetic materials as it does not include synthetic fibres. At the end of its lifetime, wool insulation material can be recycled and therefore, has a low impact on the environment. The introduced wool insulation blankets are blended with polymer and treated with natural boron salt to increase the natural fire resistance as well as to provide a vermin, mould and insect resistance. [36] The floor is upgraded with 60 mm of EPS insulation material. This insulation material can be installed due to the partly accessible underfloor space that allows installing EPS between the existing floor joists. Furthermore, the ground underneath the floor construction is covered with a ground cover membrane that can permanently protect the timber floor construction against possible ground moisture.

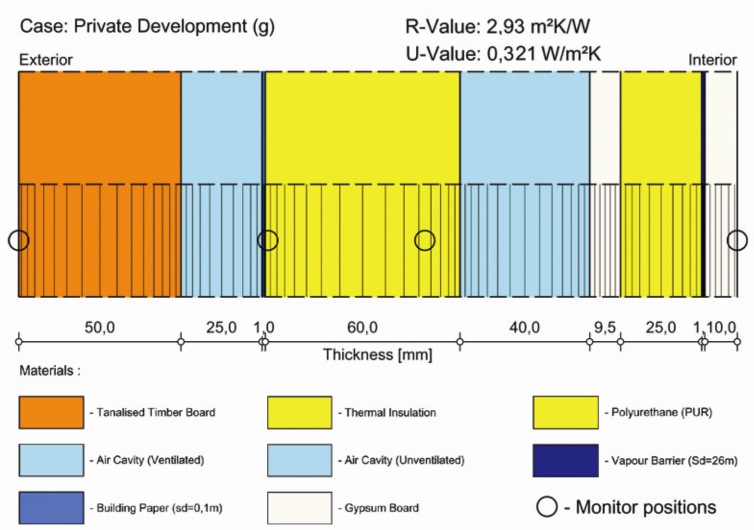


Figure 9.27
WUFI: Private Development
The WUFI calculation of the retrofitted external wall shows an R-value of 2.9 m²·K/W which will meet the thermal insulation requirements of the NZBC.

The WUFI calculation of the existing external wall component shows that it meets the requirements of the post-insulation period (1.5 m²·K/W) but it does not meet the requirements of the NZBC today (refer to figure 9.24). Therefore, a new insulation layer of polyurethane (PUR) between battens in combination with a vapour barrier is installed on the internal surface of the existing wall component. PUR insulation board is made of a rigid polyurethane foam core that is covered on both sides with a bright and multi-layered complex of kraft and metal foil. Compared to glass or cellulose fibre, PUR offers the possibility to create a thermal insulation layer of only 25 mm that can improve the existing R-value by up to 1.1 m²·K/W due to its low k-value (λ = 0.023 W/m·K). Covered with a new gib lining, this retrofit solution for the external wall component can finally provide an R-value of approximately 2.9 m²·K/W (refer to figure 9.27). Furthermore, the WUFI calculation of the retrofitted wall construction shows that the component is able to reach its state of equilibrium after a short period of time before it starts to repeat only minor variations due to seasonal climatic changes (refer to

[36] Latitude - Natural Wool Insulation. *Thermal and Acoustic Insulation Products*. Christchurch, New Zealand, Retrieved April 27, 2009 from the World Wide Web: http://www.latitudeinsulation.com.

figure 9.28). Also the analysis of the individual material layers does not indicate the risk of moisture problems and therefore, this solution can be recommended as a possible retrofit package for this example of a private development.

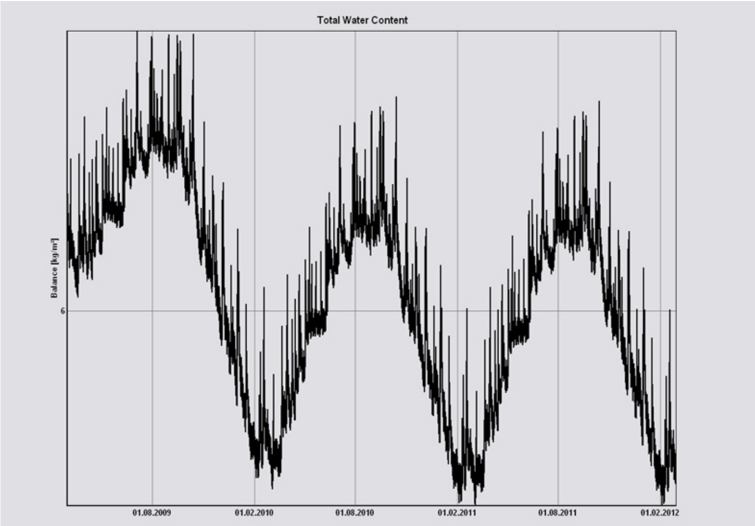


Figure 9.28
Total Water Content
The total water content of the retrofitted wall component reaches its state of equilibrium after a short period of time and repeats only minor variations that are related to the seasonal climate afterwards.

After different retrofit packages for New Zealand house typologies have been developed and presented now, the challenge will be to motivate landlords and homeowners to take up the opportunities for retrofit through incentives. That includes recognising the value of benefits of an improved living environment and health benefits which can be associated with sustainable features in homes. [37] Therefore, it is also necessary that the New Zealand government is pushing forward the introduction of a mandatory rating system for new as well as existing residential buildings. That will help homeowners to link the value of improvements to their property. Furthermore, it will make the house performance visible to potential homebuyers or tenants when their property assets are sold or rented out.

[37] New Zealand Business Council for Sustainable Development (NZBCSD), A-2008, p.35.

10. CONCLUSION

10.1. NEW ZEALAND'S DAMP HOUSING PROBLEM

New Zealand's existing housing stock consists of approximately 1.6 million homes. These can be categorised into a large number of different house typologies with different housing conditions. More than 20,000 new homes are built every year which have the potential to perform well, while more than one million of the existing homes perform poorly in terms of both energy usage and indoor air quality. In simple words, the average New Zealand house is cold, poorly insulated, has single-glazed windows and is hard to heat which describes what is known as damp housing. Regarding this, a literature review illustrates that dampness problems in homes have a negative affect on occupants' health. Furthermore, high indoor humidity levels combined with indoor air exposure and low ventilation rates present a risk factor for asthma and allergic symptoms. Considering this problem, along with the fact that New Zealand has the second highest rate of asthma in the world, it is necessary to inform New Zealand's population about the risk factors for mould growth and dampness in their homes in order to change their attitudes towards improving their home's performance.

10.1.1 THE RISK OF INTERSTITIAL CONDENSATION

A number of risk factors for mould and indoor pollutant levels can be reduced by a range of possible retrofit solutions but this thesis also shows that there is a lack of information on the quality and success of such solutions in New Zealand. Also possible "changes" in terms of building physics produced by insulation improvements in retrofitted building components do not always seem to be clear to building suppliers and designers. The current practice of retrofitting different house typologies, built between the 1950's and 1980's, proves that retrofitted insulation improves the R-value on the one hand but it also shifts the dew point within a wall component on the other. Without a ventilated air cavity and vapour control layer, this will eventually lead to interstitial condensation and moisture problems that can support mould growth within a wall component leading to a low comfort level. However, vapour movement and airtightness is still not of concern in the New Zealand Building Code which requires that all new homes throughout New Zealand have to meet new thermal insulation requirements since October 2008. These requirements will lead to warmer homes however these will also cause new mould problems that are not visible on walls and ceilings but hidden within the wall components. Regarding this, this research concludes that the complex relationships between vapour movement and interstitial condensation need further clarification and proposes different retrofit packages.

As a possible solution to determine the risk of interstitial condensation within retrofitted external walls, this thesis introduces the Glaser-method as a general tool as well as the WUFI software as a realistic simulation tool of hygric processes in particular retrofitted building components. Compared to the WUFI software, this thesis indicates that the Glaser-method cannot give enough evidence to indicate if a retrofitted wall component can be considered as "safe" but it can be used to provide a general assessment of the hygrothermal suitability of these components. In order to be able to consider the entire hygric behaviour of particular retrofitted building components at their individual location, this thesis recommends the introduction of the WUFI software. This software program can be used to calculate and to check the transient heat and moisture transport within a retrofitted wall component to achieve best possible comfort conditions in retrofitted homes.

10.1.2 A NEED FOR NEW STANDARDS AND ONE MANDATORY RATING SYSTEM

The common question is why to invest in retrofit solutions and packages for no value payback when the common retrofit opportunities for added value are usually of appearance upgrade such as a new kitchen or bathroom. Sustainable features such as insulation in the walls, floor and roof spaces that can improve the house performance are generally out of sight. As a result, this research considers that consumers need a mandatory rating system which links the value of these improvements to their property and makes their house performance visible to potential homebuyers or tenants when their property assets are sold or rented out. Otherwise, they are still not able to know if a particular building is code compliant, providing an acceptable thermal comfort and indoor air quality to affordable maintenance costs. In particular, New Zealand's local and national authorities who own social housing stock may have reasons for being concerned about mould and dampness in their houses. Therefore, this research shows that retrofit packages are a cost effective intervention to provide significant health gains to the occupants, as insulated and airtight homes are significantly warmer and drier. Combined with adequate ventilation systems that can avoid low ventilation rates, the risk factor for asthma, allergic symptoms and respiratory diseases among young children can also be reduced.

In terms of new and existing retrofitted homes, it has to be realised that high insulation levels have to be combined with vapour control layers and ventilation systems that are acceptable to reduce heat loss on the one hand and to provide moisture protection in insulation on the other. A deficient protection against moisture which does not include proper ventilation in both new and existing retrofitted homes will cause higher indoor humidity levels following condensation and in turn result in mould growth. This reduces the effectiveness of the thermal insulation and can lead to structural damages. Therefore, it is necessary to establish new residential ventilation standards for New Zealand's homes and to upgrade the New Zealand Building Code. This will especially be necessary for new homes with airtight building envelopes and specific requirements for mechanical ventilation. Including a review of housing design regulations regarding requirements of higher thermal insulation levels and the extension of low interest loans for retrofit solutions, this can have a high impact on reducing New Zealand's problem of damp housing.

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APPENDIX

1.5.3 Anerkannte Bemessungswerte von Baustoffen und Bauteilen

Für eindeutig, insbesondere durch Stoffnormen beschreibbare Baustoffe sind Bemessungswerte der folgenden Tafeln anzuwenden. Wegen „neuer Baustoffe", die als Firmenprodukte nicht normungsfähig oder noch nicht allgemein anerkannt sind, siehe auch Bundesanzeiger oder bauaufsichtliche Zulassungen des DIBt in Berlin mit ggf. **erheblich günstigeren Bemessungswerten.** Die Anwendung von Messwerten der Wärmeleitfähigkeit für wärmetechnische Berechnungen, wie z. B. $\lambda^{10,tr}$, gilt als unzulässig, wenn diese nicht mit Zuschlagwerten Z nach anerkannten Regeln auf Bemessungswerte, z. B. $\lambda = \lambda^{10,tr}(1 + Z)$, umgerechnet werden.

Die Angaben in Tafel 10.18 beruhen auf DIN V 4108-4 : 2002-02 und DIN EN 12 524 : 2000-07.

Nach Einführung der Dämmstoffnormen DIN EN 13 162 bis DIN EN 13 171 werden die Werte in Tafel 10.18, Zeile 5 geändert.

Tafel 10.18 Bemessungswerte der Wärmeleitfähigkeit und Richtwerte der Wasserdampf-Diffusionswiderstandszahl von Baustoffen nach DIN V 4108-4 und DIN EN 12 524

Zeile	Stoff	Rohdichte[a)b)] ϱ kg/m³	Bemessungswert der Wärmeleitfähigkeit λ W/(m · K)	Richtwert der Wasserdampf-Diffusions-widerstands-zahl[c)] μ
1	**PUTZE, MÖRTEL UND ESTRICHE**			
1.1	**Putze**			
1.1.1	Putzmörtel aus Kalk, Kalkzement und hydraulischem Kalk	(1800)	1,0	15/35
1.1.2	Putzmörtel aus Kalkgips, Gips, Anhydrit und Kalkanhydrit	(1400)	0,70	10
1.1.3	Leichtputz	≤ 1300 ≤ 1000 ≤ 700	0,56 0,38 0,25	15/20
1.1.4	Gipsputz ohne Zuschlag	(1200)	0,51	10
1.1.5	Wärmedämmputz nach DIN 18 550-3 Wärmeleitfähigkeitsgruppe 060 070 080 090 100	(≥ 200)	0,060 0,070 0,080 0,090 0,100	5/20
1.1.6	Kunstharzputz	(1100)	0,70	50/200
1.2	**Mauermörtel**			
1.2.1	Zementmörtel	(2000)	1,6	15/35
1.2.2	Normalmörtel NM	(1800)	1,2	
1.2.3	Dünnbettmauermörtel DM	(1600)	1,0	
1.2.4	Leichtmörtel nach DIN 1053-1 LM 36	≤ 1000	0,36	
1.2.5	Leichtmörtel nach DIN 1053-1 LM 21	≤ 700	0,21	
1.3	**Asphalt** **Bitumen als Stoff** **als Membran/Bahn**	2100 1050 1100	0,70 0,17 0,23	50 000
1.4	**Estriche**			
1.4.1	Zement-Estrich	(2000)	1,4	15/35
1.4.2	Anhydrit-Estrich	(2100)	1,2	
1.4.3	Magnesia-Estrich	1400 2300	0,47 0,70	

Table 11.1

10.18 - Thermal Conductivity and Diffusion Resistance Coefficients

Zeile	Stoff	ϱ [a)b)]	λ	μ [c)]
2	**BETON-BAUTEILE**			
2.1	**Beton nach DIN EN 206**			
	mittlere Rohdichte	1800	1,15	60/100
		2000	1,35	60/100
		2200	1,65	70/120
	hohe Rohdichte	2400	2,00	80/130
	armiert (mit 1 % Stahl)	2300	2,3	80/130
	armiert (mit 2 % Stahl)	2400	2,5	80/130
2.2	**Leichtbeton und Stahlleichtbeton** mit geschlossenem Gefüge nach DIN EN 206 und DIN 1045-1, hergestellt unter Verwendung von Zuschlägen mit porigem Gefüge nach DIN 4226-2 ohne Quarzsandzusatz[d)]	800	0,39	70/150
		900	0,44	
		1000	0,49	
		1100	0,55	
		1200	0,62	
		1300	0,70	
		1400	0,79	
		1500	0,89	
		1600	1,0	
		1800	1,3	
		2000	1,6	
2.3	**Dampfgehärteter Porenbeton** nach DIN 4223-1	300	0,10	5/10
		350	0,11	
		400	0,13	
		450	0,15	
		500	0,16	
		550	0,18	
		600	0,19	
		650	0,21	
		700	0,22	
		750	0,24	
		800	0,25	
		900	0,29	
		1000	0,31	
2.4	**Leichtbeton mit haufwerksporigem Gefüge**			
2.4.1	– mit nichtporigen Zuschlägen nach DIN 4226-1, z. B. Kies	1600	0,81	3/10
		1800	1,1	
		2000	1,4	5/10
2.4.2	– mit porigen Zuschlägen nach DIN 4226-2, ohne Quarzsandzusatz[d)]	600	0,22	5/15
		700	0,26	
		800	0,28	
		1000	0,36	
		1200	0,46	
		1400	0,57	
		1600	0,75	
2.4.2.1	– ausschließlich unter Verwendung von Naturbims	500	0,16	5/15
		600	0,18	
		700	0,21	
		800	0,24	
		900	0,28	
		1000	0,32	
		1200	0,41	
		1300	0,47	
2.4.2.2	– ausschließlich unter Verwendung von Blähton	400	0,13	5/15
		500	0,16	
		600	0,19	
		700	0,23	
		800	0,27	
		900	0,30	
		1000	0,35	
		1100	0,39	
		1200	0,44	

Table 11.2

10.19 - Thermal Conductivity and Diffusion Resistance Coefficients

Zeile	Stoff	ϱ[a)b)]	λ		μ[c)]
2.4.2.2	(Fortsetzung) – ausschließlich unter Verwendung von Blähton	1300 1400 1500 1600 1700	0,50 0,55 0,60 0,68 0,76		5/15
3	**BAUPLATTEN**				
3.1	**Porenbeton-Bauplatten und Porenbeton-Planbauplatten**, unbewehrt, nach DIN 4166				
3.1.1	Porenbeton-Bauplatten (Ppl) mit normaler Fugendicke und Mauermörtel nach DIN 1053-1, verlegt	400 500 600 700 800	0,20 0,22 0,24 0,27 0,29		5/10
3.1.2	Porenbeton-Planbauplatten (Pppl), dünnfugig verlegt	300 350 400 450 500 550 600 650 700 750 800	0,10 0,11 0,13 0,15 0,16 0,18 0,19 0,21 0,22 0,24 0,25		5/10
3.2	**Wandbauplatten aus Leichtbeton** nach DIN 18 162	800 900 1000 1200 1400	0,29 0,32 0,37 0,47 0,58		5/10
3.3	**Wandbauplatten aus Gips** nach DIN 18 163, auch mit Poren, Hohlräumen, Füllstoffen oder Zuschlägen	600 750 900 1000 1200	0,29 0,35 0,41 0,47 0,58		5/10
3.4	**Gipskartonplatten nach DIN 18 180**	900	0,25		8
4	**MAUERWERK EINSCHLIESSLICH MÖRTELFUGEN**				
4.1	**Mauerwerk aus Mauerziegeln** nach DIN 105-1 bis E DIN 105-6				
			NM/DM[f)]		
4.1.1	Vollklinker, Hochlochklinker, Keramikklinker	1800 2000 2200 2400	0,81 0,96 1,2 1,4		50/100
4.1.2	Vollziegel, Hochlochziegel, Füllziegel	1200 1400 1600 1800 2000 2200 2400	0,50 0,58 0,68 0,81 0,96 1,2 1,4		5/10
			LM21/LM36[f]	NM/DM[f]	
4.1.3	Hochlochziegel mit Lochung A und Lochung B nach DIN 105-2 und E DIN 105-6	550 600 650 700 750 800 850 900 950 1000	0,27 0,28 0,30 0,31 0,33 0,34 0,36 0,37 0,38 0,40	0,32 0,33 0,35 0,36 0,38 0,39 0,41 0,42 0,44 0,45	5/10

Table 11.3

10.20 - Thermal Conductivity and Diffusion Resistance Coefficients

Zeile	Stoff	$\varrho^{a)b)}$	λ		$\mu^{c)}$
			LM21/LM36[f)]	NM/DM[f)]	
4.1.4	Hochlochziegel HLzW und Wärmedämmziegel WDz nach DIN 105-2, $h \geq 238$ mm	550	0,19	0,22	5/10
		600	0,20	0,23	
		650	0,20	0,23	
		700	0,21	0,24	
		750	0,22	0,25	
		800	0,23	0,26	
		850	0,23	0,26	
		900	0,24	0,27	
		950	0,25	0,28	
		1000	0,26	0,29	
4.1.5	Plan-Wärmedämmziegel PWDz nach E DIN 105-6, $h \geq 238$ mm	550	0,20		5/10
		600	0,21		
		650	0,21		
		700	0,22		
		750	0,23		
		800	0,24		
		850	0,24		
		900	0,25		
		950	0,26		
		1000	0,27		
			NM/DM[f)]		
4.2	**Mauerwerk aus Kalksandsteinen** nach DIN 106-1	1000	0,50		5/10
		1200	0,56		
		1400	0,70		
	und DIN 106-2	1600	0,79		15/25
		1800	0,99		
		2000	1,1		
		2200	1,3		
4.3	**Mauerwerk aus Hüttensteinen** nach DIN 398	1000	0,47		70/100
		1200	0,52		
		1400	0,58		
		1600	0,64		
		1800	0,70		
		2000	0,76		
			DM[f)]		
4.4	**Mauerwerk aus Porenbeton-Plansteinen (PP)** nach DIN 4165	300	0,10		5/10
		350	0,11		
		400	0,13		
		450	0,15		
		500	0,16		
		550	0,18		
		600	0,19		
		650	0,21		
		700	0,22		
		750	0,24		
		800	0,25		

Table 11.4

10.21 - Thermal Conductivity and Diffusion Resistance Coefficients

Zeile	Stoff			$\varrho^{a)b)}$	λ			$\mu^{c)}$
4.5	**Mauerwerk aus Betonsteinen**							
4.5.1	Hohlblöcke (Hbl) nach DIN 18 151 Gruppe 1 [e)]				LM21 [f)]	LM36 [f)]	NM [f)]	
		Steinbreite in cm	Anzahl der Kammerreihen	500	0,22	0,23	0,26	
				600	0,24	0,25	0,29	
		17,5	≥ 2	700	0,28	0,29	0,32	
		24	≥ 3	800	0,31	0,32	0,35	5/10
		30	≥ 4	900	0,34	0,36	0,39	
		36,5	≥ 5	1000			0,45	
		49	≥ 6	1200			0,53	
4.5.2	Hohlblöcke (Hbl) nach DIN 18 151 und Hohlwandplatten nach DIN 18 148, Gruppe 2			450	0,22	0,23	0,28	
				500	0,24	0,25	0,30	
				550	0,26	0,27	0,31	
		Steinbreite in cm	Anzahl der Kammerreihen	600	0,27	0,28	0,32	
				650	0,29	0,30	0,34	
		11,5	≤ 1	700	0,30	0,32	0,36	5/10
		17,5	≤ 1	800	0,34	0,36	0,41	
		24	≤ 2	900	0,37	0,40	0,46	
		30	≤ 3	1000			0,52	
		36,5	≤ 4	1200			0,60	
		49	≤ 5	1400			0,72	
4.5.3	Vollblöcke (Vbl, S-W) nach DIN 18 152			500	0,15	0,17	0,20	
				600	0,17	0,19	0,22	
				700	0,19	0,21	0,25	5/10
				800	0,21	0,23	0,27	
				900	0,25	0,26	0,30	
4.5.4	Vollblöcke (Vbl) und Vbl-S nach DIN 18 152 aus Leichtbeton mit anderen leichten Zuschlägen als Naturbims und Blähbeton			500	0,23	0,24	0,29	
				600	0,25	0,26	0,31	
				650	0,26	0,27	0,32	
				700	0,27	0,28	0,33	
				800	0,29	0,30	0,36	5/10
				900	0,32	0,32	0,39	
				1000	0,34	0,35	0,42	
				1200			0,49	
				1400			0,57	
				1600			0,69	
				1800			0,79	10/15
				2000			0,89	
4.5.5	Vollsteine (V) nach DIN 18 152			500	0,22	0,23	0,32	
				600	0,24	0,26	0,34	
				700	0,27	0,29	0,37	
				800	0,30	0,32	0,40	
				900	0,33	0,35	0,43	5/10
				1000	0,36	0,38	0,46	
				1200			0,54	
				1400			0,63	
				1600			0,74	
				1800			0,87	10/15
				2000			0,99	
4.5.6	Mauersteine nach DIN 18 153 aus Beton			800			0,60	
				900			0,65	5/15
				1000			0,70	
				1200			0,80	
				1400			0,90	
				1600			1,1	
				1800			1,2	20/30
				2000			1,4	
				2200			1,7	
				2400			2,1	

Table 11.5

10.22 - Thermal Conductivity and Diffusion Resistance Coefficients

Zeile	Stoff		$\varrho^{a)b)}$	λ	$\mu^{c)}$
5	**WÄRMEDÄMMSTOFFE**				
5.1	**Holzwolle-Leichtbauplatten**				
	nach DIN 1101[g]				
	Plattendicke $d \geq 25$ mm				
	Wärmeleitfähigkeitsgruppe	065		0,065	
		070		0,070	
		075		0,075	2/5
		080	(360 bis 460)	0,080	
		085		0,085	
		090		0,090	
	Plattendicke d				
	15 mm $\geq d \geq$ 25 mm			0,15	
5.2	**Holzwolleschichten**[h]				
	Dicke d: 10 mm $\geq d <$ 25 mm		(460 bis 650)	0,15	
	Plattendicke $d \geq 25$ mm		(360 bis 460)		
	Wärmeleitfähigkeitsgruppe	065		0,065	
		070		0,070	
		075		0,075	2/5
		080		0,080	
		085		0,085	
		090		0,090	
5.3	**Schaumkunststoffe, an der Baustelle hergestellt**				
5.3.1	Polyurethan-(PUR-)Ortschaum nach DIN 18 159-1 (Treibmittel CO_2)	035	(> 45)	0,035	30/100
	Wärmeleitfähigkeitsgruppe	040		0,040	
5.3.2	Harnstoff-Formaldehydharz-(UF-)Ortschaum nach DIN 18 159-2	035	(≥ 10)	0,035	1/3
	Wärmeleitfähigkeitsgruppe	040		0,040	
5.4	**Korkdämmstoffe**				
	Korkplatten nach DIN 18 161-1	045		0,045	
	Wärmeleitfähigkeitsgruppe	050	(80 bis 500)	0,050	5/10
		055		0,055	
5.5	**Schaumkunststoffe** nach DIN 18 164-1[i]				
5.5.1	Polystyrol-(PS-)Hartschaum				
5.5.1.1	Polystyrol-(PS-)Partikelschaum	035		0,035	
	Wärmeleitfähigkeitsgruppe	040		0,040	
			≥ 15		20/50
			≥ 20		30/70
			≥ 30		40/100
5.5.1.1	Polystyrol-Extruderschaum	030		0,030	
	Wärmeleitfähigkeitsgruppe	035	(≥ 25)	0,035	80/250
		040		0,040	
5.5.1.2	Polystyrol-Extruderschaum außerhalb der Bauwerksabdichtung[j] bzw. Dachhaut[k]				
	Wärmeleitfähigkeitsgruppe	030	(≥ 30)	0,030	
		035		0,035	80/250
		040		0,040	
5.5.2	Polyurethan-(PUR-)Hartschaum				
	Wärmeleitfähigkeitsgruppe	020[l]		0,020	
		025		0,025	
		030	(≥ 30)	0,030	30/100
		035		0,035	
		040		0,040	
5.5.3	Phenolharz-(PF-)Hartschaum				
	Wärmeleitfähigkeitsgruppe	030		0,030	
		040	(≥ 30)	0,035	10/50
		045		0,040	
		050		0,045	

Table 11.6

10.23 - Thermal Conductivity and Diffusion Resistance Coefficients

Zeile	Stoff		ϱ [a)b)]	λ	μ [c)]
5.6	**Mineralische und pflanzliche Faserdämmstoffe** nach DIN 18 165-1[m)] Wärmeleitfähigkeitsgruppe	035 040 045 050	(8 bis 500)	0,035 0,040 0,045 0,050	1
5.7	**Schaumglas**				
5.7.1	Schaumglas nach DIN 18 174 Wärmeleitfähigkeitsgruppe	045 050 055 060	(100 bis 150)	0,045 0,050 0,055 0,060	n)
5.7.2	Schaumglas nach DIN 18 174 außerhalb der Bauwerksabdichtungen Wärmeleitfähigkeitsgruppe	045 050 055	(110 bis 150)	0,045 0,050 0,055	n)
5.8	**Holzfaserdämmplatten** nach DIN 68 755 Wärmeleitfähigkeitsgruppe	035 040 045 050 055 060 065 070	(110 bis 450)	0,035 0,040 0,045 0,050 0,055 0,060 0,065 0,070	5

Veränderungen in Zeile 5 oder Tafel 10.18 nach Einführung der Produktnormen DIN EN 13 162 bis DIN EN 13 171

Für Produkte nach harmonisierten europäischen Dämmstoff-Normen, die nach Bauregelliste eingeführt sind, werden Nennwerte λ_D verwendet. Bei der Ermittlung des Bemessungswertes ist der Nennwert wegen der zu erwartenden Materialstreuung mit einem Sicherheitsbeiwert $\gamma = 1,2$ zu multiplizieren (Kategorie II). Dieser Sicherheitsbeiwert kann bei einer Fremdüberwachung der Produktion nach DIN EN 13 172 : 2001-10, Anhang A gleich 1,0 gesetzt werden (Kategorie I). In die Kategorie II werden alle Produkte aufgenommen, die CE gekennzeichnet sind. In die Kategorie I werden Produkte aufgenommen, die zusätzlich zur CE-Kennzeichnung der Fremdüberwachung einer von den Ländern zugelassenen Stelle unterliegen.

Table 11.7

10.24 - Thermal Conductivity and Diffusion Resistance Coefficients

Zeile	Stoff	ϱ [a)b)]	λ	μ [c)]
6	**HOLZ UND HOLZWERKSTOFFE**			
6.1	**Konstruktionsholz**	500 700	0,13 0,18	20/50 50/200
6.2	**Holzwerkstoffe**			
6.2.1	Sperrholz	300 500 700 1000	0,09 0,13 0,17 0,24	50/150 70/200 90/220 110/250
6.2.2	Zementgebundene Spanplatte	1200	0,23	30/50
6.2.3	Spanplatte	300 600 900	0,10 0,14 0,18	10/50 15/50 20/50
6.2.4	OSB-Platten	650	0,13	30/50
6.2.5	Holzfaserplatten einschließlich MDF	250 400 600 800	0,07 0,10 0,14 0,18	2/5 5/10 12/50 20/50
7	**BELÄGE, ABDICHTUNGSSTOFFE UND ABDICHTUNGSBAHNEN**			
7.1	**Fußbodenbeläge** Gummi Kunststoff Unterlagen, poröser Gummi oder Kunststoff Filzunterlage Wollunterlage Korkunterlage Korkfliesen Teppich/Teppichböden Linoleum	 1200 1700 270 120 200 < 200 > 400 200 1200	 0,17 0,25 0,10 0,05 0,06 0,05 0,065 0,06 0,17	 10 000 10 000 10 000 15/20 15/20 10/20 20/40 5 800/1000
7.2	**Abdichtstoffe, Abdichtungsbahnen**	siehe DIN EN 12 524		
7.3	**Dachbahnen, Dachdichtungsbahnen**			
7.3.1	Bitumendachbahnen nach DIN 52 128	(1200)	0,17	10 000/80 000
7.3.2	Nackte Bitumenbahnen nach DIN 52 129	(1200)	0,17	2000/20 000
7.3.3	Glasvlies-Bitumendachbahnen nach DIN 52 143	–	–	20 000/60 000
7.3.4	Kunststoff-Dachbahnen nach DIN 16 729 (ECB)	–	–	50 000/75 000 (2,0K) 70 000/90 000 (2,0)
7.3.5	Kunststoff-Dachbahnen nach DIN 16 730 (PVC-P)	–	–	10 000/30 000
7.3.6	Kunststoff-Dachbahnen nach DIN 16 731 (PIB)	–	–	400 000/ 1 750 000
7.4	**Folien**	siehe DIN EN 12 524		
7.4.1	PTFE-Folien Dicke $d \geq 0{,}05$ mm	–	–	10 000
7.4.2	PA-Folie Dicke $d \geq 0{,}05$ mm	–	–	50 000
7.4.3	PP-Folie Dicke $d \geq 0{,}05$ mm	–	–	1000
8	**SONSTIGE GEBRÄUCHLICHE STOFFE** [o)]			
8.1	**Lose Schüttungen,** [p)] **abgedeckt**			
8.1.1	– aus porigen Stoffen: Blähperlit Blähglimmer Korkschrot, expandiert Hüttenbims Blähton, Blähschiefer Bimskies Schaumlava	 (≤ 100) (≤ 100) (≤ 200) (≤ 600) (≤ 400) (≤ 1000) (≤ 1200) (≤ 1500)	 0,060 0,070 0,055 0,13 0,16 0,19 0,22 0,27	 3

Table 11.8

10.25 - Thermal Conductivity and Diffusion Resistance Coefficients

Zeile	Stoff	$\varrho^{a)b)}$	λ	$\mu^{c)}$
8.1.2	– aus Polystyrolschaumstoff-Partikeln	(15)	0,050	3
8.1.3	– aus Sand, Kies, Splitt (trocken)	(1800)	0,70	3
8.2	**Lehmbaustoffe**	500	0,14	
		600	0,17	
		700	0,21	
		800	0,25	
		900	0,30	
		1000	0,35	5/10
		1200	0,47	
		1400	0,59	
		1600	0,73	
		1800	0,91	
		2000	1,1	
8.3	**Böden, naturfeucht**	≤ 1800	1,5	50
		≤ 2200	2,0	50
8.4	**Keramik und Glas, Gestein**			
	Naturglas, Floatglas	2500	2,00	n)
	kristalliner Naturstein	2800	3,5	10 000
	Sediment Naturstein	2600	2,3	2/250
	poröses Gestein, Lava	1600	0,55	15/20
	Naturbims	400	0,12	6/8
	Kunststein	1750	1,3	40/50
8.5	**Metalle**			
	Aluminiumlegierungen	2800	160	n)
	Kupfer	8900	380	n)
	Stahl	7800	50	n)
	nichtrostender Stahl	7900	17	n)
	Blei	11 300	35	n)
	Zink	7200	110	n)
8.6	**massive Kunststoffe**	siehe DIN EN 12 524		

a) Die in Klammern angegebenen Rohdichtewerte dienen nur zur Ermittlung der flächenbezogenen Masse, z. B. für den Nachweis des sommerlichen Wärmeschutzes.
b) Die bei den Steinen genannten Rohdichten entsprechen den Rohdichteklassen der zitierten Stoffnormen.
c) Es ist jeweils der für die Baukonstruktion ungünstigere Wert einzusetzen. Bezüglich der Anwendung der μ-Werte siehe DIN 4108-3.
d) Bei Quarzsand erhöhen sich die Bemessungswerte der Wärmeleitfähigkeit um 20 %.
e) Die Bemessungswerte der Wärmeleitfähigkeit sind bei Hohlblöcken mit Quarzsandzusatz für 2 K Hbl um 20 % und für 3 K Hbl bis 6 K Hbl um 15 % zu erhöhen.
f) Bezeichnung der Mörtelarten nach DIN 1053-1:1996-11:
– NM Normalmörtel
– LM21 Leichtmörtel mit λ = 0,21 W/(mK)
– LM36 Leichtmörtel mit λ = 0,36 W/(mK)
– DM Dünnbettmörtel.
g) Platten der Dicke d < 15 mm dürfen wärmeschutztechnisch nicht berücksichtigt werden (siehe DIN 1101).
h) Holzwolleschichten (Einzelschichten) mit Dicken d < 10 mm dürfen zur Berechnung des Wärmedurchlasswiderstandes R nicht berücksichtigt werden (siehe DIN 1101). Bei Berechnungen der Wasserdampf-Diffusionswiderstandszahl werden sie jedoch mit ihrer wasserdampfdiffusionsäquivalenten Luftschichtdicke s_d in Ansatz gebracht (Richtwert der Wasserdampf-Diffusionswiderstandszahl $\mu^{o)}$ = 2 bis 5).
i) Bei Trittschalldämmplatten aus Schaumkunststoffen werden bei sämtlichen Erzeugnissen der Wärmedurchlasswiderstand R und die Wärmeleitfähigkeitsgruppe auf der Verpackung angegeben (siehe DIN 18 164-2).
j) Zusätzliche Anforderungen gegenüber DIN 18 164-1. Anwendungstyp WD oder WS bei Anwendung als Perimeterdämmung
– Die Dämmplatten müssen beidseitig je eine Schaumhaut haben.
– Druckfestigkeit bzw. Druckspannung bei 10 % Stauchung ≥ 0,30 N/mm²
– Wasseraufnahme in der Prüfung nach DIN EN 12 088 im Temperaturgefälle 50 °C zu 1 °C: unter 3,0 % Volumenanteil.
k) Zusätzliche Anforderungen gegenüber DIN V 18 164-1. Anwendungstyp WD oder WS bei Anwendung als Umkehrdach
– Druckfestigkeit bzw. Druckspanung bei 10 % Stauchung ≥ 0,30 N/mm²
– Wasseraufnahme in der Prüfung nach DIN EN 12 088 im Temperaturgefälle 50 °C zu 1 °C: unter 3,0 % Volumenanteil.
– Die Dämmplatten sind mit Kantenprofilierung (z. B. Stufenfalz) auszubilden.
l) Mit diffusionsdichten Deckschichten.
m) Bei Trittschalldämmplatten aus Faserdämmstoffen wird bei sämtlichen Erzeugnissen die Wärmeleitfähigkeitsgruppe auf der Verpackung angegeben (siehe DIN 18 165-2).
n) Praktisch dampfdicht; DIN EN 12 086 oder DIN EN ISO 12 572: s_d ≥ 1500 m.
o) Diese Stoffe sind hinsichtlich ihrer wärmeschutztechnischen Eigenschaften nicht genormt. Die angegebenen Wärmeleitfähigkeitswerte stellen obere Grenzwerte dar.
p) Die Dichte wird bei losen Schüttungen als Schüttdichte angegeben.

Table 11.9

10.26 - Thermal Conductivity and Diffusion Resistance Coefficients

	Temperatur θ °C ganzzahlige Werte	Wasserdampfsättigungsdruck über Wasser bzw. Eis in Pa									
		Temperatur θ °C, 1. Dezimale									
		,0	,1	,2	,3	,4	,5	,6	,7	,8	,9
Näherungsgleichung $p_s = 288{,}68\,(1{,}098 + \theta/100)^{8{,}02}$	30	4244	4269	4294	4319	4344	4369	4394	4419	4445	4469
	29	4006	4030	4053	4077	4101	4124	4118	4172	4196	4219
	28	3781	3803	3826	3848	3871	3894	3916	3939	3961	3984
	27	3566	3588	3609	3631	3652	3674	3695	3717	3738	3759
	26	3362	3382	3403	3423	3443	3463	3484	3504	3525	3544
	25	3169	3188	3208	3227	3246	3266	3284	3304	3324	3343
	24	2985	3003	3021	3040	3059	3077	3095	3114	3132	3151
	23	2810	2827	2845	2863	2880	2897	2915	2932	2950	2968
	22	2645	2661	2678	2695	2711	2727	2744	2761	2777	2794
	21	2487	2504	2518	2535	2551	2566	2582	2598	2613	2629
	20	2340	2354	2369	2384	2399	2413	2428	2443	2457	2473
	19	2197	2212	2227	2241	2254	2268	2283	2297	2310	2324
	18	2065	2079	2091	2105	2119	2132	2145	2158	2172	2185
	17	1937	1950	1963	1976	1988	2001	2014	2027	2039	2052
	16	1818	1830	1841	1854	1866	1878	1889	1901	1914	1926
	15	1706	1717	1729	1739	1750	1762	1773	1784	1795	1806
	14	1599	1610	1621	1631	1642	1653	1663	1674	1684	1695
	13	1498	1508	1518	1528	1538	1548	1559	1569	1578	1588
	12	1403	1413	1422	1431	1441	1451	1460	1470	1479	1488
	11	1312	1321	1330	1340	1349	1358	1367	1375	1385	1394
	10	1228	1237	1245	1254	1262	1270	1279	1287	1296	1304
	9	1148	1156	1163	1171	1179	1187	1195	1203	1211	1218
	8	1073	1081	1088	1096	1103	1110	1117	1125	1133	1140
	7	1002	1008	1016	1023	1030	1038	1045	1052	1059	1066
	6	935	942	949	955	961	968	975	982	988	995
	5	872	878	884	890	896	902	907	913	919	925
	4	813	819	825	831	837	843	849	854	861	866
	3	759	765	770	776	781	787	793	798	803	808
	2	705	710	716	721	727	732	737	743	748	753
	1	657	662	667	672	677	682	687	691	696	700
	0	611	616	621	626	630	635	640	645	648	653
Näherungsgleichung $p_s = 4{,}689\,(1{,}486 + \theta/100)^{12{,}3}$	–0	611	605	600	595	592	587	582	577	572	567
	–1	562	557	552	547	543	538	534	531	527	522
	–2	517	514	509	505	501	496	492	489	484	480
	–3	476	472	468	464	461	456	452	448	444	440
	–4	437	433	430	426	423	419	415	412	408	405
	–5	401	398	395	391	388	385	382	379	375	372
	–6	368	365	362	359	356	353	350	347	343	340
	–7	337	336	333	330	327	324	321	318	315	312
	–8	310	306	304	301	298	296	294	291	288	286
	–9	284	281	279	276	274	272	269	267	264	262
	–10	260	258	255	253	251	249	246	244	242	239
	–11	237	235	233	231	229	228	226	224	221	219
	–12	217	215	213	211	209	208	206	204	202	200
	–13	198	197	195	193	191	190	188	186	184	182
	–14	181	180	178	177	175	173	172	170	168	167
	–15	165	164	162	161	159	158	157	155	153	152
	–16	150	149	148	146	145	144	142	141	139	138
	–17	137	136	135	133	132	131	129	128	127	126
	–18	125	124	123	122	121	120	118	117	116	115
	–19	114	113	112	111	110	109	107	106	105	104
	–20	103	102	101	100	99	98	97	96	95	94

Table 11.10

10.37 – Saturation Vapour Pressure

Schicht/Baustoff	d m	λ_R W/mK	μ –	R_s; d/λ_R m²K/W	μd m	θ °C	p_s[1] Pa	$\Sigma\mu d$[2] m
Übergang innen								
								0
Übergang außen								

Klima: θ_i = ___ °C, ϕ_i = ___ %, p_i = ___ Pa θ_e = ___ °C, ϕ_e = ___ %, p_e = ___ Pa	R_T m²K/W U W/(m²K)	Woher? λ_R,μ: Tafel 10.18, R_s: Tafel: 10.27a p_s: Tafel 10.37 1) Ordinate nach Schritt 2. 2) Abszisse nach Schritt 2.

Geometrisch können drei Fälle eintreten:

Fall 1: Der vorhandene Wasserdampfteildruck ist stets kleiner als p_s: keine Kondensation (Abb. 10.39a).

Fall 2: Die p-Linie berührt die Sättigungslinie p_s in einem Punkt. Es fällt Tauwasser in einer Ebene an, die durch den Berührungspunkt gegeben ist (Abb. 10.39b).

Fall 3: Die p-Linie lässt sich nur so konstruieren, dass die p_s-Linie in zwei Punkten berührt wird und zwischen diesen Punkten mit der p-Linie identisch ist. Es fällt Tauwasser in einem Bereich an (Abb. 10.39c).

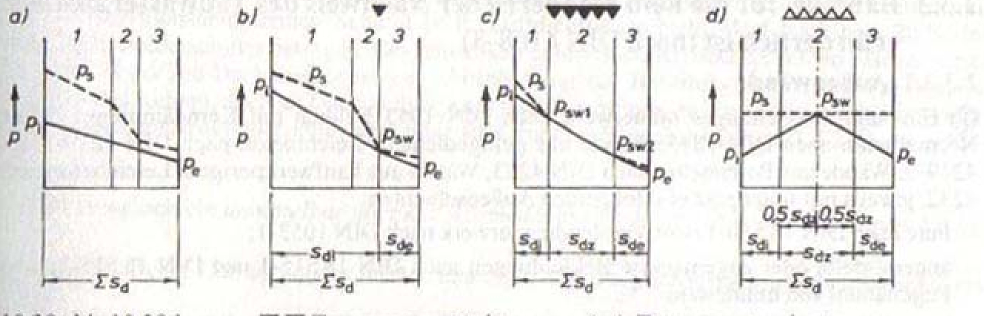


Abb. 10.39a bis 10.39d ▼▼ Tauwasser entsteht △△ Tauwasser trocknet

Schritt 3:

Bestimmung der Werte s_{di} und s_{de} der Warm- und Kaltseite mit den zugehörigen Werten p_{sw1} und p_{sw2} aus dem Diffusionsdiagramm. Im Fall 2 ist $p_{sw1} = p_{sw2}$. Die in der Befeuchtungsperiode der Dauer t_T insgesamt anfallende **Tauwassermenge $m_{W,T}$** berechnet sich nach der Gleichung

$$m_{W,T} = \frac{t_T}{1{,}5 \cdot 10^6}\left(\frac{p_i - p_{sw1}}{s_{di}} - \frac{p_{sw2} - p_e}{s_{de}}\right) \text{ kg/m}^2$$

(Differenz der ein- und ausdiffundierenden Wasserdampfmengen)

Schritt 4: (Abb. 10.39d)

Bestimmung der **Verdunstungsmenge $m_{W,V}$** analog zu Schritt 2 anhand von Diffusionsdiagrammen. Nach einem vorhergehenden Tauwasserausfall herrscht im Tauwasserbereich Sättigungsdruck. Die Verdunstung erfolgt nach innen und außen. Die Menge berechnet sich nach der Gleichung (bei Klimaannahmen nach S. 10.38 ist p_{sw} = 1403 Pa und $p_i = p_e$ = 982 Pa):

$$m_{W,V} = \frac{t_V}{1{,}5 \cdot 10^6}\left(\frac{p_{sw} - p_i}{s_{di} + 0{,}5\, s_{dz}} + \frac{p_{sw} - p_e}{0{,}5\, s_{dz} + s_{de}}\right) \text{ kg/m}^2$$

(Summe der zu beiden Oberflächen hin diffundierenden Wasserdampfmengen. Beim Tauwasseranfall in einer Ebene ist $s_{dz} = 0$.)

Table 11.11

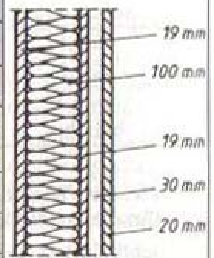
10.39 – The 3 Circumstances of Water Outfall (Glaser-Verfahren)

Zahlenbeispiel zur Berechnung des Tauwasserausfalls

Nachfolgend wird am Beispiel einer Außenwand die Untersuchung auf innere Tauwasserbildung und Verdunstung infolge von Wasserdampfdiffusion bei den Randbedingungen entsprechend DIN 4108-3 gezeigt.

Wandaufbau: Zusammenstellung der Rechengrößen für das Diffusionsdiagramm bei Tauwasserausfall

Schicht	d m	μ –	s_d m	λ_R W/(m · K)	R_s; R m²· K/W	θ °C	p_s Pa
Wärmeübergang innen	–	–	–	–	0,13	20,0	2340
						18,7	2158
Spanplatte V 20	0,019	50	0,95	0,13	0,15		
Polystyrol-Partikelschaum	0,10	20	2,00	0,04	2,50	17,2	1964
						–7,7	318
Spanplatte V 100	0,019	100	1,90	0,13	0,15	–9,2	279
Luftschicht – belüftet –	0,03	–	–	–	–	–	–
Außenschale	0,02	–	–	–	–	–	–
Wärmeübergang außen	–	–	–	–	0,08	–10,0	260
		$\Sigma s_d =$	4,85	$R_T =$	3,01		

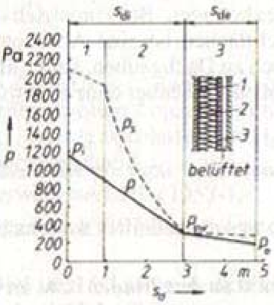


Randbedingungen

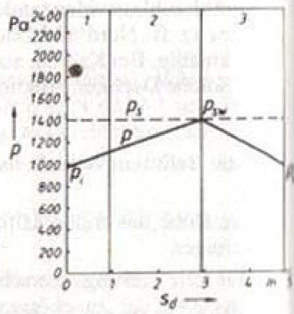
Periode	Raum-klima	Außen-klima
Tauperiode $t_T = 1440$ h		
Lufttemperatur	20 °C	–10 °C
Relative Luftfeuchte	50 %	80 %
Wasserdampf-sättigungsdruck	2340 Pa	260 Pa
Wasserdampf-teildruck	1170 Pa	208 Pa
Verdunstungsperiode $T_v = 2160$ h		
Lufttemperatur	12 °C	12 °C
Relative Luftfeuchte	70 %	70 %
Wasserdampf-sättigungsdruck	1403 Pa	1403 Pa
Wasserdampf-teildruck	982 Pa	982 Pa

Diffusionsdiagramme

a) Tauperiode



b) Verdunstungsperiode



Tauwassermasse (s. S. 10.39):

$p_i = 1170$ Pa, $p_{sw} = 318$ Pa, $p_e = 208$ Pa

$t_T = 1440$ h

$$m_{W,T} = \frac{1440}{1,5}\left(\frac{1170-318}{2,95} - \frac{318-208}{1,90}\right) \cdot 10^{-6}$$

$m_{W,T} = 0{,}222$ kg/m²

Ergebnis:
Zulässige Tauwassermasse nach DIN 4108-3 (Erhöhung des massebezogenen Feuchtegehalts der Spanplatte um nicht mehr als 3 %):

$\text{zul}\, m_{W,T} = 0{,}03 \cdot 0{,}019 \cdot 700 = 0{,}399 \text{ kg/m}^2 > m_{W,T}$

Verdunstende Wassermasse (s. S. 10.39):

$p_i = p_e = 982$ Pa, $p_{sw} = 1403$ Pa

$t_v = 2160$ h

$$m_{W,V} = \frac{2160}{1,5}\left(\frac{1403-982}{2,95} + \frac{1403-982}{1,90}\right) \cdot 10^{-6}$$

$m_{W,V} = 0{,}525 \text{ kg/m}^2 > m_{W,T}$

Ergebnis:
Die Tauwasserbildung ist im Sinne von DIN 4108-3 unschädlich, da

a) $m_{W,V} < \text{zul}\, m_{W,T}$ und

b) $m_{W,V} > m_{W,T}$

Table 11.12

10.42 – Condensation Water Outfall (Glaser-Verfahren)

Name of site = Auckland NZ
Latitude [°] = -36.920, Longitude [°] = 174.600,
Altitude [m] = 32, Climatic zone = IV, 7
Radiation model = Default (hour); Temperature model = Default (hour)
Temperature: New period = 1996-2005
Radiation: New period = 1981-2000
RR: Only 2 station(s) for interpolation
SD: Mean values of climate zone
Nearest 3 stations: Gh: Whenuapai (16 km), Auckland Airp. (21 km), Ohakea (371 km)
Nearest 3 stations: Ta: Auckland Airp. (21 km), Auckland Intl. AWS (21 km), Mokohinau AWS (122 km)

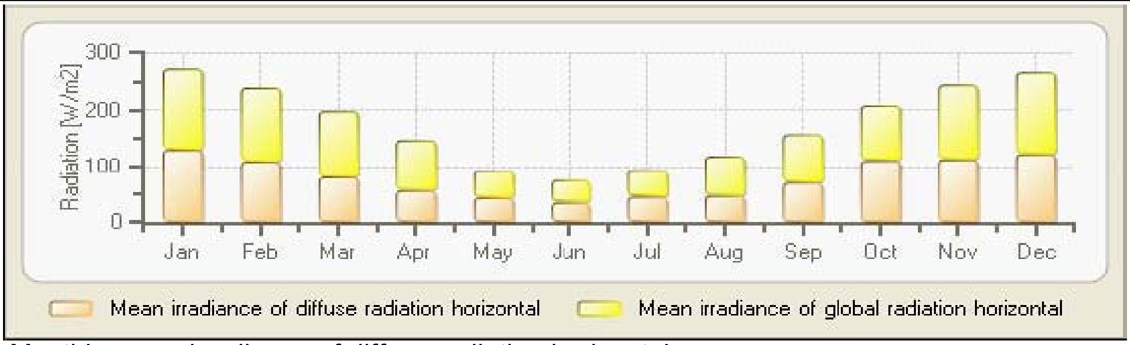
Month	N	DD	FF	FFv	RR	p	
	[octas]	[deg]	[m/s]	[m/s]	[mm]	[hPa]	
Jan	5	225	3.6	3.5	196	1011	
Feb	4	225	3.6	3.5	278	1011	
Mar	5	225	3.3	3.2	208	1011	
Apr	4	225	3.0	2.9	239	1011	
May	5	225	3.4	3.3	253	1011	
Jun	5	248	3.2	3.1	246	1011	
Jul	5	248	3.1	3.0	158	1011	
Aug	5	248	3.4	3.3	197	1011	
Sep	5	248	3.9	3.8	229	1011	
Oct	6	225	4.5	4.4	266	1011	
Nov	5	225	4.6	4.5	256	1011	
Dec	5	225	4.2	4.1	253	1011	
Year	5	232	3.7	3.5	2779	1011	
Month	Ta	Rh	G_Bh	G_Dh	Lg	Lup	Lin
	[C]	[%]	[W/m2]	[W/m2]	[cd/m2]	[W/m2]	[W/m2]
Jan	19.4	73.4	142	130	29974	362	423
Feb	20.1	73.1	130	109	26343	361	424
Mar	18.5	74.6	117	81	21734	359	414
Apr	16.1	77.8	90	57	16122	344	395
May	14.4	81.6	49	44	10277	342	385
Jun	12.0	83.1	39	36	8278	326	370
Jul	11.1	81.8	48	46	10032	317	367
Aug	11.3	79.2	70	48	12689	325	370
Sep	13.1	78.4	86	71	17064	330	381
Oct	14.5	76.7	97	111	22632	337	392
Nov	15.8	73.6	131	113	26658	340	400
Dec	18.0	74.5	144	122	29202	354	414
Year	15.4	77.3	95	81	19251	341	395

Legend:

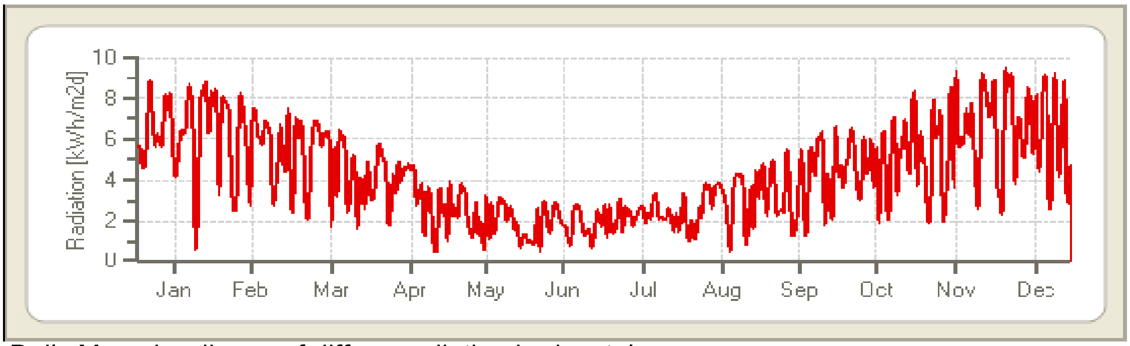
N:	Cloud cover	Ta:	Air temperature
DD:	Wind directio	Rh:	Relative humidity
FF:	Wind speed	G_Bh:	Mean Irradiance of direct radiation horizontal
RR:	Precipitation	G_Dh:	Mean irradiance of diffuse radiation horizontal
p:	Air pressure	Lg:	Global luminance
		Lup:	Mean Irradiance of longwave radiation incoming
		Lin:	Mean Irradiance of longwave radiation outgoing

Table 11.13

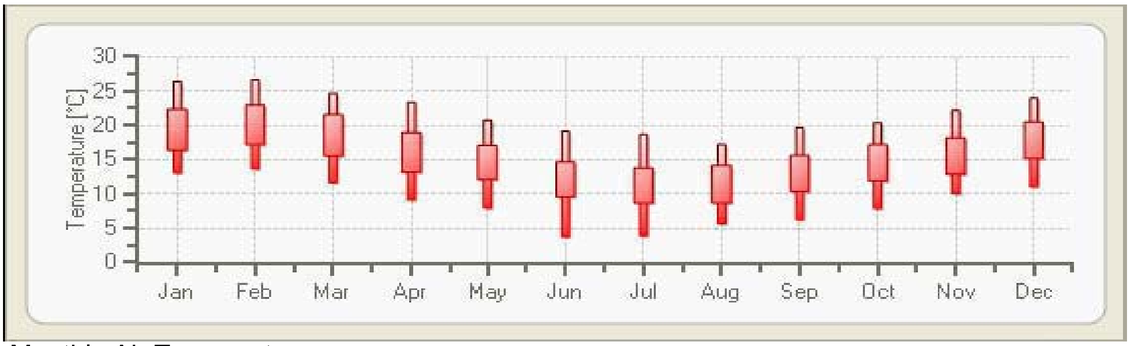
Meteonorm – Test Reference Years of Auckland



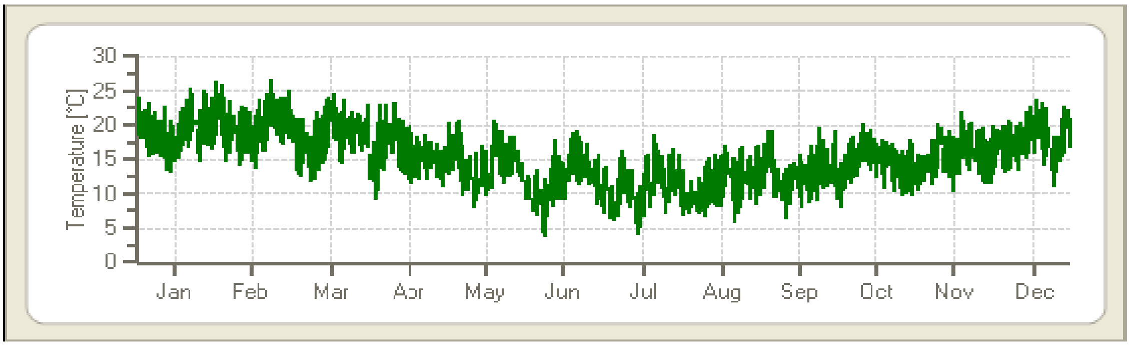
Monthly mean irradiance of diffuse radiation horizontal



Daily Mean irradiance of diffuse radiation horizontal



Monthly Air Temperature



Daily Air Temperature

Table 11.14

Meteonorm – Monthly and Daily Climate Data of Auckland