ABSTRACT
The analysis of the existing housing stock in New Zealand confirms the prevalence of indoor environmental factors negatively affecting occupant well-being. Besides being energy-consuming, New Zealand homes are known for having cold, damp and uncomfortable interiors. Furthermore, the country has one of the highest incidences of asthma and respiratory related illnesses in the developed world as well as one of the highest rates of winter related deaths.

Design issues and practical solutions for sustainable buildings in relation to construction details, ventilation and humidity control have been already investigated in several studies. This paper instead aims to demonstrate how comfortable and healthy houses are defined by measurable conditions that can be assessed by using specific tools, such as the simulation programme WUFI (Wärme und Feuchte instationär - Transient Heat and Moisture) and Blower Door tests. It has been proved that Indoor Air Quality of homes significantly affects comfort and health of their occupants. In particular, air leakages have been identified as one of the major causes of energy consumption and discomfort in the building industry. Indeed, airtightness is a crucial factor to ensure that insulation really does perform and that the building structure remains free of structural damage.

Current building practice in New Zealand suffers from the lack of use of control tools to design and build energy efficient, durable and healthy buildings. This paper presents the calculative assessment through WUFI simulations of thermal and hygric processes in the external wall assemble of old, retrofitted and new buildings. In addition it compares results from previous airtightness measurements with those from Blower Door tests performed on some modern buildings, to investigate the levels of airtightness currently being achieved in New Zealand with common building practice. The proposed calculation and assessment methods can assist practitioners in providing a general evaluation of the hygrothermal suitability of particular building components. Used as a means of verification in this study, they served to demonstrate the inadequacy and potential risks associated with certain practices of building construction and renovation.

KEYWORDS
IAQ; Healthy building; Airtightness; Moisture control; Blower Door.

INTRODUCTION
Badly designed and older houses are difficult and expensive to heat. Consequent inadequate indoor thermal comfort can have health consequences for the occupants (Boardman, 1991), by placing more physiological stress on older or sick people and children - as they spend more time inside and have weak thermoregulatory systems (Heyman, 2005). Indeed, cold houses are likely to be damp, leading to the growth of moulds, which can cause respiratory symptoms. The link between inadequate heating, damp, cold and mouldy houses and poor health has been highlighted in several international reports (Institute of Medicine, 2004). However, the causative agent in indoor air of damp houses has not been identified yet. Different types of ‘dampness’ can be easily found in homes, such as condensation on window panes or
visible mould growth. However, the U.S. Institute of Medicine (2004, p. 13) pointed out that the risk of microbial contamination is even higher than expected, because visible surfaces are not the only areas to pay attention to: attics, crawl spaces, wall cavities and other hidden areas, which are usually not investigated, can represent major sources of exposure. Regardless of the type, dampness in homes depends on indoor humidity in relation to building insulation and ventilation. Thus a healthy indoor environment only results from the control of internal sources of humidity, thermal comfort and air infiltration rates.

The analysis of the existing housing stock in New Zealand, including the most recent buildings, confirms the prevalence of indoor environmental factors negatively affecting occupant well-being. Besides being energy-consuming, New Zealand homes are known for having cold, damp and uncomfortable interiors, which results from a combination of factors. These include the high outdoor humidity and the poor performance of the current housing stock (approximately 1.6 million homes) in terms of both energy efficiency and Indoor Air Quality (IAQ), with inadequate amount of insulation and heating (Howden-Chapman, 2005). A recent study by the Energy Efficiency and Conservation Authority (EECA) found that a major cause of energy and health issues is the lack of insulation in New Zealand homes (EECA, 2009). Indeed, as it was only in 1978 a minimum level of insulation became mandatory for all new constructions, homes built prior to this date - 1.04 million homes, equal to 65% of the current housing stock - were not required to install any insulation for consent approval. As a consequence, about 900,000 homes across New Zealand have inadequate amount of insulation. Furthermore, despite the high consumption of energy for house heating, the indoor temperature remains alarmingly low. An important study carried out by the Building Research Association of New Zealand (BRANZ) has shown that the indoor temperature is very low in winter, with average daily values for living room and bedrooms of 15.8°C and 14.1°C respectively, far below the range 18-24°C suggested by the World Health Organization (WHO) (Pollard et al., 2006; Howden-Chapman et al. 2007a). Furthermore, the relative indoor humidity is almost always above 65% in winter providing ideal conditions for mould growth (Rosemeier, 2007). These indoor living conditions have harmful economic and health effects, which will intensify by 2051, when 36% of the New Zealand householders will be over the age of 65 and the number of people aged over 80 will increase (Ministry of Social Development, 2002).

Several studies, dating back from the 70s, have proved indoor dampness and mould growth to be common problems in New Zealand houses, with a higher incidence in northern cities (Trethowen, 1972). A BRANZ house condition survey involving 465 houses, carried out in 1998-99, showed that 40% to 50% of the houses in the country were judged as considerably damp in winter (Clark et al., 2000). The same percentage was confirmed recently by a major report, which was published by the New Zealand Business Council for Sustainable Development (NZBCSD): the outcomes of the two year research project indicated that one million houses of the existing housing stock are performing poorly in terms of insulation and 45% of them are reported as mouldy (NZBCSD, 2008a).

Despite the population’s propensity for outdoor sports and activities, in New Zealand – as in other developed countries - people end up spending most of their time indoors. Thus indoor air becomes a cardinal exposure factor for them from a health and well-being perspective: the indoor environment in homes plays a crucial role for the prevalence of allergies, as well as for airways infections and Sick Building Syndrome (SBS). Indeed, there have been many studies linking cold and damp New Zealand homes to asthma, cold, flu and other winter related conditions (Howden-Chapman, 2005; Howden-Chapman, 2007a). New Zealand, along with countries like Australia and Great Britain, has one of the highest rates of asthma in the developed world, with approximately 15% of the adult population and 20% of children under the age of 15 affected by asthma. This equates to approximately 1 in 6 New Zealanders being affected, especially Maori and Pacific Island people, and those from lower socio-economic groups. Over the last 30 years hospital admissions for asthma have doubled, making the disease the most common cause of hospitalization for children. A prominent report published in 2007 by the Wellington’s School of
Medicine of the University of Otago, in Dunedin (NZ), confirmed that incidences of asthma in children are higher in homes with colder, damper indoor environments (Howden-Chapman, 2007b).

CONTAMINANTS IN DAMP RESIDENTIAL BUILDINGS

Generally, the term ‘air quality’ refers to the degree of pollution of the clean air. In regards to built environments IAQ gives a measure of physical, chemical and biological properties of the indoor air in order to provide healthy and comfortable living or working conditions (Sateru et al., 2004). Thus, a lower concentration of airborne pollutants – i.e. substances which can affect human health and comfort - in the indoor environment leads to a higher IAQ. As the evidence for a true association between pollutants in indoor air and cough, wheezing and asthma, as well as airways infections and Sick Building Syndrome is strong (Institute of Medicine, 2000), the implementation of an appropriate IAQ control strategy requires identification of sources of contaminants in the indoor environment and proper management of their concentration by means of source control and adequate ventilation. While building materials are typical sources of contaminants in homes (Zhang, 2005), the major risk in New Zealand is associated with mould presence in the indoor environment, as mould is a key trigger for allergic reactions. Generally mould includes all species of microscopic fungi that grow in the form of multi-cellular filaments: at least 60 varieties of mould types are known which can cause serious health problems. The most prevalent type, which is also the most aggressive disease trigger, is Stachybotrys, commonly called ‘black mould’. Compared to other mould types which prefer warmer temperatures, black mould grows well also at lower temperatures (between 2°C and 40°C) and it is common in colder and damper houses. As it needs the presence of liquid water to grow, it is found in abundance in buildings with leaks and condensation problems. New Zealand’s un-insulated houses, with average relative humidity (RH) between 65% and 85% and possible condensation issues due to water vapour transfer from inside to outside as shown by WUFI calculations, provide ideal conditions for Stachybotrys mould as it thrives especially when RH is above 70% (Zhang, 2005, p. 29).

Humid indoor environments also enable the development of mites, especially house dust mites (HDM), which are a trigger for the most common allergic problem in the world: asthma. HDM are microscopic, spiderlike 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. Dust mites (e.g. Dermatophagoides Farinae and Dermatophagoides pteronyssinus), which absorb the water from the air to survive, require a humid indoor environment with humidity levels ranging between 52% and 75% RH as well as an ideal indoor temperature ranging between 15° to 30°C.

Despite the relevance of this subject, research relating indoor environmental conditions, contaminants and health effects is still insufficient. It can be difficult because some factors affect various contaminants’ growth to different degrees (e.g. 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 (Rose, 2005, p. 24) and any specific threshold limit values for moulds to prevent hypersensitivity, irritant or toxic responses have not been established yet. However, considering that about 45% of New Zealand homes suffer from problems associated with excess moisture and dampness, this issue must be addressed. According to the WHO, the solution is provided by controlling the building envelope quality in terms of air infiltration, exfiltration, and pathways of water intrusion, assuring an adequate thermal insulation and by controlling moisture sources, indoor temperature, humidity and air velocity (WHO Regional Office for Europe, 2007).

AIRTIGHT BUILDINGS

The airtightness of the building envelope is a fundamental factor for energy efficiency and effective ventilation - directly affecting indoor air quality and comfort. The quality of the airtightness is determined
by the freedom from leakages in the building envelope: the more leakages there are on the inside of the building envelope the poorer will be the airtightness. The most common method to determine the airtightness is the so-called Blower-Door test as described in the European Standard EN 13829:2000 (CEN, 2000). A Blower Door is a diagnostic tool which helps locate air leakage within the building envelope. It consists of a calibrated fan for measuring an airflow rate, and a pressure-sensing device to measure the air pressure created by the fan flow. The combination of pressure and fan-flow measurements is used to determine the building airtightness. Measurements performed in pressurised or depressurised buildings, where climatic or other external influences are minimized due to high pressure difference created by means of a fan, allow a reliable prediction of ventilation rates in buildings.

Basically, the term ‘airtightness’ means protecting the thermal insulation in the building envelope against uncontrolled air movement or infiltration. A leak on the inside of the building envelope has a major impact in relation to the building durability. Air flowing from the inside towards the outside through leaks in the airtightness layer transports a great deal of heat and consequently leads to a higher heating energy demand. Furthermore, as air flows through the thermal insulation, the warm air cools and condenses within the outer wall. The precipitating moisture is referred to as condensation and may lead to mould. As a consequence, the leakage of the building envelope substantially impairs comfort for occupants and healthy indoor leaving conditions. Indeed, airtightness is an important part for effective functioning of the thermal insulation layer. It is also a critical element in ensuring that the construction is free from structural damage and in maintaining a pleasant interior living and working climate both in wintertime and in summertime, by assuring effective ventilation. Without airtightness (i.e. low infiltration rate through the building envelope) effective ventilation, either active or passive, is not achievable due to constant uncontrolled air movement. Like all the other buildings though, airtight buildings require adequate ventilation for health and comfort, which may include operable windows as well as fans etc. Literature on ‘dampness’, especially when considering ‘inside condensation on window’ as indicator, shows that inadequate ventilation in homes represents a major risk factor for health effects (cough, wheeze, asthma and airways infections). Thus the only difference will be that in airtight buildings unplanned infiltration is avoided. Additional costs of creating an adequately airtight building can be negligible but result in considerable benefits for health and comfort, beside the long term savings in energy.

The effects of inadequate airtightness were investigated by the Fraunhofer Institut für Bauphysik in Stuttgart, Germany, with a measurement study in 1989 (Wagner, 1989). The Institute tested both the thermal insulation effect and moisture penetration through an outside wall with an interior vapour barrier together with 140 mm mineral wool insulation – which was the thermal insulation standard in Germany at the time. Leakages were created at the centre of the 1 m² vapour barrier surface area, but not in the thermal insulation itself. The two parameters under investigation, thermal insulation effect and moisture transmission, were measured with the seamless vapour barrier at various pressure differences. The structure with various leakages at different widths was then investigated, at all pressure differences. Pressure differences on the building envelopes are produced both as a result of temperature difference between inside (mostly warm) and outside (mostly cold) and by wind pressure and wind suction. Given a temperature inside of 20°C, a pressure difference of 20 Pa is produced, for instance, at an outside temperature of -10°C and wind force 3 or outside temperature of 0°C and wind force 4. The measurement results were alarming and shocked specialists at the time. When investigating the performance of the 140 mm thick thermal insulation with the seamless vapour barriers, the measured heat transfer coefficient confirmed the theoretical value of 0.30W/m²K. The thermal insulation was then measured with the leakages of various widths at the various pressure differences. Even with the smallest leakage width of 1 mm and a pressure difference of 20 Pa, there was a reduction in insulation effect by a factor of 4.8 (heat transfer coefficient = 1.44 W/m²K).

In New Zealand, for the majority of the locations, there are not as extreme weather conditions as those used for the 1989 study. However, as indoor air temperatures are expected to increase up to 18-24°C as
suggested by the WHO for healthy IAQ, pressure differences between inside and outside will also increase, thus airtightness becomes a key issue for effectiveness of thermal insulation and ventilation, especially in exposed coastal areas in high wind zones.

The relevance of airtightness for energy efficiency and IAQ is confirmed by the recent implementation of many national and international standards, in particular the European Directive on Energy Performance of Buildings (EPBD) (European Parliament and of the Council, 2003). The Directive 2002/91/EC, which came into force in January 2003, defines airtightness requirements for new constructions, thus contributing to renew focus on air leakage as one of the major causes of energy consumption and discomfort in the building industry of many European countries. Since the implementation of the Directive into their national law (by January 2006 or 2009), the Member States of the European Union have addressed the issue of airtightness very differently. Results of a recent study comparing a total of 1094 $n_{50}$ values from field measurements collected from 7 European countries (Belgium, Greece, The Netherlands, France, Norway, Finland and Germany) prove that there is no standard approach for airtightness across Europe: remarkable differences exist between the mean $n_{50}$ values for houses among the different countries, varying from 1.09 in Norway (followed by Germany and The Netherlands) to 6.38 in Greece (with Belgium being close at 5.51) (Papaglastra et al., 2008). Despite the variety of performance (differences were also found between countries with similar climatic conditions), most of the countries take into account envelope air-tightness in their energy performance calculation procedures and some of them (e.g. Czech Republic, Germany, Denmark, Spain, The Netherland, Norway) even define minimum requirements on air-tightness in their regulations. In particular, in Luxembourg airtightness requirements for new buildings, which came into force on 1st January 2008, require a limit value $n_{50}$ [1/h] $\leq$ 3.0 for “buildings without ventilation equipment” and $\leq$1.5 for “buildings with ventilation equipment” (European Commission, Table 2, p. 135). Although not compulsory, envelope pressurization tests are largely used in Germany and Denmark. In particular, The German Energy Efficiency Regulation (EnEV 2009) requires the Blower Door test to prove that new occupied buildings (with heating system) meet airtightness requirements.

**Previous findings of airtightness in New Zealand**

Although airtightness has been proved to be a crucial factor for energy efficiency and health, the New Zealand Building Code and Standards related to ventilation do not set airtightness targets for residential buildings. As the majority of them rely on natural ventilation, the Compliance Document G4 Ventilation (Department of Building and Housing, 2008a) only require openable areas (window and doors) $\geq$ 5% of the floor area for air quality needs and summer cooling. Thus traditionally in New Zealand the satisfaction of ventilation needs relies also on background infiltration, which occurs though as a consequence of poor construction practices and materials used for the envelope. However, while natural ventilation refers to the air movement through opened windows, shutters and doors, the terms ‘infiltration’ simply describes the uncontrolled access of outdoor air into a building through leaks in the envelope such as openings, joints and cracks in walls, floors and ceilings, as well as around windows and doors. Infiltration is normally driven by wind and air pressure differences between the indoor and outdoor air.

The Compliance Document H1 Energy Efficiency of the New Zealand Building Code (Department of Building and Housing, 2008b) clearly states that airtightness of the building envelope has to be taken into account (H1.3.3 c). Interestingly, the airtightness profile of New Zealand houses has been investigated as one factor for the development of an indoor moisture control design tool for meeting criteria of the New Zealand Building Code (Cunningham, 1999). The BRANZ database of over 100 residential building airtightness measurements (Basset, 2001) was used to develop a classification of New Zealand house airtightness in four type categories, each characterized by a “base level infiltration rate”. The analysis of the database suggests an increase of airtightness associated to more recent buildings, especially due to
better performance of building components, e.g. aluminium joinery, much more air tight than earlier timber windows, or the replacement of strip internal linings.

Older buildings, such as the Victorian villas and bungalows or later Labour State houses, built before 1960 without insulation and building paper within the building envelope can be described as leaky and draughty buildings. Very high air infiltration rates heavily affect indoor ventilation, which cannot be controlled at any time (National Institute of Public Health, 1999, pp. 65-67). However also the most recent buildings included in the database appear to be subjected to high uncontrolled air exchange rate, with possible negative effects on energy efficiency, mould growth and effectiveness of the ventilation system. Indeed the “airtight type” is characterized by an air infiltration rate equal to 5 ac/h at 50 Pa, which appears extremely high compared to more restrictive European and American standards.

Table 1. Classifications of residential building airtightness.

<table>
<thead>
<tr>
<th>Type description</th>
<th>Airtightness ac/h at 50 Pa</th>
<th>Building description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airtight</td>
<td>5 ac/h</td>
<td>Post 1960 houses with a simple rectangular single story floor plan of less than 120 m2 and airtight joinery (windows with airtight seals)</td>
</tr>
<tr>
<td>Average</td>
<td>10 ac/h</td>
<td>Post 1960 houses of larger simple designs with airtight joinery</td>
</tr>
<tr>
<td>Leaky</td>
<td>15 ac/h</td>
<td>Post 1960 houses of more complex building shapes and with unsealed windows</td>
</tr>
<tr>
<td>Draughty</td>
<td>20 ac/h</td>
<td>All pre 1960’s houses with strip flooring and timber windows</td>
</tr>
</tbody>
</table>

Test results of airtightness measurements of new buildings

As most of the existing airtightness data for New Zealand houses relate back to Blower Door testing in 1980’s, a small test series was conducted in 2007 on houses located north of Auckland. All five test houses had the same design and layout. All buildings had a floor area of about 200 m² and an indoor volume of nearly 500 m³. The aim of the airtightness measurements was to determine if the infiltration levels continued to decline due to new construction methods or materials.

The Blower Door measurements for all five houses were between 4.47 and 5.58 ac/h at 50 Pa - the lower n50 of the first building being due to a different, more airtight front door in comparison to the other buildings. The measurements done on these contemporary houses show that infiltration levels have not continued to decrease and are nowhere near the required levels of the EPBD. In New Zealand the increasing temperature differences between inside and outside due to higher insulation levels (higher R-values and double glazing) and space heating (winter) or cooling (summer) will create pressure differences. In winter, warm air moving through convection into the building envelope will result in, beside lower energy efficiency, higher humidity concentration in the insulation (RH > 80%) and mould growth in the building envelope, leading to more health issues. Thus, in order to verify this hypothesis of higher moisture content in building envelopes in New Zealand simulations have been run considering old, renovated and new houses. Results show that also in the mild climate of Auckland moisture issues are likely to be found.
SIMULATION METHOD OF THERMAL AND HYGRIC PROCESSES

As already discussed, the balance of thermal conditions, air moisture content and IAQ in residential buildings can have a significant influence on the performance of buildings and the well-being of their occupants. In New Zealand practice though, no methods are currently used to simulate (thus to control) the process of moisture transport within building components in relation to the indoor climate conditions. The absence of an anticipatory approach increases the risk of designing uncomfortable indoor environments and poorly performing building envelopes, with long-term degenerative effects at different scales. It has been already said that “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?” (NZBCSD, 2008b, p. 23)

A fundamental progress in controlling housing quality and performance can be realized by recognizing the complete ‘objectivity’ and ‘measurability’ of building performance – which, in terms of energy, comfort and IAQ, can be comprehensively assessed by measuring temperature, relative humidity, airtightness and ventilation rates, all well defined by scientific literature and international standards. Thus, calculation methods and simulation programmes as well as measurement tools (e.g. the Blower Door test), can assist in providing a general assessment of the hygrothermal performance of buildings, demonstrating potential risks associated with certain practices of construction and renovation.

Although more extensive research is required to define airtightness levels of contemporary New Zealand houses, the sample measurements described above show no major improvement in reduced infiltration rates since the 1980s. At the same time though, following the international trend, in New Zealand the thermal insulation levels have also risen in the last few years, as confirmed by the new R-values of the updated New Zealand Building Code Compliance Document H1 Energy Efficiency (Department of Building and Housing, 2008b). Although still far less restrictive than other standards, e.g. national implementations of the European Directive on Energy Performance of Buildings (European Parliament and of the Council, 2003), the new H1 has increased the thermal performance of the envelope, which
results in an increased proportion of energy lost to draughts (BRE, 2002, p. 3). Further increase of thermal insulation levels would be (and sometimes already is) unproductive if airtightness is not addressed, as air leakage has been shown to reduce substantially the effectiveness of thermal insulation.

In order to verify if actual New Zealand construction and renovation methods would be appropriate to meet international standards on comfort and IAQ – which define a design indoor temperature zone around 20°C (Olesen, 2004, p. 18) - in 2009 a research project was started at the University of Auckland, aiming to develop innovative and effective (in terms of indoor environmental control and energy efficiency) construction systems for the building envelope. As part of the initial investigation phase, different housing typologies, of both retrofitted and new constructions, were simulated using a software program called WUFI (Wärme und Feuchte instationär - Transient Heat and Moisture) (Fraunhofer-Institut für Bauphysik, 2009). WUFI is a non-steady simulation software developed by the Fraunhofer Institute for Building Physics (IBP), that can provide customized solutions to moisture engineering and damage assessment problems for various building envelope systems.

The selection of types for simulation covered a large portion of the existing New Zealand housing stock and included Victorian villas and cottages (1870-1920), Californian bungalows (1918-1930) (Zhang, 2009), Labour state houses (1930 - 1970), Multi-unit and private development houses (1960’s), Pre and Post-insulation houses (1970 - 1989) (De Groot, 2009) and more recent examples of standard timber frame housing with and without intelligent vapour checks. Despite the wide range of climatic conditions and topography characterizing the country, the same basic mass housing types were initially used throughout New Zealand. They were mainly timber framed houses (Fowler, 1983, p. 7) with metal roofs and little or no insulation. Later changes appeared in house typology as a consequence of shifts in society, culture and building regulation updates, especially the introduction of mandatory insulation. However current types share many similarities with the older ones.

In the attempt to improve their poor original thermal performance, a great number of older homes have been renovated placing insulation within the existing wall frame. However, for certain conditions of temperature and wind pressure, this method can lead to serious moisture damage to the timber structure over time, as trapped and absorbed moisture can build up over time and lead to decaying of the timber structure. In response to this, some practitioners have resulted to leaving the walls uninsulated and only insulating the roof and under-floor crawl space, but this solution is unable to address the great proportion of heat loss and to provide acceptable comfort conditions. Simulations with WUFI of these retrofitted types highlight possible issues of interstitial condensation and mould growth.

**Case-study: a retrofitted Labour state house in Auckland**

Figure 2 shows graphic results of the WUFI simulation of thermal and hygric processes in a Labour state house located in Auckland, pre and post-retrofitting interventions. Reference R-values were taken from the New Zealand Standard NZS 4218:2004, which, since October 2008, requires all new homes to meet new thermal insulation requirements formulated for different climate zones (Standards New Zealand, 2004). Although not applicable to the existing building stock or to retrofitting interventions, the new R-values of the updated standard can be used as a minimum target to achieve acceptable thermal comfort.

As the roof construction is usually accessible and ventilated, it is possible to retrofit the roof space with 120 mm of a good insulation layer ($\lambda = 0.04$ W/mK), to achieve an acceptable R-value of minimum 2.9 m$^2$K/W. In terms of the floor construction, the most common solution is installing 60 mm of expanded polystyrene (EPS) underneath the accessible and ventilated floor construction, which provide a minimum R-value of 1.3 m$^2$K/W. Regarding the external wall construction, it is common practice to fill in the existing frame cavities with thermal insulation material, generally fibreglass ($\lambda = 0.04$ W/mK), improving the wall thermal resistance to an acceptable R-value of minimum 1.9 m$^2$K/W. The absence of a ventilated gap between the weatherboards and the timber frame can improve the insulation ability of the external
wall but also increase the risk of moisture build up. Indeed, WUFI simulations show that interstitial condensation occurs and the moisture content of the insulation layer remains always very high, with relative humidity over 80% (outdoor temperature as for climate data file for Auckland; indoor temperature and humidity as for WHO recommendation. De Groot, 2009, pp. 97-105.)

In order to maintain the moisture content of the insulation within acceptable levels two alternative options were tested: the addition of a ventilated air cavity between the weatherboards and the building paper and the combination of a humidity-variable vapour check (vapour transmission resistance: 1.275 MNs/g – 53 MNs/g, humidity variable) with a new layer of building paper. The analysis of individual layers with WUFI shows acceptable moisture levels within each material of the two alternative solutions and does not indicate any moisture build up. As this program does not take into account convention effects, further benefits are expected from the correct installation of a vapour check in order to provide a continuous airtight layer (De Groot, 2009, p. 108).

Due to analogue construction systems, similar results were obtained for the other older types analysed. Although further testing is recommended, the results of this preliminary set of simulations run using the mild Auckland climate confirm that a different approach to retrofitting is required in New Zealand, especially in those climate zones where more severe conditions apply.

![Figure 2. Labour State House. WUFI animation: Assessment of interstitial condensation formation in the external wall, with insulation but no ventilated cavity (RH reach 100% during the calculation period of 3 years) (De Groot, p. 127).](image)

WUFI calculations of more recent examples of standard timber frame housing with and without intelligent vapour checks indicate that the greater the temperature difference between the inside and outside of a building the more important the internal moisture control becomes in winter time as well as in summer time. Due to the climate conditions in New Zealand, beside the protection of the building envelope from internally driven moisture, the drying potential from within the building envelope towards the inside is essential to ensure the structure is free from structural damage. Vapour barriers, as used in predominately cold climates, will not provide a solution for New Zealand climate conditions due to the
non existing diffusion openness towards the inside which would allow moisture in the building envelope to move towards the inside of the building where it can be removed through ventilation. The advantage of modern intelligent vapour checks is that these systems can be used as an airtightness layer at the same time and the effectiveness can be quantified on every building by conducting a Blower Door test.

CONCLUSION
A number of risk factors for mould and indoor pollutant levels can be found in different housing types, both old and new, of the New Zealand building stock. Design for moisture control means providing an adequate building envelope quality in terms of air leakage and thermal insulation and controlling moisture sources, indoor temperature, humidity and air velocity. In New Zealand practice though, in absence of airtightness requirements by national regulations, no methods are currently used to simulate (thus to control) the process of moisture transport within building components in relation to the indoor climate conditions, increasing the risk of long-term degenerative effects at different building scales.

The use of simulation programmes, such as WUFI, and Blower Door tests can assist New Zealand practitioners to provide a general assessment of the hygrothermal suitability of particular building components. Used as a means of verification in this study, they showed no major improvement in reduced infiltration rates of New Zealand houses since the 1980s and highlighted the potential inadequacy and the risk associated with certain practices of building construction and renovation. More extensive research is required to define airtightness levels of contemporary New Zealand houses and long-term effects of increasing occupant comfort and energy efficiency requirements. Although WUFI predictions still need to be related to field data for validation, it is now evident that increases in thermal performance of the envelope would be unproductive, or even counterproductive, if airtightness is not addressed.

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