Exploring the Use of Mould Estimation Software in New Zealand Houses

By

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PREFACE

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Executive Summary

The 2015 Building Research Association of New Zealand House Condition Survey reported that 46% of owner-occupied residential properties, and 54% of rented residential properties had some form of mould growth in them. Being regularly exposed to mould spores in houses has been shown to increase the risk of developing respiratory diseases and exacerbating asthma symptoms. This means that a large portion of the population could be at risk of suffering from these adverse health effects. Increased air-tightness in new houses could also be at risk of being under-ventilated, potentially exacerbating this mould issue

It is unknown whether the current New Zealand Building Code, at the time of writing, provides sufficient ventilation requirements to prevent new houses from being under-ventilated. It also does not consider existing houses, which is where most of the mould in the HCS was found.

The aim of this thesis was to test if simulation software can be used to estimate the risk of mould growth in New Zealand bathrooms, and if so, test how mould mitigation strategies can affect this risk. The intent of this was to determine what strategies would be best to recommend to home occupiers to help address the mould reported by the House Condition Survey, and to designers to ensure that new houses aren't more susceptible to mould. The following research objectives were established to help achieve this aim:

1. Identify what strategies are recommended to New Zealand home occupiers.
2. Establish whether representative models capable of testing the risk of mould can be created using House Condition Survey data and WuFi-Bio.
3. Determine what interventions are most effective at reducing mould in New Zealand bathrooms.
4. Establish hierarchy of interventions that can be used to inform occupants and designers what the best methods are to reduce mould growth.

A literature review of publicly available material from New Zealand Government agency websites was conducted to meet research objective one. Four sources were found that provided guidance: Ministry of Business, Innovation, and Employment, Housing New Zealand, Energy Efficiency Commission Agency, and Building Research Association of New Zealand. Their consensus was that existing mould should be removed via cleaning or disposing of infected material, with ventilating during showers, heating during showers, and insulating used as means of prevention

A pilot study was conducted to meet research objective two. This involved modelling two bathrooms from the House Condition Survey in WuFi-Pro, estimating the risk of mould in them using WuFi-Bio, and comparing these results to mould observations from the House Condition Survey. The intent of this was to establish a modelling methodology that could be used to model the other 15 bathrooms that were used in this study. The results from this did not align with the observations from the House Condition Survey, and uncertainty caused by limited data from the House Condition Survey made it unclear whether models that did align emulated the risk of mould in the actual bathrooms.

An initial data analysis was conducted to test if assumptions made during the pilot study contributed to the results not aligning with the House Condition Survey. This consisted of modelling all 17 bathrooms, conducting sensitivity analyses of their orientation, insulation, and exterior finishes, and using WuFi-Bio and WuFi Mould Index VTT to estimate the risk of mould in the variations. The results still did not align with the House Condition Survey, indicating that none of these assumptions contributed to the results not aligning.

A parametric study was conducted to explore if research objective three could be achieved despite being unable to get the results to align with the House Condition Survey. This involved trying to generate an artificial risk of mould in the 17 bathrooms, and making variations of each bathroom to represent the strategies identified as part of research objective one. But no significant risks of mould could be generated, and mould mitigation strategies could not be tested.

The cause of this could not be determined. However, a short estimation period (4 months) caused by limited time-series data of internal conditions, and lack of knowledge about how the mould in the bathrooms grew were identified as likely contributors. These factors also prevented further exploration into identifying the actual cause. It was concluded that a controlled experimental study aimed at understanding a few houses in-depth would be a more appropriate method to test mould mitigation strategies, and help address the mould issue in New Zealand houses.

ABSTRACT

Regularly being exposed to the types of mould spores that can grow in houses has been shown to lead to adverse health effects such as respiratory diseases, and the exacerbation of asthma. While susceptible groups such as children, the elderly, and atopic persons are more susceptible to these effects, adverse health effects from mould spores have been shown to affect non-topic populations.

The 2015 Building Research Association of New Zealand House Condition Survey found that 46% of owner-occupied properties, and 54% of rented properties in a representative sample of the New Zealand housing stock have some form of mould in them. This means that a large portion of the population could be at risk of suffering from the adverse health effects associated with mould growth in houses. Increased air-tightness in new houses could also be at risk of being under-ventilated, potentially exacerbating this mould issue

It is unknown whether the current New Zealand Building Code, at the time of writing, provides sufficient ventilation requirements to prevent new houses from being under-ventilated. It also does not consider existing houses, which is where most of the mould in the HCS was found.

This study explored whether data from the House Condition Survey and WuFi-Bio could be used to test mould mitigation strategies in New Zealand residential bathrooms. This was done by modelling a subset of houses from the House Condition Survey in WuFi-Pro, estimating the risk of mould in them with WuFi-Bio, and comparing this to the observations from the House Condition Survey. Parameters in the models were then changed to reflect the impact that strategies would have on the humidity and temperature in the bathrooms. The aim of this was to develop a hierarchy of recommendations that could help home occupiers and designers determine the most appropriate methods they could use to prevent mould from growing in their homes/designs.

However, the results did not align with the observations from the House Condition Survey, and testing the validity of the models by exploring the impact of assumptions showed they had no significant impact. The cause of this misalignment could not be determined, however a lack of internal condition time-series data and information about how observed mould from the House Condition Survey were identified of areas of uncertainty and prevented further exploration.

The exploration that was conducted revealed the importance of having enough data to understand the conditions that lead to any observed mould if an existing bathroom is being assessed using WuFi-Bio. It was concluded that attempting to assess a large number of houses with little data using WuFi-Bio was impractical. A controlled experimental study aimed at understanding a few houses in-depth would be a more appropriate method to test mould mitigation strategies, and help address the mould issue in New Zealand houses.

List of Abbreviations

BRANZ	Building Research Association of New Zealand
CMC	Critical Moisture Content
EECA	Energy Efficiency and Conservation Authority
HCS	2015 BRANZ House Condition Survey
HIG	BRANZ 2015 House Insulation Guide
HNZ	Housing New Zealand
IRHS	Initial Relative Humidity of the Model Mould Spore
LIM	Lowest Isopleth for Mould
MBIE	Ministry of Business, Innovation, and Employment
NHLBI	U.S. National Heart, Lung, and Blood Institute
NIWA	National Institute of Water and Atmospheric Research
NZ	New Zealand
NZBC	New Zealand Building Code
OVBS	Occupant Ventilation Behaviour Study
VTT	WuFi Mould Index VTT
WCoS	Water Content of Model Spore
WHO	World Health Organisation

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Chapter 1: Introduction

Introduces the gap in knowledge and problem that the research in this thesis is trying to address. The aim, research approach, and general overview of the thesis are presented.

1.1 Background

1.1.1 Impact of mould in homes

The occupants of damp and mould infested homes are more likely to suffer from a wide range of health symptoms, including minor discomfort such as coughing, and more severe issues such as respiratory infection (Heseltine, Rosen, & WHO, 2009, p. 93). There is also evidence suggesting that visible or odorous mould infestations are linked to an increased risk of developing asthma (Quansah, Jaakkola, Hugg, Heikkinen, & Jaakkola, 2012, p. 8), and it's exacerbation (Fisk, Lei-Gomez, & Mendell, 2007, p. 289). To make sure that homes are comfortable and provide a healthy environment for their occupants, measures need to be taken during the design stage and occupation to ensure that a favourable indoor environment for mould growth is not created (Heseltine et al., 2009, p. 93).

1.1.2 Presence of mould in New Zealand homes

In 2015, the Building Research Association of New Zealand (BRANZ) conducted the House Condition Survey. This study is undertaken every 5 years, and aims to collect data on the New Zealand (NZ) housing stock that can then be analysed to identify trends and issues faced by NZ buildings (White, Jones, Cowan, & Chun, 2017, p. 1).

The results showed that 46% of owner-occupied properties, and 54% of rented properties have some form of mould present. Mould was most commonly found in the bathrooms (White et al., 2017, p. 25), with many potentially being under ventilated due to half not having mechanical ventilation (White & Jones, 2017, p. 19). This suggests a large number of house occupants are being exposed to some level of mould on a regular basis, and are at risk suffering from the symptoms mentioned in section 1.1.1.

1.1.3 POTENTIAL EXACERBATION OF MOULD ISSUE

In 2015, a survey was conducted that measured the airtightness of 36 random houses built after 1994. The results from this were compared to previous studies that measured the air tightness of older buildings, and a showed a continued trend that newer homes were being built more air-tight (McNeil, Plagmann, McDowall, & Bassett, 2015, p. 56).

The findings from this study indicate that new homes being put into the housing stock are likely to be more air-tight than existing ones. The more air and vapour tight a building is, the more likely it is to suffer from being under-ventilated and lead to the accumulation of pollutants such as CO_2, and moisture (Howieson, Sharpe, & Farren, 2014, p. 484). This could lead to more mould-prone homes being added to a housing stock that already has an extensive mould problem, unless controlled ventilation and mould mitigation strategies are implemented to compensate.

1.1.4 NZ BUILDING CLAUSES RELATED TO MOULD

The accumulation of internal moisture has been shown to be the main variable that allows mould to grow (Koskinen, Husman, Meklin, & Nevalainen, 1999, p. 1367). Ventilation has been shown to be the one of the main methods used to prevent this accumulation (Peat, Dickerson, & Li, 1998, p. 125). The minimum requirements for these variables that homes need to meet are dictated by the NZ Building Code (NZBC) clauses “E3 Internal Moisture” and “G4 Ventilation”. These are the main method used to combat the issue identified by the HCS (White et al., 2017, p. 25) and the potential exacerbation of this issue by more air-tight homes being put into the housing stock (McNeil et al., 2015, p. 56).

"E3 Internal Moisture" is intended to ensure that buildings are designed with adequate moisture management and systems to prevent fungal growth and damage caused by the presence of moisture. The clause's objectives are (MBIE, 2017a, p. 3):

a) Safeguard people against illness, injury, or loss of amenity that could result from the accumulation of internal moisture.
b) Protect household units and other property from damage caused by free water from another household unit in the same building.

The clause achieves this through prescriptive solutions that require all buildings to meet a minimum standard for thermal resistance, condensation control, and ventilation (MBIE, 2017a, p. 3). For thermal resistance a building must have a minimum R-value of $1.5m^2\,^{o}C/W$ or $0.6m^2\,^{o}C/W$ for walls, depending on the type of construction, $1.5m^2\,^{o}C/W$ for all roofs and implement prescribed construction elements to minimise thermal bridges and air leaks (MBIE, 2017a, p. 13). Condensation control is dictated by requiring all areas where condensation accumulates to be drained to the outside, and the provision of a list of acceptable interior surfaces that can be used in wet areas e.g. bathrooms and kitchens. Ventilation is dictated by Clause G4 which is discussed later in this section (MBIE, 2017a, p. 14).

No verification method has been adopted into Clause E3 that can be used to show compliance (MBIE, 2017a, p. 11). This means that the simplest way to meet the performance criteria is to use the prescriptive solutions outlined in the clause. Clause E3 received its last major revision (not including amendments) 21 years ago, at the time of writing. It is unknown whether the increased air-tightness in new houses would make it easier for mould to grow due to increased moisture accumulation, and if the requirements of Clause E3 are sufficient to prevent this (Jaques, Berg, & McNeil, 2016, p. 1)

"G4 Ventilation" requires that buildings are designed to provide adequate ventilation to remove air pollutants and protect against building damage. The clauses' stated objective is (MBIE, 2017b, p. 3):

a) The objective of this provision is to safeguard people from illness or loss of amenity due to lack of fresh air.

The clause achieves this through prescriptive solutions that require all buildings to meet minimum standard window areas, passive ventilation schemes, and flow rates for mechanical systems (MBIE, 2017b, p. 3). Windows in occupied spaces and wet areas (e.g. bathrooms, kitchens) are required to have a minimum area of no less than 5% of the floor area of the room (MBIE, 2017b, p. 13). Recommended passive systems are trickle ventilators, and passive stack ventilators, required to achieve air flow extraction rates specified in AS1668.2 (MBIE, 2017b, pp. 15-16). Mechanical systems are required to meet the flow rates specified in AS 1668.2 (MBIE, 2017b, p. 18). However, it is unknown whether these solutions are sufficient to alleviate the housing stocks mould growth identified in the HCS (White et al., 2017, p. 25).

Means of ventilation that Clause G4 regulates such as windows and manually controlled extractor fans effectiveness is dependent on how occupant decides to use them. The study discussed in section 1.1.3 surveyed 36 randomly selected homes, and found most of them were not opening windows much during the 3-4 week survey period (McNeil et al., 2015, p. 28). While the small sample size cannot be considered representative of the whole housing stock, this does indicate that there is a risk that some occupants may be under ventilating their homes. This poses the risk that any solutions Clause G4 recommends are not preventing moisture from accumulating in some homes due to occupants not utilising the systems that it suggests/requires.

The two clauses discussed here only apply to the design of new buildings. However, most of the homes surveyed during the HCS that had mould in them were built before these clauses were implemented, and thus did not need to meet these requirements. The Building Act does require existing buildings to meet some standards when making an alteration, but this does not include moisture management or ventilation systems. This means that any regulation introduced to help address the amount of mould in the housing stock would have no effect on most of the homes with mould in them, unless it is made retrospective.

1.2 PROBLEM STATEMENT

The following is a summary of the main points that were established in section 1.1:

1. Mould growing in homes can lead to an uncomfortable, and potential unhealthy, indoor environment.
2. Approximately half of the homes in the NZ housing stock have mould in them.
3. The increasing air-tightness of new homes could add more mould prone homes into this housing stock.
4. It is unknown whether the current requirements of the NZBC are suitable to prevent mould growing in new homes.
5. The NZBC has no way of introducing strategies into existing homes, which are most of the homes with mould found in them.

Based on these statements, the following problem and gap in knowledge has been identified:

Problem:	A method for introducing effective mould mitigation strategies at a scale capable of combatting the mould found in the NZ housing stock is unknown.
Gap in Knowledge:	It is unknown what the most effective means of mould prevention would be in NZ homes.

Identifying what mould prevention strategies that work best in NZ homes could help address this gap in knowledge. Using those strategies to provide guidance to home occupiers and designers could help address this problem.

1.3 AIMS, OBJECTIVES, AND SIGNIFICANCE

Findings from the 2015 BRANZ House Condition Survey (HCS) have shown that their significant mould growth in a large number of NZ homes, mostly in their bathrooms (White et al., 2017, p. 25). Existing literature has shown that having mould in a residential building can lead to an uncomfortable indoor environment and respiratory infection in more serious cases (Heseltine et al., 2009, p. 93). Based on the findings from the HCS (White et al., 2017, p. 25), half of the buildings in the NZ housing stock are at risk of creating mould conductive environments. To combat the housing stocks mould issue, effective measures to reduce mould growth in NZ buildings needs to be found and implemented.

The aim of this thesis is to test if simulation software can be used to estimate the risk of mould growth in NZ bathrooms, and if so, test how mould mitigation strategies can affect this risk. This would help identify what strategies would be the most worthwhile to implement. This information could then be used to provide guidance to home occupiers with mould in their bathrooms, designers putting new buildings into the housing stock, and contribute to developing changes to relevant NZBC clauses such as G4 and E3. Implementing these changes will help reduce the number of bathrooms with mould, and subsequently help create more comfortable and healthy environments in NZ homes.

1.3.1 RESEARCH OBJECTIVES

To achieve this aim, the following research objectives were established:

5. Identify what strategies are recommended to NZ home occupiers.
6. Establish whether representative models capable of testing the risk of mould can be created using HCS data and WuFi-Bio.
7. Determine what interventions are most effective at reducing mould in NZ bathrooms.
8. Establish hierarchy of interventions that can be used to inform occupants and designers what the best methods are to reduce mould growth.

1.4 RESEARCH APPROACH

Models of bathrooms from the NZ housing stock were created in WuFi-Pro, changes were then made to emulate mould mitigation strategies, and WuFi-Bio and VTT were used to assess the risk of mould between these changes. Data on these bathrooms was obtained as part of the 2015 House Condition Survey (HCS), and the Occupant Ventilation Behaviour Study (OVBS) both conducted by BRANZ. The research was separated into three parts; the pilot study, used to develop a modelling methodology; the initial data analysis, testing the impact of assumptions made during modelling process; and the parametric study, testing the impact of interventions.

The purpose of this thesis was to test what mould mitigation strategies would most effectively alleviate mould in NZ bathrooms. This could then provide guidance to occupants and designers to help them address the housing stocks mould issue. Research questions were established to help guide this investigation and test whether what is proposed in section 1.3 can be done, and if so, dictate the method used to establish the most effective strategies.

The following are the research questions and how they influenced the research approach.

1. **What mould mitigation strategies are currently used by or recommended to NZ house holders?**

   The strategies currently being used in bathrooms need to be known. This would identify what strategies have been shown alleviate mould, which do occupants currently use, what ones do designers implement, and ultimately, which ones were tested in this thesis. A literature review was conducted to establish what the consensus was in existing literature about the most effective strategies around the world and what were common strategies be used or recommended in NZ. This literature review is presented in Chapter 2:.

2. **Can models capable of testing mould mitigation strategies be created using HCS data and WuFi-Bio?**

   Whether the HCS includes all the required information and WUFI can produce usable models needed to be known. If models that did not represent actual NZ bathrooms were used, then it couldn't be determined whether the simulated effect of each strategy would be like the real effect. The results of this comparison would then determine whether it was worthwhile continuing on to investigate strategies.

   A pilot study was used to test if usable models of two bathrooms could be produced, and is presented in section Chapter 5:.

3. **Do the assumptions made to produce the models have an impact on the risk of mould?**

   Assumptions had to be made during the modelling process, but it was unknown whether the impact of making an incorrect assumption would be significant. It is important to know whether the impacts of any tested strategies may be different in bathrooms that do not align with what was assumed. An initial sensitivity analysis was conducted to test the differences between plausible variations of assumptions. The initial data analysis is presented in Chapter 6:.

4. **What commonly used mould mitigation strategies are most effective at reducing the risk of mould in NZ bathrooms?**

   To discern what strategies would most effectively alleviate mould, they need to be tested in NZ bathrooms. This would help determine what strategies should be recommended to occupants of existing homes and designers putting new homes into the housing stock. A parametric study, changing parameters in a way that emulates mould mitigation strategies in models representing NZ bathrooms was used to test this. This parametric study is presented in section 6.1.

1.5 THESIS OUTLINE

The following outlines the rest of this thesis and what is discussed in each chapter.

Chapter 2: presents the findings from the literature review. An overview of the concepts around mould, what strategies are commonly recommended to NZ home occupiers, and how WuFi-Bio has been used in previous studies are discussed.

Chapter 3: presents a summary of the HCS and the data used from it. The summary includes an explanation of the HCS scope and the data collection process. The houses that were used from the HCS and the data about them that was used in this study is presented and discussed.

Chapter 4: presents an overview of the software that was used in this study: WuFi-Pro, WuFi-Bio, and WuFi Mould Index VTT. Brief summaries of how they work and why they were used are presented. How they were used with the data presented in Chapter 3: is discussed.

Chapter 5: presents the pilot study that was used to develop the modelling and estimation methodology. Going through the methodology, identifying issues and limitations, and the implications that those limitations have on the scope of the study are discussed. At the end a revised methodology is presented.

Chapter 6: presents the initial data analysis that was conducted to test the impact of major assumptions made in Chapter 5:. The sensitivity analyses used to test these assumptions, the results from thee analyses, and how the assumptions made could have affected the risk of mould are discussed.

Chapter 7: presents the parametric study that was used to test the impact of mould mitigation strategies on the risk of mould growth. What strategies were included, how they were modelled, and the results from this process are discussed.

Chapter 8: discusses potential reasoning's for the results obtained throughout Chapter 5: to Chapter 7:. How the lack of data restricted further exploration of the obtained results is discussed.

Chapter 9: discusses how the findings from this thesis fit into the wider research field of mould growth in houses and mould estimation software. Areas of potential future research are identified.

Chapter 10: presents the conclusions made based on the findings discussed in 7.5. How the study did or did not meet the research objectives in section 1.3.1 is discussed.

Chapter 2: Literature Review

A systematic literature review was conducted to establish a consensus between existing literature on mould and strategies used to alleviate it. The strategies recommended to home occupiers, strategies shown to be effective, and how WUFI has been used in previous studies are discussed.

A literature review was conducted answer research question one and establish consensus about existing knowledge that was needed to complete this study. It also provides context to some of the decisions made later in this thesis.

This review is separated into the following three sections:

1. A summary of information that provides context to the concepts discussed in this thesis, including the World Health Organisations stance on mould in indoor environments and related ASHRAE standards to mould growth.
2. Review of New Zealand government recommendations to alleviate mould
3. Systematic review of the use of WuFi-Bio in previous studies

2.1 OVERVIEW OF MOULD IN HOUSES

This section provides background information about mould, how it grows in houses, and standards associated with its prevention and alleviation.

2.1.1 WORLD HEALTH ORGANISATION GUIDELINES

This section summarises information from the World Health Organisations *"WHO guidelines for indoor air quality: dampness and mould"* that provides context to the concepts around mould that are discussed and explored in this thesis. This 2009 study was a comprehensive review of existing literature at the time of publication about the health implications, causes, and means to alleviate and prevent mould in indoor environments (Heseltine et al., 2009).

WHO identified mould as a health risk factor when growing in the indoor environment because buildings are enclosed spaces and people often spend a substantial amount of time in them. This results in regular exposure to mould spores that have been shown to increases the risks of developing respiratory infections, and the exacerbation of asthma (Heseltine et al., 2009, p. 93). Groups that are susceptible to these risks include children, the elderly, and allergic persons (Heseltine et al., 2009, p. 1). However, adverse health effects have also been found in non-atopic populations, and occurs in low, middle, and high income countries (Heseltine et al., 2009, p. 93).

The design and conditions created in buildings all contribute to whether mould will grow in an indoor environment, although indoor dampness was established as the main factor. High air humidity, condensation, and water damage provide suitable environments for mould to germinate (Heseltine et al., 2009, p. 93). All of these variables contribute to increased water activity on and inside surface materials (Riordan & Tsongas, 2016, p. 32). This provides water needed by mould spores that have been carried into a building by external air to germinate and continue to grow (Clarke et al., 1996, p. 32)

The following lists common moisture related issues that can result in water activity on or in materials that create suitable environments for mould germination (Heseltine et al., 2009, p. 36):

- Leaky building (Rainwater or groundwater leaking into building envelope)
- Capillary suction of rainwater, or other sources of moisture, through porous materials that do not tolerate wetting.
- Enclosure of wet materials in the building envelope that cannot be dried.
- Excessive internal moisture production that is not ventilated out of the building.
- Poor drainage that allows build up condensation in wet rooms.

Management of moisture and well-designed, and well-constructed building envelopes were deemed the most effective means to reduce the risk of mould growing in buildings. Moisture management is conducted with ventilation and heating which prevents the accumulation of moisture from indoor activities and the build-up of condensation on building materials. Well-designed exterior envelopes avoid thermal bridges that allow loss of excessive heat, are free from leaks that allow external moisture to infiltrate the envelope, prevent the condensing of water vapour in the envelope, and allow the drying out of moisture-laden materials used during construction (Heseltine et al., 2009, p. 36). Efforts need to be made during the design stages, and maintenance over the life of the building to ensure these benefits are ongoing.

2.1.2 ASHRAE STANDARDS

The conditions required to create a favourable environment that supports mould germination and growth are dependent on multiple factors, including access to oxygen, nutrients, water, and temperature. However, the availability of water and temperature are the variables that designers and occupants have the most control over, and thus are the main focus when implementing mould prevention strategies (Clarke et al., 1996, p. 32). This can result in an oversimplified (and misunderstood) method of determining whether mould will grow (Riordan & Tsongas, 2016, p. 33).

Riordan and Tsongas have compiled a summary of this issue in the AHRAE Journal article *Minimum Conditions for Visible Mould Growth* (Riordan & Tsongas, 2016). Commonly in research and building practice the ambient air relative humidity and temperature are used to indicate whether mould will grow. For example, EECA recommends to home occupants that the air relative humidity and temperature should not be above 65% (recommended by ASHRAE Standard 62.1-2016(ASHRAE, 2016b)) nor below 18ºC (recommended by ASHRAE Standard 55-2017 (ASHRAE, 2017)) most of the time (EECA, 2019).

However, this approach does not consider the time-to-humidity link, where the relative humidity of the air making contact with a surface needs to be higher for mould to germinate in a shorter period (Riordan & Tsongas, 2016, p. 33). This also does not consider the time variable that is required to test if favourable conditions are being maintained for long enough for mould to germinate, or if frequent drying periods halt this process. It also substitutes the actual indicator of the risk of mould for the ambient air relative humidity. The actual indicator is the water activity occurring on, or in, a material, which is dependent on more than just the ambient air relative humidity (Riordan & Tsongas, 2016, p. 33).

A method for estimating whether mould will grow was presented in ASHRAE 160-2009 (ASHRAE, 2009) that considers water activity at the surface of a material and time of wetness. For a 30 day running period, the average relative humidity over that period should not exceed 80% to prevent mould germination, and should not exceed 85% to prevent visible mould growth.

ASHRAE 160-2016 (ASHRAE, 2016a) superseded ASHRAE 160-2009 and replaced the criteria described above in favour of Viitanen's mould index system. This approach also considers how sensitive a material is microbial activity. The criteria given below is quoted directly from ASHRAE 160 (ASHRAE, 2016a), with some changes in wording in references to tables and equations to suit the format used for this thesis:

In order to minimize problems associated with mould growth on the surfaces of components of building envelope assemblies, the mould index, calculated in accordance with equations Equation 1 through Equation 7, shall not exceed a value of three (3.00).

The building material surface under analysis shall be assigned to one of the following four sensitivity classes: Very Sensitive, Sensitive, Medium Resistant, or Resistant. Examples of materials included in each class are shown in Table 1.

TABLE 1 RECOMMENDED MOULD SENSITIVITY CLASSES FOR VARIOUS MATERIALS AS PER ASHRAE 160

Sensitivity Class	Materials
Very sensitive	Untreated wood; includes lots of nutrients for biological growth
Sensitive	Planed wood, paper-coated products, wood-based boards
Medium resistant	Cement or plastic based materials, mineral fibres
Resistant	Glass and metal products, materials with efficient protective compound treatments

The initial value of the mold index (M) shall be zero ($M = 0$ at time t = 0). The mold index shall be accumulated for each hour using Equation 1:

$$M_t = M_{t-1} + \Delta M$$

EQUATION 1 MOULD ACCUMULATION PER HOUR

Where:

M_t	=	mould index for the current hour
M_{t-1}	=	mould index for the previous hour
ΔM	=	change in mould index, calculated for each hour using Equation 4 or Equation 7 according to the conditions specified below

The mould index shall have a minimum value of zero; if $M_{t-1} + \Delta M$ yields a negative number at any time step, then M_t shall be set equal to zero at that time step.

If the surface temperature (T_s) is greater than 0°C at the current hour, then the critical surface relative humidity for mould initiation (RH_{crit}) (expressed as a percentage) shall be calculated using equations Equation 2 and Equation 3 corresponding with the selected sensitivity class of the material being assessed:

<u>Very Sensitive Class or Sensitive Class</u>

$$RH_{crit} = -0.00267T_s^3 + 0.160T_s^2 - 3.13T_s + 100 \; when \; T_s \leq 20 \; ^oC,$$
$$80 \; when \; T_s > 20 \; ^oC \; [T_s \; in \; ^oC]$$

EQUATION 2 CRITICAL RELATIVE HUMIDITY FOR VERY SENSITIVE AND SENSITIVE SURFACES

<u>Medium Resistant Class or Resistant Class</u>

$$RH_{crit} = -0.00267T_s^3 + 0.160T_s^2 - 3.13T_s + 100 \; when \; T_s \leq 7 \; ^oC,$$
$$85 \; when \; T_s > 7 \; ^oC \; [T_s \; in \; ^oC]$$

EQUATION 3 CRITICAL RELATIVE HUMIDITY FOR MEDIUM RESISTANT AND RESISTANT SURFACES

If the relative humidity at the material surface (RH_s) (expressed as a percentage) is greater than RH_{crit} at the current hour, then an increase in the mold index shall be calculated using Equation 4:

$$\Delta M = \frac{k_1 k_2}{168 * exp(-0.68 \ln T_s - 13.9 \ln RH_s + 0.14W + 66.02)}$$
$$[T_s \; in \; ^oC]$$

EQUATION 4 MOULD ACCUMULATION

Where:

k_1	=	mould growth intensity factor selected from Table 6.1.2 according to material sensitivity class and current value of M.
K_2	=	mould index attenuation factor calculated using Equation 6-5
W	=	parameter selected from Table 2 according to material sensitivity class

TABLE 2 PARAMTERS FOR EQUATIONS AS PER ASHRAE 160

Sensitivity Class	k_1 $M < 1$	$M \geq 1$	W	A	B	C
Very sensitive	1	2	0	1	7	2
Sensitive	0.578	0.386	1	0.3	6	1
Medium resistant	0.072	0.0907	1	0	5	1.5
Resistant	0.033	0.014	1	0	3	1

The mould index attenuation factor (k_2) shall be calculated using Equation 5:

$$k_2 = max\{1 - exp[2.3(M - M_{max})], 0\}$$

EQUATION 5 MOULD INDEX ATTENUATION CALCULATION

Where M_{max} is the maximum mould index corresponding to the surface temperature and relative humidity at the current hour, calculated using Equation 6:

$$M_{max} = A + B\left(\frac{RH_{crit} - RH_s}{RH_{crit} - 100}\right) - C\left(\frac{RH_{crit} - RH_s}{RH_{crit} - 100}\right)^2$$

EQUATION 6 MAXIMUM MOULD INDEX CALCULATION

Where the coefficients A, B, and C are selected from Table 2 according to material sensitivity class.

If $T_s \leq 0$°C or $RH_s \leq RH_{crit}$ at the current hour, then a decline in the mould index shall be calculated using Equation 7:

$$\Delta M = \begin{cases} -0.00133 \times k_3 \text{ when } t_{decl} \leq 6 \\ 0 \text{ when } 6 < t_{decl} \leq 24 - \\ -0.000667 \times k_3 \text{ when } t_{decl} > 24 \end{cases}$$

EQUATION 7 MOULD INDEX DECREASE CALCULATION

Where:

K_3 = mould index decline coefficient specific to the material surface

T_{decl} = number of hours from the moment when conditions for mould growth changed from favourable ($T_s > 0$°C and $\mathrm{RH}_s > \mathrm{RH}_{crit}$) to unfavourable ($T_s \leq 0$°C or $\mathrm{RH}_s \leq \mathrm{RH}_{crit}$).

2.1.3 Species of mould

Multiple species of mould can grow in buildings, with some of them releasing spores and compounds into the air that have adverse effects on human health. The health effects of each species of mould is not fully understood, and thus WHO suggests that the presence of any mould should be avoided (Heseltine et al., 2009, p. 2). BRANZ has identified some common species of mould that grow on indoor surfaces and in building envelopes including Stachybotrys Cladosporium, Pencilium sp., and Aspergillus sp (Cunningham, Shorter, Waipara, & Crane, 2013, p. 68).

Stachybotrys Cladosporium is of particular concern due to this species being linked to pulmonary bleeding (Yike & Dearborn, 2004), and being dangerous for all occupants, even those not prone to allergy. This species has only been shown to grow in the building envelope of "leaky" NZ homes, and not on interior surfaces. However, for this thesis it was assumed that any risk of visible mould should be considered problematic.

2.1.4 Mould germination vs. visible mould

Mould germination is the point where a mould spore begins to grow, while visible mould is mould that can be seen with the naked eye. Mould germination leads to microscopic mould, but not always to visible mould, as favourable conditions for growth may be interrupted frequently by dry periods. Non-visible mould (microscopic mould) rarely leads to adverse health effects and is usually acceptable in buildings depending on what species it is, and how close it is to being visible (Riordan & Tsongas, 2016, p. 43). Both concepts are discussed in this thesis, and it is important to understand the distinction.

2.2 STRATEGIES RECOMMENDED TO OCCUPIERS

As identified in the HCS, mould is a common issue in NZ homes. Government agencies related to houses and health often provide guidance to home occupiers to help them address mould growing in their homes. The aim of this section was to identify what strategies were recommended to home occupiers, and whether there were similarities or differences between what they recommended. The intent of this was to establish what interventions occupants were likely to implement if they found mould in their homes so whether they were effective could be tested later in the thesis

2.2.1 SEARCHING AND SELECTION STRATEGY

A different approach for was taken for this section compared to the rest of the review. Instead of screening academic journal databases, the websites and other publicly available information of government agencies related to buildings and building research firms were screened. This was done using the following methodology:

1. Government agencies listed on the NZ government website were searched for any departments that related to buildings or health. This included departments related to energy, earthquake strengthening, and fire safety.
2. The term “mould” was searched for using the websites built in search function. This was to search for any articles on the websites that used to word mould.
3. The titles of any articles or documents that were returned were screened. Ones that indicated they referred to mould growth were selected to be read.
4. The articles were read and any that provided advice on the alleviation, or mitigation of mould were included in the literature review.
5. A google search was also undertaken with the key words “mould”, “house”, and “New Zealand”. This was to emulate how a typical occupant might search ways to address mould if they found it in their homes. Articles on the first page of results were also screened in the same manner as step four. This was to see what information occupants would typically be exposed to. News articles were excluded from this process.

The results for each step in this process are summarised in Appendix B. The rest of this section only represents the final results from this process, and the comparison between the recommendations

2.2.2 COMPARING AGENCIES RECOMMENDATIONS

The following agencies were found to provide information about mould growth in homes. Their suggestions for alleviating existing mould and preventing it from growing again are presented in Table 3. Coloured words show similarities between the recommendations

- The Ministry of Business, Innovation, and Employment (MBIE)
- Housing New Zealand (HNZ)
- The Energy Efficiency and Conservation Authority (EECA)
- The Building Research Association of New Zealand (BRANZ)

The Tenancy Services department also had information on mould in houses but was excluded due to this being a department of MBIE and providing the same information. BRANZ is not a government agency but was found during the Google search in step six.

TABLE 3 AGENCIES RECOMMENDED METHODS TO DEALING WITH MOULD

Agency	Reference	Alleviation	Prevention
MBIE	(MBIE)	• Cleaning w/ commercial mould cleaner	• Increased ventilation, particularly during showers • Heating • More insulation
HNZ	(HNZ)	• Cleaning w/ vinegar solution	• Wipe away condensation • Increased ventilation, particularly during showers • Heating. Open a window if using a portable gas heater
EECA	(EECA, 2019)	• Cleaning	• Humidity should be below 65% most of the time • Temperature should be minimum 18°C. • Use extractor fan to ventilate during showers. • Air out home regularly • Heating. No unflued gas heaters • More insulation
BRANZ	(BRANZ, 2018)	• Cleaning w/ bleach solution while wet • Remove infested materials.	• Ventilation. Use extractor fans ducted to outside • Heating • Install insulation

All four sources in Table 3 recommending cleaning existing mould with either commercial cleaner, vinegar solution, or bleach solution. BRANZ (2018) also recommended removing infested materials. There were no conflicts about what should be done to remove existing mould between the four sources. Considering that this recommendation is presented across multiple publicly available sources (three also being found on the first page of a Google search), it is likely that this is a common measure that occupants take to remove mould. This could have had implications for the results of the HCS, see Chapter 3:.

All four sources mentioned using extractor fans or opening windows in bathrooms to prevent mould from growing. MBIE (n.d.), HNZ (n.d.), and EECA (2019) recommended that the extractor fans should be used and windows opened during showers. BRANZ (2018) recommended that the extractor fans should be ducted to the outside. Considering that using an extractor fan and opening windows is presented across multiple publicly available sources, it is likely that this is a common measure that occupants take to prevent mould. This was included as a strategy to be tested in the parametric study in Chapter 7:.

All four sources mentioned using heating in bathrooms to prevent mould from growing. MBIE (n.d.), EECA (2019), and BRANZ (2018) recommended not using unflued gas heaters as a heat source because they produce moisture. HNZ (n.d.) did not exclude unflued gas heaters, but did recommend opening a window if using one. The Household Energy End Use Project showed that occupants rarely heat utility rooms such as bathrooms (Isaacs et al., 2010, p. 75), indicating this may not be a common method of mould prevention. Heating was included as a strategy to test to see the potential effect it could have on mould.

MBIE (n.d.), EECA (2019), and BRANZ (2018) recommended retrofitting houses with insulation to prevent mould. However, they do not specify how much insulation would be needed. HNZ (n.d.) did not mention insulation, although it is possible that this is because there recommendations are intended for occupants of the state houses they manage (HNZ, 2018), and fitting insulation into them could be HNZ's responsibility. Adding insulation was included as a strategy to be tested so that the amount of insulation that was needed could be tested.

2.3 HOW WUFI-BIO WAS USED IN PREVIOUS STUDIES

When the research for this thesis was being started, it was unknown what WuFi-Bio could be used for and how to use it. A systematic review of existing literature was conducted to identify how WuFi-Bio had been used in previous studies, and what issues or limitations may have been identified. The following is the question that this part of the review aimed to answer:

"What methods or means of investigation has WuFi-Bio been used in existing literature?"

2.3.1 SEARCH PROTOCOL

A search protocol was established to determine what articles were to be included in the review. The PICOS (Methley, Campbell, Chew-Graham, McNally, & Cheraghi-Sohi, 2014, p. 9) analysis in Table 4 was used to break down the research question in order to develop an inclusion criteria. The aim of this is to make sure that only studies that actually used WuFi-Bio, and thus were able to test how useful it was for different applications, were included.

TABLE 4 INCLUSION CRITERIA FOR WUFI-BIO REVIEW

	Include
Population	WuFi-Bio users
Intervention	Methodology that includes WuFi-Bio
Comparison	N/A
Outcome	Effective use or identification of issues with WuFi-Bio
Study Design	Journal articles

2.3.2 SEARCHING STRATEGY

A scoping search was conducted in the following journal article databases to determine which ones were likely to return results that met the inclusion criteria in Table 4, using the search term "**WuFi Bio"**. Only the abstracts, keywords, and titles of articles were searched for to exclude articles that simply mentioned WuFi-Bio, rather than actually used it:

- Scopus
- ScienceDirect
- Proquest
- SAGE

This scoping search returned few enough results (<20) that all of their abstracts could be screened manually. The abstracts of the first few results returned in each database were preliminarily screened to check if WuFi-Bio had been referred to by any other terms. This revealed that the method WuFi-Bio used was often referred to as a biohygrothermal model.

The term "**biohygrothermal**" was also searched for in all databases, but always returned the same results as WuFi-Bio. Because of this, **"WuFi Bio"** was the only search term used for this review. All results were exported to the citation management software, Endnote, to have their abstracts screened and selected. Endnote's duplicate detection feature and a manual search was used to remove duplicate articles.

The abstracts and titles of all articles were read and papers selected to have their full texts read. This was done to quickly eliminate articles that did not meet the inclusion criteria in Table 4. Selected articles had to demonstrate that they used WuFi-Bio to explore the risk of mould for some form of building technology, material, or construction type.

The full texts of the selected articles were read and assessed against the criteria in Table 4. For articles to be included they had to describe what WuFi-Bio was used for, how it was used, and present results from using it.

A summary sheet was created in Microsoft Excel for each article. The sheets were used to assess each article against the criteria in Table 4, but also summarised important the articles aims, methodology, and findings.. An example of one of these sheets is provided in Appendix A.

The *U.S. National Heart, Lung, and Blood Institute's* Study Quality Assessment Tools (NHLBI, n.d.) instrument was used to assess whether the articles were likely to provide accurate information, honest reporting of the research conducted in them, and had no conflicts of interest. This was done by recording any questions from the tools that were not answered with "yes", and applying the final rating of "Good, Fair, or Poor". An article had to achieve a "Good" or "Fair" rating to be included in the review. Usually these tools are used by two assessors, but only the author of this thesis reviewed the articles for quality assurance.

A pivot table was created in MS Excel that summarised comparable information about the articles use of WuFi-Bio and their methodologies. This was done to easily identify similarities and conflicts between their methodologies.

The following are limitations of the searching and selection strategy that may have allowed literature that met the inclusion criteria to not be included in the review:

- Any non-English written articles that were found had to be excluded from the literature review. This was done because the assessor could not read them.
- Articles where the full-text could not be found could not be assessed and had to be excluded from the review.
- Only one assessor assessed articles for inclusion in the review. The selection of articles was subject the assessor biases for what met the criteria in Table 4.

2.3.3 ARTICLES INCLUDED IN THE REVIEW

This section summarises the results from the searching strategy in section 2.3.2. The results from the searching and screening process are presented in Table 5. Points of note or issues in the process are discussed afterwards, and lastly the articles selected to be included in this review are presented and compared in Table 6.

TABLE 5 RESULTS FROM WUFI-BIO SEARCHING PROCESS

Stage	Outcome
All results from all sources	43
Duplicates removed	9
Abstracts to screen	34
Abstracts removed	22
Full texts to read	12
Full texts removed	4
Texts for QA	8
Texts removed from QA	1
Texts included in review	7

One article was removed from the results as part of quality assurance process using the *NHLBI* *Study Quality Assessment Tools* (NHLBI, n.d.). This article was titled *Evaluation of Mould Growth on Wall Surface in South China* by He et al. (He, Chen, Luo, & Ge, 2017). It was excluded because it described the software, but did not explain how they were used.

Seven articles were found that used WuFi-Bio to evaluate the risk of mould. Table 6 summarises their methodologies and compares important comparable information about how WuFi-Bio was used. Coloured sentences highlight similarities between the research methods used. The colour of each sentence is only applicable to the column that it is in.

TABLE 6 COMPARISON OF ARTICLES INCLUDED IN REVIEW RELATED TO WUFI-BIO

Author	Title	Reference	Description	Used WuFi-Bio too	Technology being assessed	Methods	Model Validation	Estimation period	Supporting software
Finken, G. Bjarløv, S. Peuhkuri, R.	Effect of façade impregnation on feasibility of capillary active thermal internal insulation for a historic dormitory – A hygrothermal simulation study	**(Finken, Bjarløv, & Peuhkuri, 2016)**	Tested the mould risk potential of capillary active/hydrophilic insulation and the effect of adding façade impregnation	Evaluate building technology	Capillary active/hydrophillic insulation, Façade impregnation	Case studies	Compare to on site measurements (not included in study)	10 years	WuFi-Pro
Gradeci, K. Labonnote, N. Time, B. Köhler, J.	A probabilistic-based methodology for predicting mould growth in façade constructions	**(Gradeci, Labonnote, Time, & Köhler, 2018)**	Develop methodology that could be used to test probability of failure taking into consideration major factors that affect mould growth	Test methodology, Compare to other estimation methods	Facades	Parametric study, Sensitivity analyses	N/A	One year, 10 years	WuFi-Pro, MATLAB, MRD, VTT
Havinga, L Schellen, H	Applying internal insulation in post-war prefab housing: Understanding and mitigating the hygrothermal risks	**(Havinga & Schellen, 2018)**	Tested the mould risk potential of adding internal insulation in post ware pre-fab housing	Evaluate building technology	Internal insulation	Sensitivity analyses, Case studies	Compared to on site measurements HAM model	One year	HAM, COMSOL
Holzhueter, K. Itonaga, K.	An evaluation of WUFI-bio to predict mold growth in straw bale walls in Japan	**(Holzhueter & Itonaga, 2017)**	Tested the mould risk potential in six straw bale buildings in Japan and compared with Holzhueter and Itonaga's interstitial temperature and relative humidity guideline.	Evaluate building technology, Compare to other estimation methods	Straw bale walls	Case studies	Used measured hygrothermal conditions	One year	N/A
Ito, K.	Numerical prediction model for fungal growth coupled with hygrothermal transfer in building materials	**(Ito, 2012)**	Tested sensitivity of mould risk parameters of building materials	Evaluate effect of variables, Compare with other estimation methods	Concrete, Insulation Board, Gypsum plaster, Composite wall	Sensitivity analysis	N/A	168 hours	WuFi-Pro, VTT
Ricardo, A. Barreira, E	Monte Carlo Simulation to Evaluate Mould Growth in Walls: The Effect of Insulation, Orientation, and Finishing Coating	**(Ricardo & Barreira, 2018)**	Assessed the importance of insulation, orientation, and finishing coat on risk of mould	Evaluate effect of variables, Compare with other estimation methods	Typical Portuguese wall construction	Sensivity analysis, Case studies	Typical wall construction	One year	WuFi-Pro, VTT
Ryu, S. H. Moon, H. J. Kim, J. T.	Evaluation of the influence of hygric properties of wallpapers on mould growth rates using hygrothermal simulation	**(Ryu, Moon, & Kim, 2015)**	Assess the risk of mould in different wallpapers hygeric properties	Evaluate effect of variables	Hygeric properties of wallpapers	Case studies	Measured water vapour permanence	One year	WuFi Plus

2.3.4 PREVIOUS USE OF WUFI-BIO

From the final seven articles in this review, the following are the most common roles for which WuFi-Bio has been used. At least one of these methods was used in all seven articles.

- Evaluate building technology
- Compare to other mould estimation methods
- Evaluate effect of variables

Finken et al. (2016), Havinga and Schellen (2018), and Holzhueter and Itonaga (2017) all used WuFi-Bio to assess the risk of mould in building technologies. The former two use it to test the effect of adding internal insulation which are technologies gaining popularity in their respective countries, while the latter assesses common straw bale wall constructions. The only comparable difference between their methods was that that Finken et al. developed a theoretical typical model (Finken et al., 2016, p. 204), and the latter two based their models on inspected buildings (Havinga & Schellen, 2018, p. 632) (Holzhueter & Itonaga, 2017, p. 358).

Gradeci et al. (2018), Holzhueter and Itonaga (2017), Ito (2012), and Ricardo and Barreira (2018) compared WuFi-Bio to other mould estimation methods in order to validate their results. The most common comparison was with the VTT model (see section 4.3), which was used by all articles except Holzhueter and Itonaga. All three of these sources found that WuFi-Bio tended to overestimate mould growth potential (Gradeci et al., 2018; Ito, 2012, p. 853; Ricardo & Barreira, 2018, p. 11).

Ito (2012), Ricardo and Barreira (2018), and Ryu et al. (2015) used WuFi-Bio to test the sensitivity of parameters that they identified could affect mould growth potential in their models. The former two did this through sensitivity analyses using justified variations (Ito, 2012, pp. 849-850; Ricardo & Barreira, 2018, p. 4), and the latter imported laboratory measured hygrothermal data. The two that used sensitivity analyses did so to test the impact of variables they had no other means to validate.

2.3.5 THE METHODS THAT WUFI-BIO WAS INVOLVED IN

The following are the most common means of investigation that WuFi-Bio was found to be used throughout the seven studies:

- Sensitivity analyses
- Case studies

Gradeci et al. (2018), Havinga and Schellen (2018), Ito (2012), and Ricardo and Barreira (2018) used sensitivity analyses as their methodology or part of their methodology. All of these involved determining what variations of the tested parameters were considered reasonable, then comparing the results to see how they affected mould growth potential. There were no comparable differences between how these were done other than what and how parameters were changed. The changed parameters included orientation, finishes, insulation, internal condition data, exterior condition data, and interior linings, with how they were changed being dependent on what other software was used.

Finken (Finken et al., 2016), Havinga (Havinga & Schellen, 2018), Holzhueter (Holzhueter & Itonaga, 2017), Ricardo (Ricardo & Barreira, 2018), and Ryu (Ryu et al., 2015) all used case studies to explore how parameters effected mould growth potential. These were used to determine what sort of building or construction was modelled, while Havinga and Schellen used it to validate their 3-d heat transfer model that determined the conditions exported into WuFi-Bio (Havinga & Schellen, 2018, p. 633).

2.3.6 HOW THE MODELS USED IN THE STUDY WERE VALIDATED

Most articles used some method to validate the models they had, however this was always done for the models created before WuFi-Bio was used to assess mould growth potential. The two methods of validation that were found were: using measured hygrothermal data (measured conditions on surfaces and in constructions); and comparing simulated conditions to measured conditions. All articles that had a means of validation seemed to assume that a validated set of hygrothermal data would produce reliable results in WuFi-Bio. No information could be found about whether this is a reasonable assumption.

2.3.7 HOW LONG WERE WUFI-BIO ESTIMATIONS RAN FOR

All estimations had a period of one year except for Finken et al. (2016) and Gradeci et al. (2018), which used 10 year periods, and Ito (Ito, 2012), which used 168 hours. Gradeci et al. argued that using one year estimations (specifically using the Moisture Design Reference Year system) was insufficient for the following reasons (Gradeci et al., 2018, p. 34). However, no evidence was provided to support these points.

- A single year of external climate data would not take into account fluctuations temperature or rain load that could lead to suitable conditions for mould growth in one year, and not another.
- A single year is too short to provide realistic results, especially if risk is assumed to decrease in unfavourable conditions. The accumulation of slow-growing mould could not be assessed over multiple years.

2.3.8 WHAT OTHER PROGRAMS WERE USED WITH WUFI-BIO

WuFi-Pro was the most commonly used program with WuFi-Bio. Finken et al. (2016), Gradeci et al. (2018), Ito (2012), and Ricardo and Barreira (2018) all used WuFi-Pro to emulate the hygrothermal conditions of the materials they were testing to export into WuFi-Bio. Ryu et al. (2015) used WuFi Plus instead, which had the advantage over WuFi-Pro by allowing multiple surfaces to be tested in a 3-d model. Gradeci et al. (2018), Ito (2012), and Ricardo and Barreira (2018) also used VTT to compare with any results from WuFi-Bio.

Chapter 3: House Condition Survey

A brief summary of the HCS and parts of the methodology that could have affected this study are discussed. The bathrooms used from the HCS for this study and the corresponding data used in this study is presented

In 2015, the BRANZ conducted the House Condition Survey (HCS). This study is undertaken every 5 years, and aims to collect data on the condition of the NZ housing stock and identify trends and issues that NZ homes are facing (White et al., 2017, p. 1). HCS involved collecting data on 560 households throughout the country. The houses were intended to be a representative sample of the NZ housing stock (White et al., 2017, p. 1), and were selected proportionally to the total number of houses in each area (White et al., 2017, p. 3). This ensured that houses in all areas and climates zones were proportionally included.

Three data collection methods were used during the HCS; a telephone interview asking about maintenance and socio-economic factors, a questionnaire about appliance use to be completed by the householder, and a physical inspection. The construction data used for this study was collected as part of the physical inspection, where assessors observed and recorded information about the construction and condition of each house (White et al., 2017, p. 1).

Most of the assessors that conducted the site assessments had experience working in the building sector, and all received the same training to minimise inconsistent observations. However, inconsistencies between the assessors were still possible, and could have affected the data (White et al., 2017, p. 5). It is unknown whether this had an impact and it is a limitation that cannot be accounted for within the scope of this study.

The HCS also included observations about whether the houses were shaded by external factors (e.g. trees, other buildings) and sheltered from wind/rain on a five-point category scale. However, this did not provide details on which areas of the house were exposed or when. This meant that factors such as shading and sheltering from wind were not known and could not be taken into consideration in this study.

3.1 OCCUPANT VENTILATION BEHAVIOUR STUDY

A follow-up study to the HCS was conducted on a subset of the houses (Plagmann & White, 2017, p. 68). This Occupant Ventilation Behaviour Study (OVBS), collected more data on how the occupants of these houses ventilated (Plagmann & White, 2017, p. 68).

The study took place throughout winter 2016 on a subset of 64 HCS houses. Measurements of temperature and relative humidity (RH) were recorded in the bathrooms and bedrooms of each house. Data logger hygrometers took time-marked recordings whenever the relative humidity or temperature changed (Plagmann & White, 2017, p. 68). Measurements of how often windows and doors were open were also taken, however only the temperature and RH measurements were used in this thesis.

3.2 HOUSES USED IN THIS STUDY

A random sample, made by BRANZ, of seventeen houses from the sixty-four included in both the HCS and OVBS were chosen to be included in this thesis. The following lists the data about each house that was used for this study:

- ID assigned by BRANZ
- Location
- Whether it was built before or after 1978 (Implementation of NZS 4218)
- Amount of observed mould found in their bathrooms

- Interior lining and finish
- Exterior cladding
- Whether the exterior wall had a cavity
- Wall construction

This data was provided by BRANZ under confidentiality, with no access to addresses or other identifying information. These houses, their ID's, locations, age, and whether they had observed mould or not are shown in Table 7.

TABLE 7 HOUSES IN THIS STUDY

New ID	Location	Age	Observed Mould
DN-NM-NI-01	Dunedin	Pre-1978	No
DN-NM-NI-02	Dunedin	Pre-1978	No
BH-NM-I-01	Blenheim	Post-1978	No
BH-NM-I-02	Blenheim	Post-1978	No
BH-NM-I-03	Blenheim	Post-1978	No
NL-NM-I-01	Nelson	Post-1978	No
BH-NM-I-04	Blenheim	Post-1978	No
MT-NM-I-01	Motueka	Post-1978	No
MT-NM-I-02	Motueka	Post-1978	No
PR-NM-NI-01	Porirua	Pre-1978	Yes
WL-NM-I-01	Wellington	Post-1978	No
WL-NM-I-02	Wellington	Post-1978	No
WL-NM-I-03	Wellington	Post-1978	No
WL-NM-NI-01	Wellington	Pre-1978	No
WL-NM-NI-02	Wellington	Pre-1978	No
WL-NM-NI-03	Wellington	Pre-1978	No
WL-NM-NI-04	Wellington	Pre-1978	No

The HCS assessed visible mould using the following qualitative five-point scale:

1. No visible mould
2. Specks of mould
3. Moderate patches of mould
4. Large patches of mould
5. Extensive blackened areas

For this study, this scale was simplified to whether there was visible mould or not. Houses that were rated as 'No visible mould' or 'Specks of mould' were reclassified as *no visible mould*, and 'Moderate patches of mould', 'Large patches of mould', and 'Extensive blackened areas' as *visible mould*. 'Specks of mould' was classified as *no visible mould* because mould in this quantity could have been caused by a variety of factors that the software used later in this study could not take into account (e.g. leaks, condensation pooling). This simplification was done to make it easier to compare to the results of the software used, which is further discussed in section 5.3.

A breakdown of the distribution of attributes in Table 7 is shown in Table 8. Only one house had visible mould in the bathroom. This is further discussed in section 7.1.1. Discussions were had with BRANZ about getting data for more mould-present houses. However, data was available on only three other houses suitable for this study, but the data could not be supplied and processed within the time available for this thesis.

TABLE 8 TALLY OF HOUSES LOCATIONS, MOULD OBSERVATIONS, AND AGE

Location	
Dunedin	2
Blenheim	4
Nelson	1
Motueka	2
Porirua	1
Wellington	7

Observed Mould	
No Mould	16
Mould Found	1

Age	
Pre-1978	7
Post-1978	10

BRANZ used their own coding system to identify each house. However, due to the houses being selected at random, this system does not use any information relevant to this thesis to identify them by. A new coding system was implemented based on the location, age, and presence of mould of the houses. A breakdown of this coding system can be seen in Figure 1.

Both the BRANZ coding system and the new coding system has been shown in Table 7 so the results from this thesis can be related back to the original data. However, only the new coding system is used for the remainder of this thesis.

Location	
Dunedin	DN
Blenheim	BH
Nelson	NL
Motueka	MT
Porirua	PR
Wellington	WL

Observed Mould	
No Mould	NM
Mould Found	M

Age	
Pre-1978	NI
Post-1978	I

$$\underbrace{\text{DN}}_{\textit{Location}} - \overbrace{\text{NM}}^{\textit{Observed Mould}} - \underbrace{\text{NI}}_{\textit{Age}} - \overbrace{\text{01}}^{\textit{Identifier}}$$

FIGURE 1 EXPLANATION OF CODING SYSTEM

Chapter 4: Software Summary

This chapter presents a brief summary about how the software used in this study work, and how it was used with the data in Chapter 3:.

4.1 WuFi-Pro

WuFi-Pro is a hygrothermal calculation software designed to assess moisture conditions within a building envelope developed by Fraunhofer IBP. The software does this by performing a one dimensional calculation of a cross-section of a wall, floor, or roof and applying internal and external climatic conditions to this cross-section (Kunzel, 1995, p. 44). How the moisture content in this cross-section changes over the set calculation period is estimated based on the applied internal and external conditions (Kunzel, 1995, p. 44).

Figure 2 shows an example of how a cross-section that is modelled in WuFi-Pro, and how this represents a section of an actual building envelop. It also shows all the inputs that are required to successfully run a calculation. The inputs are labelled to reflect how they are organised in the WuFi-Pro interface. Each input is discussed further afterwards.

Fraunhofer IBP also maintains a 3-D version of WuFi called WuFi-Plus. The 3-D version allows for an entire room to be modelled rather than one section of the building envelope. This allows the hydrothermal properties of all construction elements of a room to be modelled and all surfaces to be tested for the risk of mould.

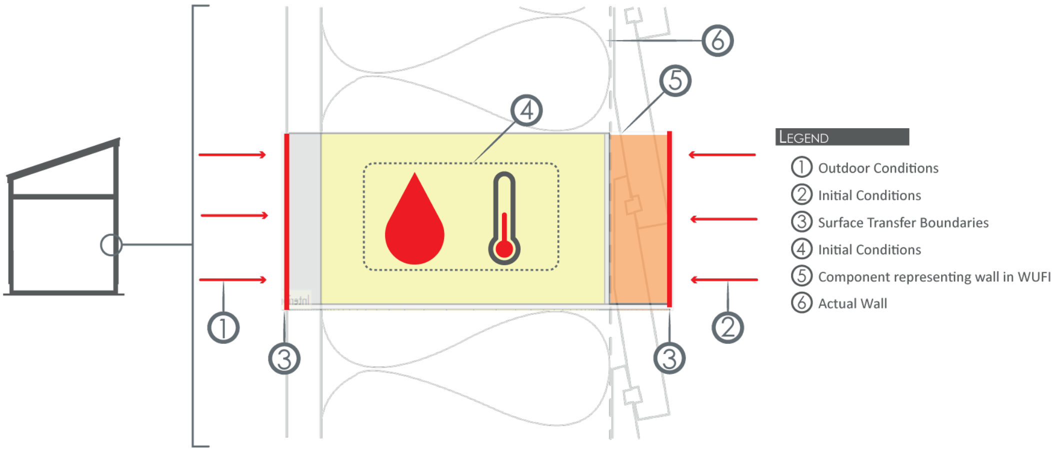

FIGURE 2 DIAGRAM OF WUFI-PRO MODEL

Component: The cross-section is made up of material data arranged in layers, with each one representing a component in the building envelope (e.g. cladding, insulation). The moisture content and temperature at various points in each layer is calculated, with the location of the points being dictated by a user set grid. These calculations are then compared to show how moisture and heat is transported through the envelope. This is done for each user-defined time step over the desired calculation period.

WuFi-Pro has a built-in library of data for common construction materials that can be used to set each layer in the cross-section. There is no material data available for common materials used in NZ. However, custom materials can also be added if data about the material's moisture storage ability, porosity, and thermal conductivity are known (Kunzel, 1995, p. 44).

Orientation/Inclination/Height: The cross-section's orientation, inclination, and height above ground level are set to determine how exposed its boundaries are to the external climate (Kunzel, 1995, p. 30). Whether the cross-section represents a straight wall, sloped wall, or floor/roof is set by the inclination. The orientation and inclination determines the cross-section's exposure to solar radiation, and the height determines its exposure to wind and rain (Kunzel, 1995, p. 32). All three of these inputs need to be known to perform a calculation.

Surface Transfer Coefficient: The surface transfer coefficients determine how resistant the boundaries of the cross-section are to interior and exterior climatic conditions. This determines how easily moisture and heat can enter or exit from the cross-section (Kunzel, 1995, p. 30). These coefficients need to be set to run a calculation and information about the finish on the interior surface and cladding of the building envelope need to be known to set this. The coefficients are determined by the sd-value of the exterior and interior surfaces.

An s-d value represents a layer's vapour diffusion thickness, which is a layers ability to resist vapour diffusion. It is calculated using the equation below, and is dependent on the on the materials vapour diffusion resistance (μ) and its thickness. It is commonly used to determine the vapour resistance of layers such as vapour retarders and surface coatings, where the actual thickness of these layers can be difficult to determine (Sedlbauer, 2001, p. 10)

Initial Conditions: The initial moisture content and temperature of each layer in the cross-section at the start of the calculation needs to be set (Kunzel, 1995, p. 44). This represents the conditions of layer of material at the start of the calculation period. This information is required to run a calculation.

Outdoor Conditions: The outdoor conditions are the climatic conditions that are being applied to the exterior boundary of the cross-section. The data that forms these conditions are the rain load, solar radiation, air temperature, and relative humidity. All of this data is required to perform a calculation and must span the whole time period of the calculation (Kunzel, 1995, p. 48).

WuFi-Pro allows the user to set the location of the building being modelled and will use an available weather file that represents a typical year in that location using data collected from a local weather station. Alternatively, custom data can be imported in the form of an .epw weather file. WuFi-Pro can only import one year's worth of climate data and will reuse the weather file if the calculation period is longer than one year (Kunzel, 1995, p. 48).

Indoor Conditions: The indoor conditions are the climatic conditions that are being applied to the interior boundary of the cross-section. Only the relative humidity and air temperature of the interior of the building are needed as inputs (Kunzel, 1995, p. 57). WuFi-Pro provides a few options for predicting what the indoor conditions would be based on standardised means of prediction such as ASHRAE 160, EN 15026/WTA 6-2, and ISO 13788. There is also the option to import custom data in the form of an .epw file if measured data from the building has been collected. Indoor conditions are needed to run calculations, and like the outdoor conditions, needs to span the entire calculation period, and only one year's worth of data can be imported (Kunzel, 1995, p. 57).

WuFi-Pro cannot take into consideration the condition of the existing construction elements, or the quality of construction workmanship (Kunzel, 1995, p. 57). Most of the bathrooms used in this study were in good condition or only had superficial defects, which helped minimise the difference between the models and the actual bathrooms. However, it is unknown how the condition of the building would affect the risk of mould in the bathrooms, and this could not be tested due to the limitations of the software.

For this study, WuFi-Pro was only used to calculate the water content on the interior lining, and the humidity and temperature of its surface. This information was then imported into WuFi-Bio and VTT to estimate the risk of mould.

4.2 WUFI-BIO

WuFi-Bio is a post-processor program that estimates how much mould will grow on the interior surface of the building envelope modelled in WuFi-Pro. Figure 3 shows a visual representation of the theoretical model that WuFi-Bio uses when estimating the risk of mould. The internal micro-climate conditions are the results of the moisture content and surface temperature of the internal lining calculated by WuFi-Pro, and the interior surface and spore characteristics are set in WuFi-Bio (Sedlbauer, 2001, p. 90).

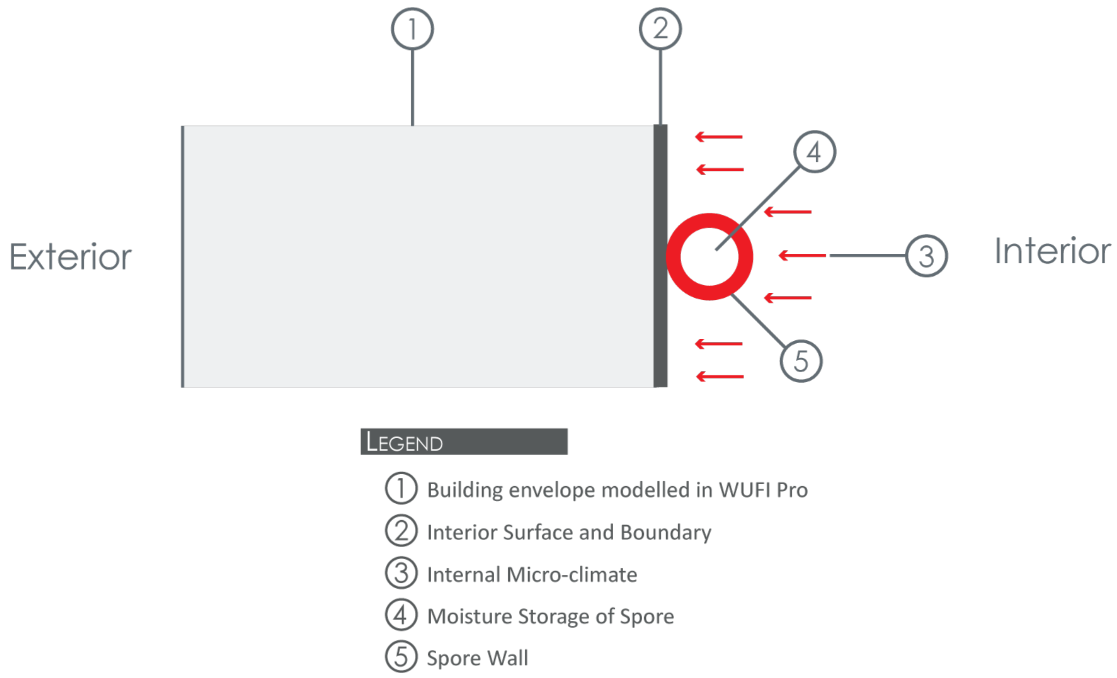

FIGURE 3 THEORITICAL MODEL OF HOW WUFI-BIO MODELS MOULD

The interior lining itself is set in WuFi-Bio by choosing one of three “substrate classes”, which determines that sd-value (see section 4.1) of the spore wall (Sedlbauer, 2001, p. 90). Each class represents a group of materials that have similar sd-values (Sedlbauer, Krus, & Breuer, 2003, p. 596). The model spore is treated as an object that absorbs water from its surrounding environment, with the spore wall delaying the exchange of moisture between the environment and the contents of the spore. The higher the sd-value, the more that the exchange of moisture between the environment and the spore is delayed (Sedlbauer et al., 2003, p. 599).

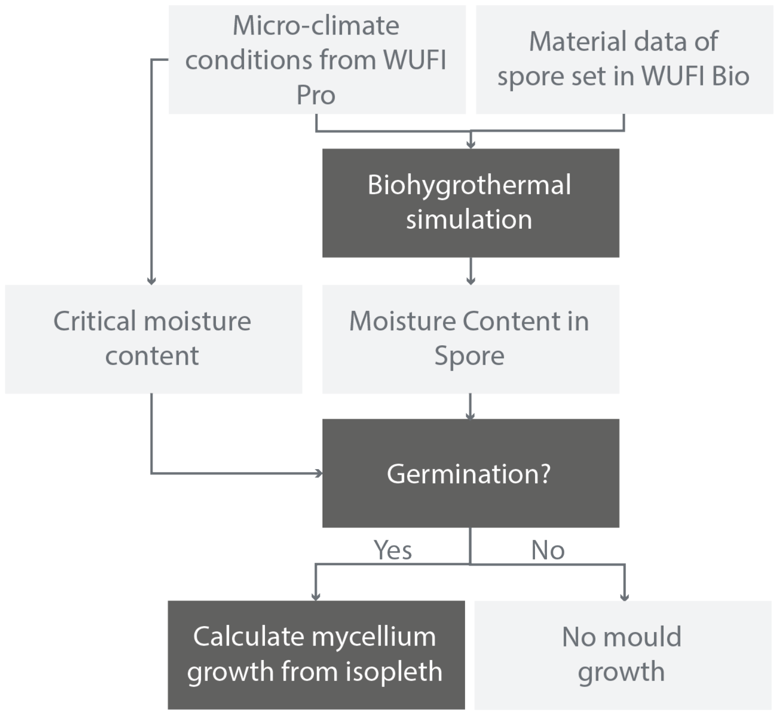

FIGURE 4 ESTIMATION PROCESS CONDUCTED BY WUFI-BIO

Figure 4 shows a visual representation of the process that WuFi-Bio goes through to estimate the risk of mould using the previously described theoretical model. The model uses the interior lining set in WuFi-Bio and the internal micro-climate conditions to calculate the water content of the model spore (WCoS) at each time interval over the estimation period (Sedlbauer, 2001, p. 99). It also estimates a critical moisture content (CMC) based on the internal micro-climate conditions, which is the lowest moisture content that the model spore needs to reach to allow it to germinate and mould to grow (Sedlbauer, 2001, p. 99).

The calculated WCoS and the estimated CMC are compared at each time interval. WuFi-Bio assumes that the spore will immediately germinate if its moisture content equals or exceeds the critical moisture content. The more that the WCoS exceeds the CMC, the faster the risk of mould increases (Sedlbauer, 2001, p. 100).

The rate at which mould grows is based on a lowest isopleth for mould (LIM) system that was established for each substrate class (Sedlbauer et al., 2003, p. 597). An isopleth is a combination of ambient relative humidity and temperature that needs to be met for a species of mould to grow at a certain rate (Sedlbauer et al., 2003, p. 597).

This information is usually communicated in the form of graph, an example of which can be seen in Figure 5. The Y-axis shows the relative humidity, the X-axis shows the temperature, and the lines on the graphs show the minimum conditions that need to be met for that species to grow at the annotated rates. A growth isopleth system is a combination of various isopleths for species of mould that are commonly found in buildings, and determine the lowest combination of conditions that need to be met for any of these species of mould to grow for each substrate class (Sedlbauer et al., 2003, p. 597). An example of a growth isopleth system can be seen in Figure 6.

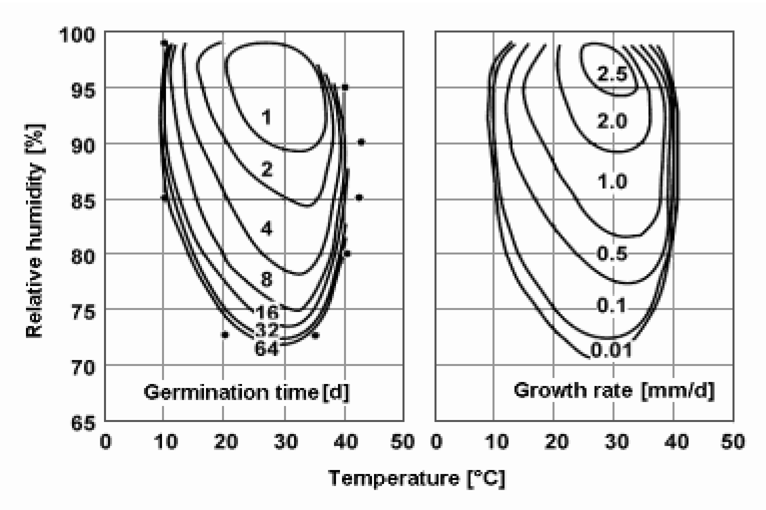

FIGURE 5 EXAMPLE ISOPLETH FOR GERMINATION TIME AND GROWTH RATE OF ASPERGILLUS RESTRICTUS (SEDLBAUER, 2001)

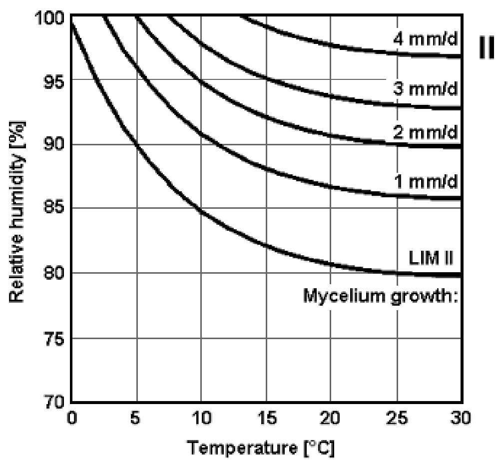

FIGURE 6 GROWTH ISOPLETH SYSTEM FOR COMBINING ALL MOULD SPECIES FOUND IN BUILDINGS (SEDLBAUER, 2001)

WuFi-Bio estimates the risk of mould in mm/day growth and converts this to the mould index metric that is used by ASHRAE 160 (see section 2.1.2). It is important to note that despite using mm/year, the software is actually estimating that *there is a risk that this amount of mould could grow*, not *this amount of mould will grow* (Fraunhofer IBP, 2011). For the rest of this study, only the mould index metric from ASHRAE 160 is used so that the results could easily be compared to the results from WuFi Mould Index VTT. A summary of what the metrics mean is presented in section 4.3.

WuFi-Bio then uses a signal light system to indicate whether the estimated risk of mould is acceptable. The system can only be used if the estimation period is longer than one year, however the WuFi-Bio manual does not specify a minimum estimation period if this system is not used. This system is only intended to be used as an easy to interpret guide, and was not required for this thesis (Fraunhofer IBP, 2011). Figure 7 shows the criteria that needs to be met for each signal to be given. All values are expressed in the maximum mould index that is estimated.

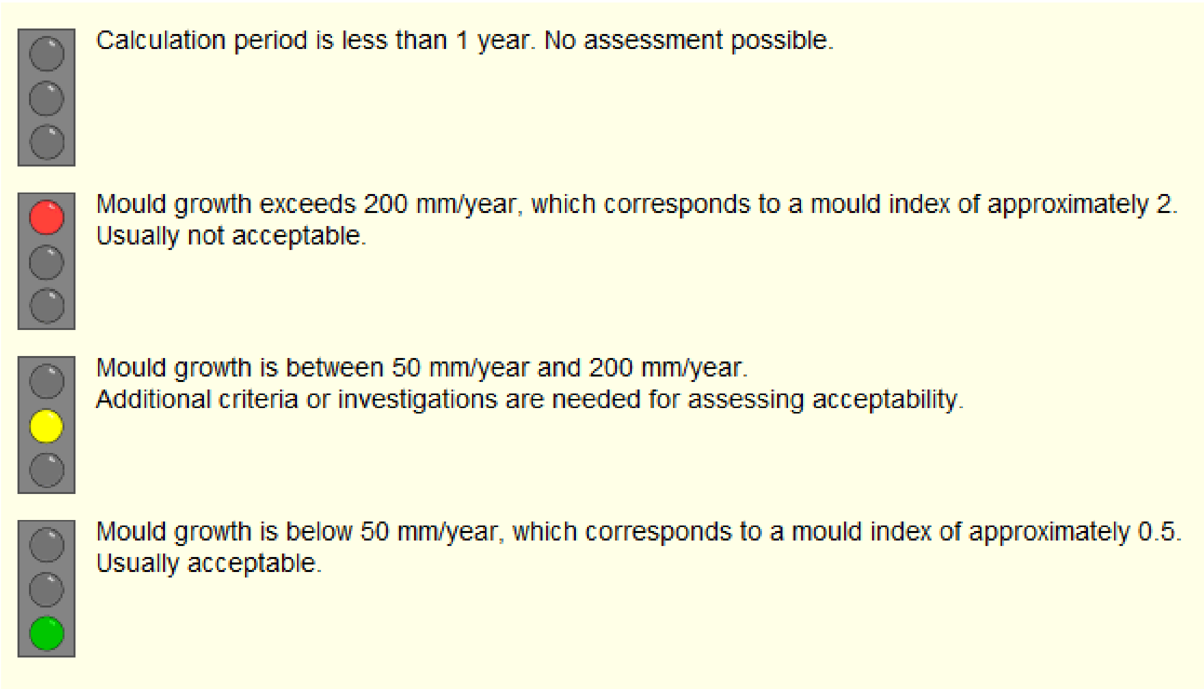

FIGURE 7 CRITERIA FOR WUFI-BIO SIGNAL LIGHT SYSTEM (FRAUNHOFER IBP, 2011)

The following are the known limitations of WuFi-Bio stated in its help guide (Fraunhofer IBP, 2011), that were relevant to how the software was used:

> WuFi-Bio simplifies the mould germination and growth process by not taking into account factors such as pH value, salt content, oxygen content, surface quality, and bio genic factors. It is assumed that the conditions needed to allow mould for these variables are met, and they do not impede the germination or growth process. This means that the software has a tendency to over-estimate how much mould there is a risk of, and how quickly mould starts to form.
>
> The software cannot estimate the mould growth in individual materials, only the substrate classes that are set in it.
>
> The model only estimated the risk of mould on the interior surface, not mould in a construction or the exterior surface.
> WuFi-Bio cannot consider the occupants attempts to treat or reduce existing mould, such as cleaning.

4.3 WUFI MOULD INDEX VTT

“WuFi Mould Index VTT” (VTT) is a post-processor program for WuFi-Pro. This program is similar to WuFi-Bio, but uses the calculation method outlined in ASHRAE 160 (see section 2.1.2), known as the Viitanen model. The Viitanen model uses regression models to determine how long it takes for mould to start germinating, and growth rates in increasingly favourable conditions (Hukka & Viitanen, 1999, p. 484). Mould is estimated to start growing when a critical relative humidity is reached, which in this software is determined by the results from WuFi-Pro (Fraunhofer IBP, 2018, p. 8).

The results from this software show how the risk of mould changes over time, and estimates this in mould index. The mould index represents the mould growth level and ranges between 0-6, with a value of 1.0 meaning of non-visible mould, and 3.0 meaning there is a risk of visible mould (Fraunhofer IBP, 2018, p. 3). A more detailed summary of what the values of mould index can be found in Table 9. However, a maximum value equalling or above 1.0 meaning non-visible mould, and a value equal or above 3.0 meaning visible mould is all that is relevant to this study.

TABLE 9 MOULD INDEX GROWTH RATES

Mould index	Growth rate
0	No growth
1	Initial stages of growth. **Microscopic mould forms**.
2	<10% coverage of mould on surface.
3	10-30% coverage of mould on surface. **Visually detectable mould forms**
4	30-70% coverage of mould on surface.
5	>70% coverage of mould on surface.
6	Nearly 100% coverage of mould on surface. Very dense.

VTT uses the interior lining conditions calculated by WuFi-Pro similar to those used by WuFi-Bio. The material properties for the interior lining need to be set in VTT, but the initial relative humidity of a model spore does not. Instead of grouping together similar materials into substrate classes like WuFi-Bio, VTT has pre-sets for individual materials with there being an appropriate pre-set for all interior linings in this study.

Originally the Viitanen method could only be used to test wooden surfaces, however it was expanded to be able to test others. This was done by introducing the following sensitivity classes (Ojanen et al., 2010, p. 7):

- Very sensitive
- Sensitive
- Medium resistant
- Resistant

Each class represents how resistant a material is compared to the original wood used in the laboratory tests to develop the regression models. This controls how quickly the growth rate increases and decreases (Ojanen et al., 2010, p. 7). The software allows the user to select a pre-made material, and will set the appropriate sensitivity class (Fraunhofer IBP, 2018, p. 7). In this thesis, classes for materials were selected according to ASHRAE 160-2016 (ASHRAE, 2016a) (see section 2.1.2).

VTT decreases mould growth activity during non-favourable conditions (Hukka & Viitanen, 1999, p. 480), while WuFi-Bio does not (Fraunhofer IBP, 2011). This difference was the main reason that VTT was also used in this study. It was unknown how WuFi-Bio's tendency to overestimate the risk of mould, or how long drying periods would affect any results.

Like WuFi-Bio, VTT simplifies the mould germination process by assuming that variables such as pH value, salt, exposure to light, and surface quality do not impede mould growth. This typically results in faster germination times than what would actually happen, but is less effected by overestimating maximum mould index due to the risk of mould decreasing during unfavourable conditions (Fraunhofer IBP, 2018, p. 9).

VTT also cannot take into consideration the condition or any defects of the modelled surface. It also cannot include the effect that occupants attempt to clean or treat mould would have. This could lead to inconsistencies between the HCS observations and the VTT results.

Like WuFi-Bio, VTT uses a signal light system to indicate whether the estimated risk of mould is acceptable. The system can only be used if the estimation period is longer than one year Figure 8 Criteria for VTT signal light system (Fraunhofer IBP, 2018, p. 21).Figure 8 shows the criteria that needs to be met for each signal to be given. All values are expressed in the maximum estimated mould index.

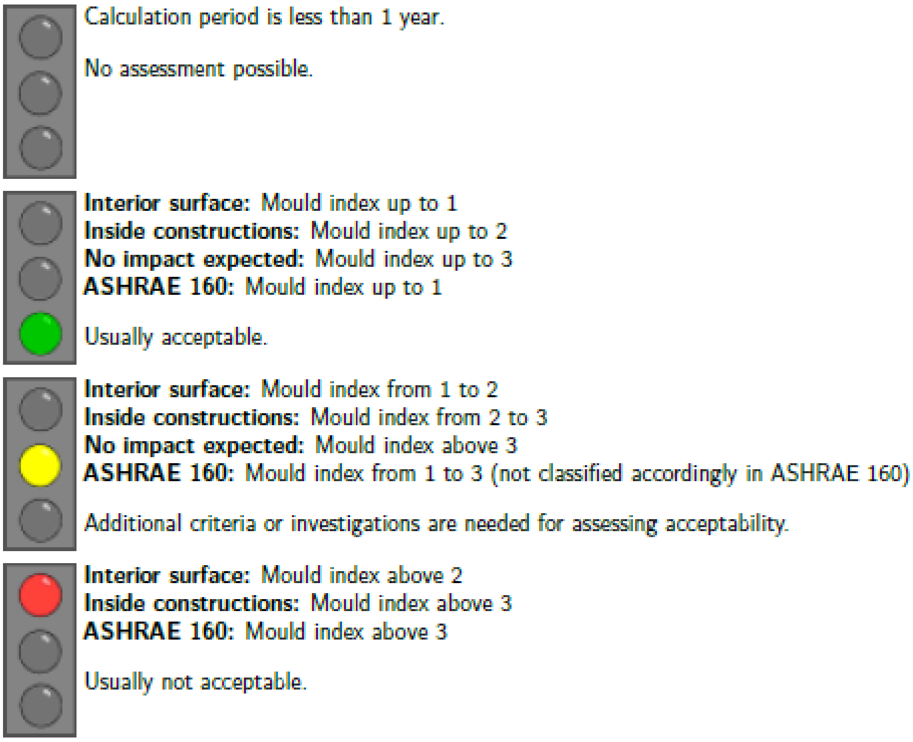

FIGURE 8 CRITERIA FOR VTT SIGNAL LIGHT SYSTEM (FRAUNHOFER IBP, 2018, P. 21)

4.4 HOW THE DATA WAS USED FOR MODELLING

To meet objective 2 in section 1.3.1 and answer question 2 in section 1.4, models of the bathrooms in Table 7 were created in WuFi-Pro. This section describes the general process used to import the HCS and OVBS data, and export this data into WuFi-Bio and VTT to estimate the risk of mould. This section defines the starting methodology that was refined during the pilot study described in Chapter 5:. How the HCS data was imported into WuFi-Pro, what data was used for the external conditions, and the how the results from WuFi-Bio and VTT would be compared to the real bathrooms for validation are discussed.

4.4.1 USING HCS FOR CROSS-SECTION

The data needed to create a cross-section of the bathrooms' building envelope was taken from the HCS. Only one section of the envelope can be modelled in one model, and ideally the modelled section would have been the same as where mould was observed to be in the actual bathroom. However, the data reported from the HCS gave no indication of where the mould grew.

Selecting the section that was most likely to show the first signs of mould growth was deemed the most suitable criteria for selecting what section should be modelled. Mould is more likely to grow on colder surfaces where the heat is lost through the building envelope (Hugo, 2014, p. 6). In uninsulated NZ homes, most heat is lost through the roofs, then windows, then walls (White & Jones, 2017, p. 6).

However, the external walls were selected to be modelled. This was because it was unknown what elements were exposed to external conditions (e.g. all interior walls, or having another storey above the bathroom), and it was more likely that each bathroom had an external wall than a roof. This can be seen in the HCS by almost all bathrooms surveyed having an openable window (White & Jones, 2017, p. 19), which was most likely in an exterior wall. Table 10 summarises the data that was reported during the HCS about the exterior walls of the seventeen bathrooms in this study. Empty cells mean that no data was reported for the corresponding element.

TABLE 10 CONSTRUCTION DATA EXTRACTED FROM HCS

House ID	Interior Lining	Cladding	Interior Finish	Cavity
DN-NM-NI-01	Plasterboard	Fibre Cement Weatherboards		Yes
DN-NM-NI-02	Hardboard	Brick Veneer		
BH-NM-I-01	Plasterboard	Brick Veneer	Tiles	Yes
BH-NM-I-02	Plasterboard	Brick Veneer	Tiles	Yes
BH-NM-I-03	Plasterboard	Timber Weatherboards	Tiles	Yes
NL-NM-I-01	Factory Finished Panel	Concrete Brick Veneer		Yes
BH-NM-I-04	Plasterboard	Brick Veneer	Tiles	Yes
MT-NM-I-01	Plasterboard	Fibre Cement Sheets		Yes
MT-NM-I-02	Plasterboard	Brick Veneer		Yes
PR-NM-NI-01	Matchlining	Fibre Cement Sheets		No
WL-NM-I-01	Plasterboard	Timber Weatherboards		No
WL-NM-I-02	Factory Finished Panel	Fibre Cement Sheets		No
WL-NM-I-03	Plasterboard	Timber Weatherboards		Yes
WL-NM-NI-01	Factory Finished Panel	Timber Weatherboards		No
WL-NM-NI-02	Plasterboard	EIFS		No
WL-NM-NI-03	Plasterboard	Timber Weatherboards		No
WL-NM-NI-04	Plasterboard	Fibre Cement Sheets	Tiles	No

Walls using framing do not have a consistent cross-section, with thermal bridges being created where studs are located, while insulation or air gaps are found where there are no studs. For each bathroom, both of these cross-sections were modelled in WuFi-Pro to ensure that the most vulnerable parts of the wall were modelled.

4.4.2 MONITORED RELATIVE HUMIDITY AND TEMPERATURE DATA FOR OVBS

The relative humidity and temperature measurements collected during the Occupant Ventilation Behaviour Study (OVBS) where used to create the indoor conditions acting on the interior of the external wall. The conditions for each house were assigned to the wall models that represented the monitored bathroom. This data was used rather than relying on WuFi-Pro's alternative indoor condition estimation methods, because it has been shown that WuFi-Pro produces more reliable results when climatic boundary conditions are known exactly (Kunzel, 1995, p. 48).

The time period that data was collected over ranged between May 2016 and January 2017, with each house usually having data measured for six months. The results that were produced from WuFi-Bio had to be able to be compared, and thus the calculation time periods had to be the same for all houses. Since the start and end dates for which data was collected differed for each house, a sub-set of the total period when all houses had data being collected was chosen. This was between June 8th and October 8th 2016. This is a likely time for mould growth due to lower temperatures, and potentially greater accumulation of moisture from occupants not opening windows as frequently during winter (McNeil et al., 2015, p. 1)

The internal condition data for all bathrooms had an issue where there were only 23 measurements each day, and the hour 00:00 had no data recorded for it. This could have affected the results of the calculations conducted in WuFi-Pro as the software reads empty cells as 50% relative humidity. This would have resulted in the relative humidity acting on the interior surface of the cross-section periodically dropping to 50% at midnight every day, which is not representative of the behaviour of moisture in the real bathroom.

These empty cells were changed to be the average of the readings immediately before and after them at hours 23:00 and 01:00. While it is unknown if this change is reflective of the internal conditions in the actual bathrooms, it is a more plausible scenario than the relative humidity changing to 50%.

The bathroom internal data obtained from OVBS consisted of relative humidity and temperature readings taken when either variables changed stored in a .csv file. However, to be imported into WuFi-Pro the data had to be in an .epw file format with hourly readings. The following method was used to convert the data into the required format:

1. An .epw weather file of typical Wellington weather data from NIWA was converted to a .csv file using the Energyplus Weather Statistics and Conversion tool.
2. Microsoft Excel was used to extract hourly data (00:00, 01:00, 02:00 etc.) from the original OVBS data. This was done by using the measurement immediately before the hour mark as the measurement for each hour. This was done because

the measurements would not have changed between the these points due to how the sensors recorded data.

3. The extracted hourly data was imported into the appropriately labelled temperature and relative humidity columns in the .csv weather file. This overwrote the original data in the converted weather file. Any other data in the file was deleted
4. The OVBS internal weather file was converted back to an .epw file using the Energyplus Weather Statistics and Conversion tool for import into WuFi-Pro.

4.4.3 DATA FOR EXTERNAL WEATHER CONDITIONS

The location of the houses was taken from the HCS and used to determine the outdoor conditions to be applied. Using weather data that was collected at the same time as the OVBS was being conducted was deemed more likely to produce reliable results than using WuFi's built-in, location-based weather files. This was because these files represented a typical year of weather data which may have differed from the weather while data was being collected for the OVBS, having an impact on the produced results (Kunzel, 1995, p. 57).

The National Institute of Water and Atmospheric Research's (NIWA) Cliflo[1] service was used to obtain weather data collected at the same time as the OVBS. Hourly data for the required inputs described in the *outdoor conditions* part of section 4.1, were taken from weather stations that were in the same areas as the houses shown in Table 7. The data used was for the same period that the calculations were ran for in WuFi-Pro, as established in section 4.4.2.

The data from Cliflo came in the form of .csv files. The same approach for creating custom .epw files was used as described in section 4.4.2. The only differences were that the data from Cliflo was already hourly data so no extraction was required, and the replaced data included solar radiation, and rain load, as well as air temperature and air relative humidity. This process produced individual weather files for each of the six house locations.

[1] Cliflo URL: https://cliflo.niwa.co.nz/

Weather stations located in the suburbs where the bathrooms were most likely to be were not always suitable due to not collecting all the required climate data. This meant that climate data had to be sourced from place that were close to elements that could have altered the exterior climatic conditions e.g. waterfront, hill, city outskirts. It is unknown whether this difference in location would have significant impact on the exterior conditions which in turn could affect the risk of mould in the bathrooms.

As noted, not all weather stations collected all the climate data needed by WuFi-Pro. While one weather station that measured the minimum amount of data needed was found for each bathroom location, no data about atmospheric counter radiation could be obtained. This meant that the models could not use WuFi-Pro's Explicit Radiation Balance and consider night time overcooling. The effect this could have on the risk of mould is unknown.

4.4.4 VALIDATING THE MODELS

After the data mentioned in sections 4.4.1 to 4.4.3 had been imported into WuFi-Pro, the conditions acting on the interior surface could be calculated. These results would then be imported into WuFi-Bio and VTT to estimate the risk of mould. This was done using WuFi-Pro's direct importation feature.

Any results produced by WuFi-Bio or VTT were compared to the observed mould in each bathroom shown in Table 7. This was to ensure that the model estimated mould represented the actual bathroom mould This would make it more likely that the effects of any tested mould mitigation strategies represented their actual impacts.

The only indicator of the risk of mould in that bathrooms included in the HCS was the presence of visible mould. For the models to be validated, the results from WuFi-Bio and VTT had to show that there was a risk of visible mould. This meant that the results for bathrooms with visible mould in them had to equal or exceed mould index 3.0 within the estimation period. Bathrooms without visible mould had to remain below 3.0.

Chapter 5: Pilot Study

A pilot study was conducted to develop a modelling and estimation methodology that could be used. Going through the modelling process with two bathrooms, the results from this, and the implications this had on the study are presented and discussed. VTT was only introduced into this study after the Pilot Study, and thus only WuFi-Bio was used to estimate the risk of mould during this stage.

The data that was obtained for this study (shown in section Chapter 3:) was not enough to fulfil all the inputs that are required to produce a working model in WuFi-Pro. To address this a pilot study was conducted by modelling two buildings from the seventeen that are listed in Table 7, and using the outputs to produce working estimations in WuFi-Bio. The aim of this was to develop a methodology that could be used to model the remaining bathrooms. This was done by reviewing the data importation process described in section 4.4 and identifying what assumptions were needed to produce working estimations and any limitations of the software or data being used.

5.1 Reviewing the initial methodology

5.1.1 Starting methodology

Figure 9 shows an initial modelling and estimation methodology developed based on the data importation and model validation process described in section 4.4. This allowed the two bathrooms used in the pilot study to be modelled and any missing data needed to produce working calculations to be identified.

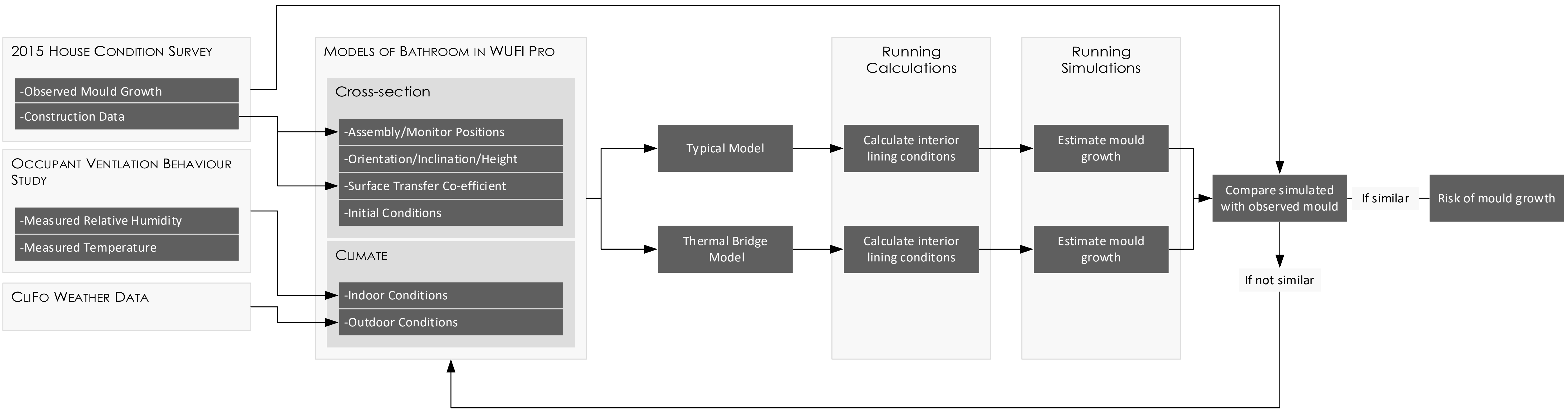

FIGURE 9 STARTING MODELLING METHODOLOGY

5.1.2 DESCRIPTIONS OF HOUSES USED IN THE PILOT STUDY

This section gives a brief explanation of the two houses that were selected for the pilot study and the data that was collected from during the HCS.

Two bathrooms from Table 7 (houses PR-M-NI-01 and WL-NM-I-01) were selected to be included in the pilot study. One of these bathrooms had visible mould while the other did not. These bathrooms were selected to test if the methodology that was developed during this pilot study would show a risk of visible mould in bathrooms with mould, and no risk in bathrooms without any.

Bathroom PR-M-NI-01: This was the main bathroom from a pre-1978 detached dwelling located in Porirua, near Wellington. The house is on an exposed site and rarely receives shading from external factors. Visible mould was found. The external wall construction was fibre cement sheet cladding with match-lining for the interior lining, and no cladding cavity.

Bathroom WL-NM-I-01: This was the main bathroom from a post-1978 detached dwelling that was refurbished within the past 10 years. The house is located in Wellington on a semi-exposed site and is rarely shaded by external features. No visible mould was found in the bathroom. The construction type of the wall consisted of bevel-back weatherboard cladding, standard plasterboard interior lining, and had no cladding cavity.

5.1.3 MODELLING THE CROSS-SECTIONS OF EXTERNAL WALLS IN WUFI-PRO

The two bathrooms in section 5.1.2 were modelled following the general explanation presented in section 4.4. This section discusses the issues and limitations of modelling the cross-section of the bathrooms external walls in WuFi-Pro.

5.1.3.1 COMPONENT

An attempt was made to model the external walls for the bathrooms described in section 5.1.2 in WuFi-Pro, following the data importation process in section 4.4. However, this could not be completed only using the data from the HCS due to the following reasons:

- The structure inside the walls was not known.
- The presence or amount of insulation was not known.
- The thicknesses of the cladding, interior lining, and cavity was not known.

- The type of timber used for the bevel-back weatherboards for house WL-NM-I-01 and the match-lining interior lining in house PR-M-NI-01 was not known.

The amount of information that was not collected during the HCS makes it impossible to make accurate assumptions about the construction of either bathrooms' exterior walls. In lieu of this, the data that has been obtained can be used to identify what the construction would likely be, based on common construction types used in the NZ housing stock. This will help make it more likely that the assumptions made about this data are reasonable, and that the models still represent plausible NZ wall constructions.

Typical wall constructions were taken from the BRANZ 2015 House Insulation Guide (HIG). This book is intended to help designers assess the thermal performance of levels of insulation and construction types that are commonly used in the NZ housing stock (BRANZ, 2014, p. 6). This book provides information on the internal structure, insulation, and thickness of materials used in the construction of the external walls, all of which are needed to produce models in WuFi-Pro. Both bathrooms were assigned a construction type that matches the data collected from the HCS, and this was used to fill in missing inputs for WuFi-Pro.

The HCS could not collect information on wall insulation. NZS 4218:1977 was used to determine whether the modelled walls were likely to be insulated or not. This standard introduced NZ's first regulatory requirement to install insulation in homes and was introduced in 1978 (Standards NZ, 1978). Houses constructed before 1 April 1978 were unlikely to have insulated walls, while houses constructed afterwards as insulation was mandatory (White & Jones, 2017, p. 6). The external wall of the post-1978 house was assumed to be insulated, while the pre-1978 house was not.

Houses that were constructed after 1978 were assumed to meet the minimal requirements for thermal insulation that were established in NZS 4218. These requirements were that the total R-value of all external walls had to be equal or greater than $1.2m^2\,^{o}C/W$ (Standards NZ, 1978). Insulation was added to the cross-sections of houses that were constructed after 1978 until the total R-value in WuFi-Pro equalled $1.2m^2\,^{o}C/W$.

Figure 10 and Figure 11 show an illustration from WuFi-Pro of the cross-sections of bathrooms PR-M-NI-01 and WL-NM-I-01y. These were created using the data from the HCS, the HIG, and NZS 4218. The cross-sections on the left show the typical construction of each wall and the cross-sections on the right show the thermal bridge variations representing where a stud and cavity batten are being cut through.

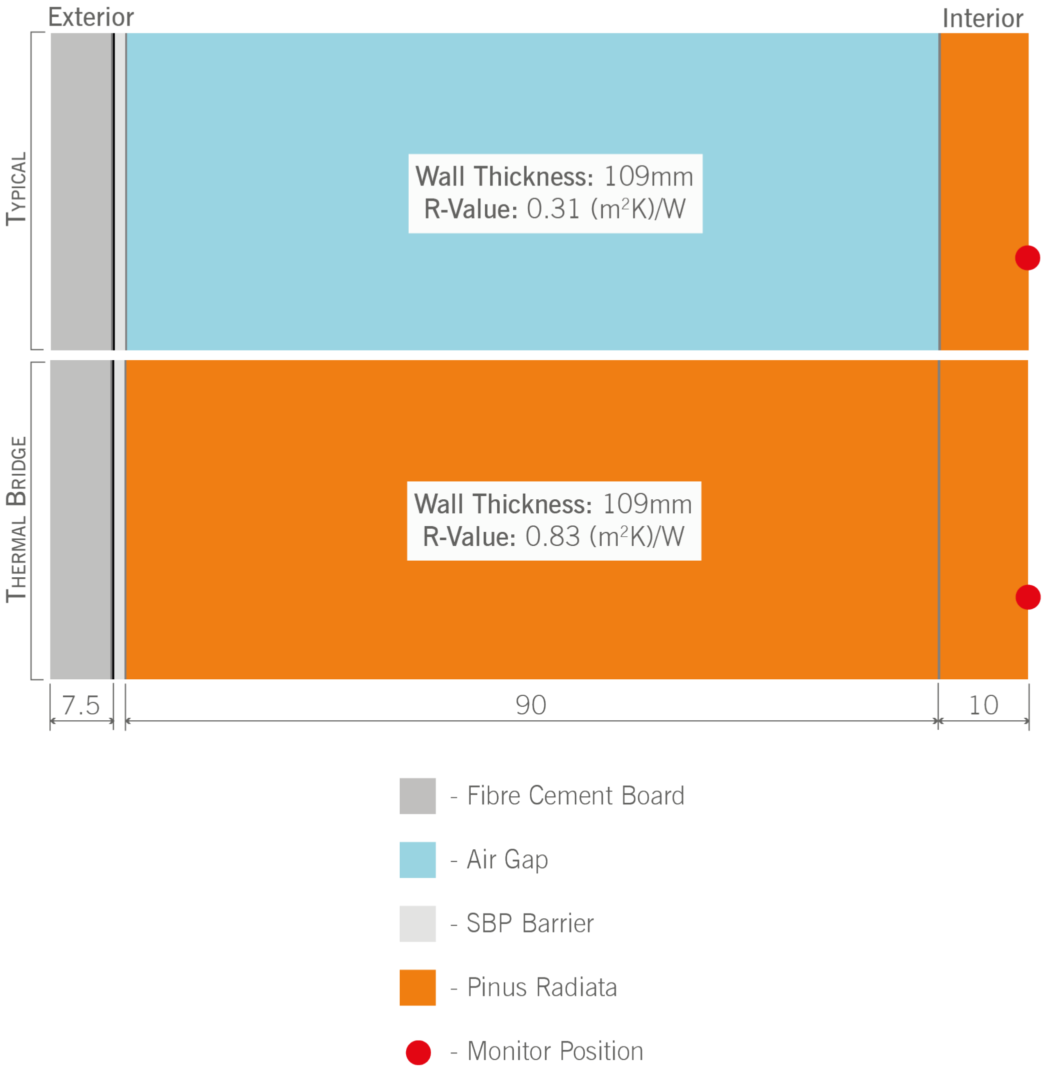

FIGURE 10 BATHROOM PR-M-NI-01 MODELS

Bathroom PR-M-NI-01 was assigned the construction type from page 114 of the HIG (timber framing and solid timber cladding construction). The following is the information that was taken from this construction type to complete the cross-section of the exterior wall:

- The structure of the wall would be a 90mm thick lightweight timber construction that is common in the NZ housing stock (BRANZ, 2014, p. 114).

- A wall underlay was added under the cladding
- The thickness of the fibre-cement sheet cladding was set to 7.5mm (BRANZ, 2014, p. 20).

No information could be found in the HIG about the thickness of the matchlining used for the interior lining of the bathroom and other sources of information had to be used. The thickness of matchlining has historically been between 9mm and 13mm (BRANZ, n.d.). The thickness of the matchlining in the cross-section was set to 9mm to consider a worst-case scenario.

The HCS and HIG give no indication of what type of wood was used for the structure or interior lining of the wall. Pinus radiata was assumed as this has been the most commonly used in NZ residential construction since the 1970's (BRANZ). No pinus radiata data was included in the WuFi-Pro materials library, so a custom material was created using material data provided by BRANZ via personnel communication. This was assigned to timber structure in the thermal bridge variation and the interior lining in both variations.

The remaining materials in the variations had to use material data from the WuFi-Pro materials library. To account for this not using local materials, the thermal conductivities were changed to reflect typical NZ materials (BRANZ, 2014, p. 20). The following materials were used for each layer:

- **Fibre-cement sheet cladding:** Used 'fibrecementboard' from the LTH Lund University database.
- **Wall underlay:** Spun Bonded Polyolefin Membrane.
- **Wall cavity:** Generic Air Layer

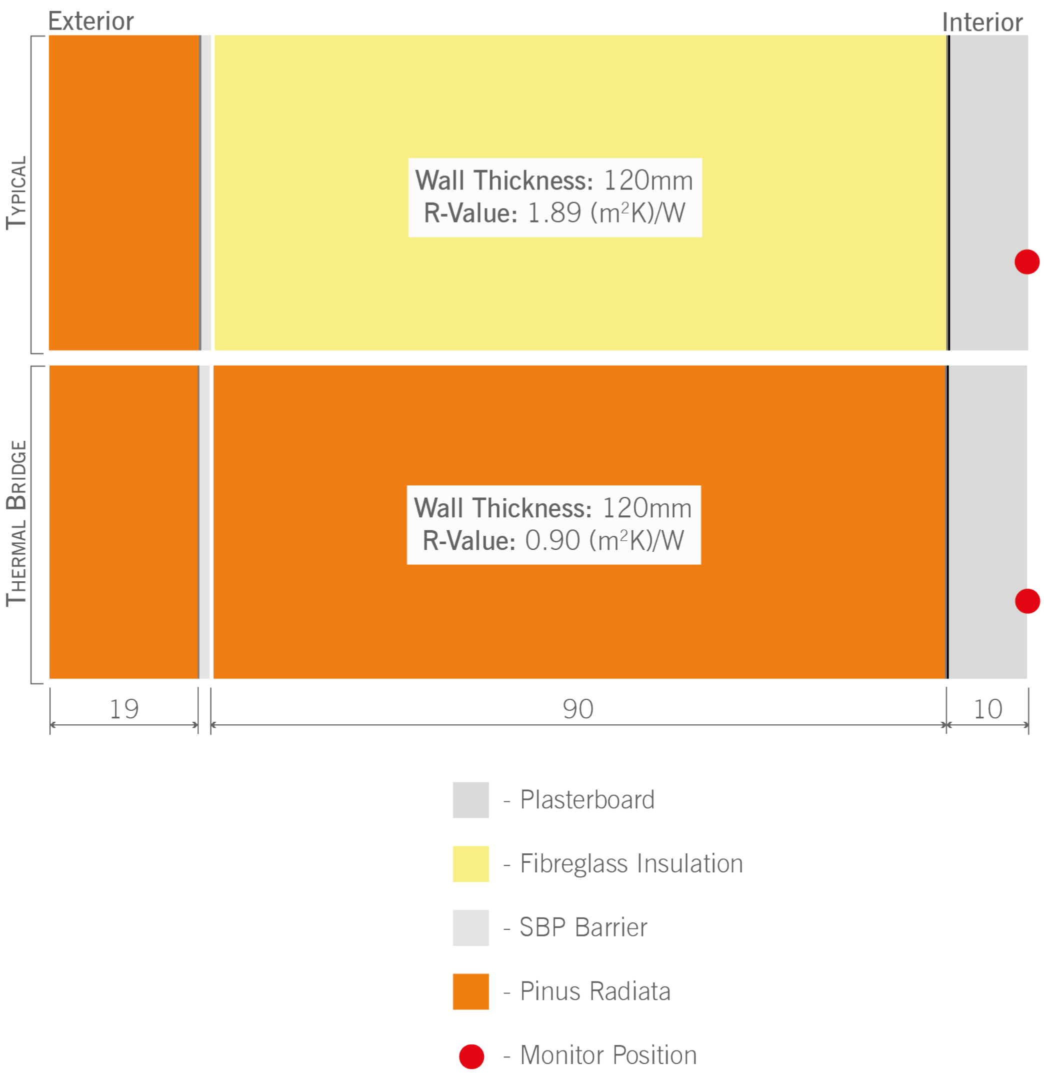

FIGURE 11 BATHROOM WL-NM-I-01 MODELS

Bathroom WL-NM-I-01 was assigned the construction type from page 66 of the HIG (timber framing and weatherboard construction). The following is the information that was taken this construction type to complete the cross-section of the exterior wall:

- The structure of the wall would be the common 90mm thick lightweight timber construction (BRANZ, 2014, p. 114).
- A wall underlay was added under the cladding
- The weatherboard cladding was set to 19mm thick (BRANZ, 2014, p. 20).
- The plasterboard interior lining was set to 19mm thick (BRANZ, 2014, p. 20).

Pinus radiata was again assumed to be the most likely type of wood to be used for the structure and the weatherboards. These used the same pinus radiata custom material used for the structure and interior lining for bathroom PR-M-NI-01 model.

All other materials for the cross-sections used data from the WuFi-Pro materials library, but had their thermal conductivity as noted above. The following are what materials were used for each layer:

- **Plasterboard Interior Lining:** Interior Gypsum Board from North American database.
- **Insulation:** Used Fibre Glass from North American database.
- **Wall underlay:** Spun Bonded Polyolefin Membrane.

5.1.3.2 ORIENTATION/INCLINATION/HEIGHT

The orientation, inclination of the walls, and their heights needed to be included in the WuFi models to determine exposure to outdoor conditions. However, the House Condition Survey did not collect information on any of these factors. Assumptions about these variables had to be made to account for the missing data.

There is no way to make a reasonable assumption about the orientations of the walls being modelled, and the effect that incorrectly assuming this would have on the models ability to estimate mould growth was unknown. A sensitivity analysis was conducted to determine what these impacts would be, which is further discussed in section 5.3.3. The orientation for both cross-sections was set to north so that calculations could be conducted in WuFi-Pro and the pilot study could continue.

WuFi-Pro has four pre-set categories of varying heights - one for short buildings under 10m tall, and the other three being for tall buildings. The height for both walls was set to the 'short buildings under 10m' category as it was known the two houses are detached single family dwellings.

5.1.3.3 SURFACE TRANSFER CO-EFFICIENT

The transfer co-efficient of the exterior and interior surfaces of the wall had to be calculated to determine the influence the surrounding environment. Information about the finishes of these surfaces is required to calculate this. Most of the required information was collected during the HCS except for inputs needed to determine radiation absorptivity, reflectivity, and exterior finishes. A sensitivity analysis was conducted to determine the impact of possible exterior finishes which is further discussed in section 5.3.5.

5.1.3.4 INITIAL CONDITIONS

WuFi-Pro requires the initial internal relative humidity and temperature of each layer in a cross-section to be set before running a calculation. However, only the air relative humidity and temperature in the bathroom was measured during the OVBS. A test simulation was run for each model to determine when the humidity and temperature of the materials in the wall would reach equilibrium after it was constructed. It was assumed that these values would remain constant until measurements started being taken in the OVBS.

The time period for the first simulation began in June 2016, and continued until October 2016. The initial conditions for these simulations were set to the measured air relative humidity and temperature at the corresponding time period that the simulation began. The simulation was run until the relative humidity and temperature in the wall reached equilibrium (levelled out), and the values they reached equilibrium at were used as the initial conditions. The modelling result was that the initial conditions were set to 73% relative humidity and 12.5ºC temperature for both bathrooms.

5.1.4 SETTING OUTDOOR CONDITIONS IN WUFI-PRO

The procedure for creating external weather files using data from Cliflo presented in section 4.4.3 was followed for both bathrooms. The data was collected from a weather station located in Kelburn, Wellington and was used to represent the Wellington Central climate zone for house WL-N-I-01. The data that was taken from Clifo included the dry bulb temperature, relative humidity, rain factor, global radiation, direct solar radiation, and wind speed. An .epw weather file produced by NIWA that used average values was edited to use the data from Clifo instead. A weather station that had the required data could not be found near Porirua, so the weather file for Wellington Central was also used for House PR-M-NI-01.

5.1.5 SETTING INDOOR CONDITIONS IN WUFI-PRO

The process described in section 4.4.2 was completed for both bathrooms and produced two internal conditions .epw files that would be used for their respective models. However, there were some large sections of missing data (approximately 2-3 days' worth) in the OVBS files where average value from the surrounding days could not be used. By default WuFi-Pro assumes that the relative humidity drops to 50% when reading missing values while the temperature remains constant until a non-missing value is read.

Missing values in the relative humidity for both bathrooms were changed to match the last non-missing value in the data, so that WuFi-Pro would treat relative humidity data similar to the way it treated missing temperature data. The periods where there was missing data were recorded and not included while analysing the results. This was done because the relative humidity dropping to 50% may not be reflective of how the humidity behaved in the actual bathroom, and arbitrarily drops like this could interfere with any trends evident in the data.

5.1.6 SIMULATING INTERNAL LINING CONDITIONS IN WUFI-PRO

With the models of both bathrooms created, the moisture and temperature conditions of their interior linings could be calculated using WuFi-Pro.

To run a calculation in WuFi-Pro, the period that the calculation ran for and monitor positions defining where moisture and temperature changes were calculated had to be set. The period was set between June 8th 2016 and October 8th 2016 to align with the models' indoor condition data time period, and the time interval between calculations was set to one hour. A monitor position was placed on the indoor boundary of the interior lining for each model needs the conditions of the interior lining to estimate surface mould growth.

The relative humidity, temperature, dew point, and water content of the interior linings for both models were calculated in WuFi-Pro. No convergence failures were found in either models and the moisture balances for bathroom PR-M-NI-01 and bathroom WL-NM-I-01 were -0.19, -0.19 and -0.07, -0.07 respectively. No convergence failures and the moisture balances being equal indicate that no numerical errors occurred in either of the models and all required inputs have been set within reasonable parameters (Zirkelbach, Schmidt, Kehrer, & Kunzel, p. 36).

5.1.7 SIMULATING THE POTENTIAL FOR MOULD TO GROW

The results for both models were imported into WuFi-Bio. WuFi-Bio has two variables that need to be set before a simulation can be run; the substrate class, and the initial relative humidity of the model mould spore (IRHS).

The substrate class variable has four inputs that group together common types of substrates (see section 4.2). Class 1 was selected for both models which represents biologically degradable materials such as plasterboard and match-lining (Fraunhofer IBP, 2011) The IRHS on the interior surface was not known for either bathroom. However, the WuFi-Bio Help Guide suggests that values between 40% and 80% are generally suitable. The effect this variable had on the results of the simulation was tested by running three simulations and changing the initial relative humidity of the spore between each one. These changes were set to the low extreme 40%, the mid-point 60%, and the high extreme 80%. The results from these simulations are shown in section 5.2.

5.2 INITIAL MOULD ESTIMATION RESULTS

This section shows the results produced by WuFi-Bio after going through the process and using the assumptions discussed in section 5.1. Testing the impact of the IRHS is presented first while the comparison to the actual bathroom is presented afterwards.

For each model, four estimations were run with the aims of testing the significance of the IRHS and comparing the estimated mould growth in WuFi-Bio to the observed mould from the HCS. The following are what changes were made between each estimations:

- Using **typical model** with IRHS set to **60%.**

- Using **thermal bridge model** with IRHS set to **60%.**
- Using **typical model** with IRHS set to **40%.**
- Using **typical model** with IRHS set to **80%.**

5.2.1 TESTING SIGNIFICANCE OF INITIAL RELATIVE HUMIDITY OF SPORE

The results from the three typical models with different IRHS were compared to each other. The results for bathroom PR-M-NI-01 and WL-NM-I-01 can be seen in Figure 12 and Figure 13 respectively. The graphs on the left show the water content in the model changing over time. The blue line shows the water content of the model spore (WCoS) and the red line shows the critical water content (CMC). When the blue line goes over the red line, mould starts to grow. The graphs on the right show how the risk of mould is changing over time, with the blue line showing this risk in mould index.

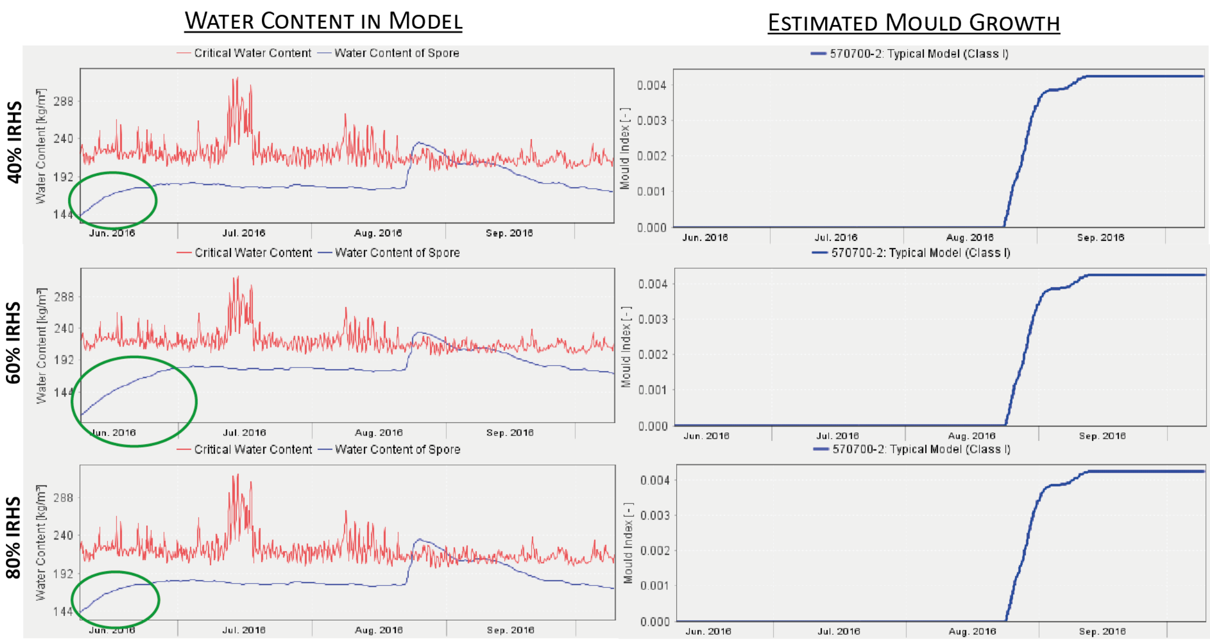

FIGURE 12 INITIAL RELATIVE HUMIDITY OF SPORE RESULTS FOR BATHROOM PR-M-NI-01

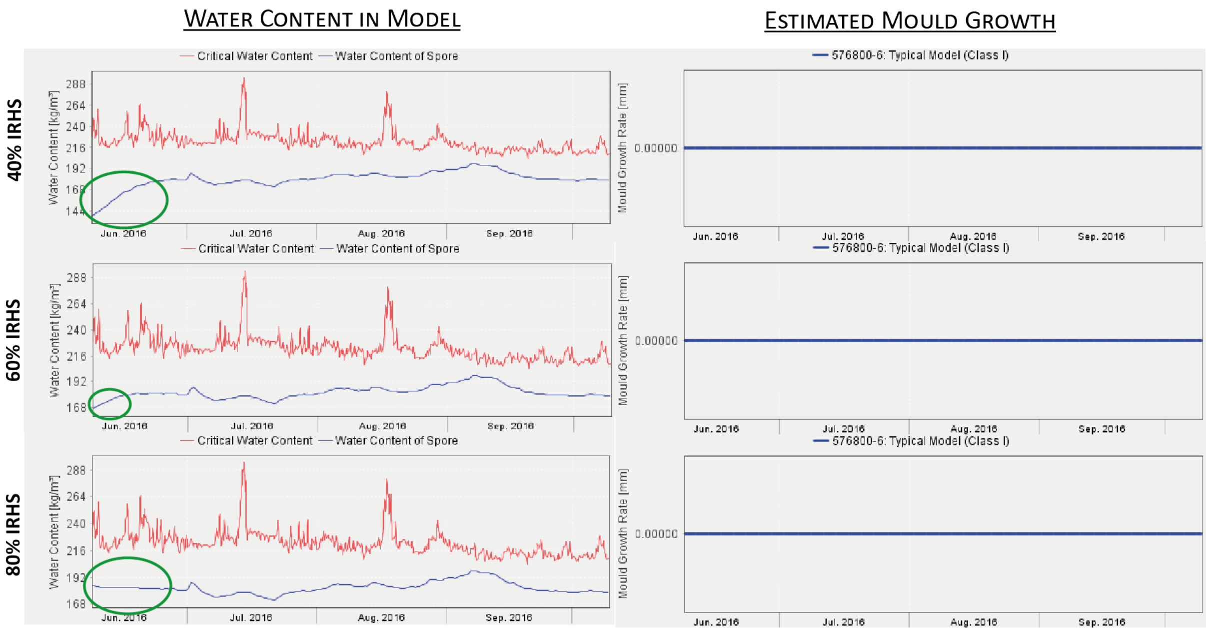

FIGURE 13 INITIAL RELATIVE HUMIDITY OF SPORE RESULTS FOR BATHROOM WL-NM-I-01

There was a risk of mould estimated to grow in bathroom PR-M-NI-01 while none was estimated to grow in bathroom WL-NM-I-01. The risk of mould in bathroom PR-M-NI-01 was maximised at 0.004 regardless of what the IRHS was set too. There was also no change in the risk of mould between the three bathroom WL-NMI-01 variations.

There were differences in how the water content behaved in both models when the IRHS was changed. These changes are highlighted by green circles in Figure 12 and Figure 13. Changing the IRHS had a noticeable impact on the WCoS, but only at the start of each estimation. After this initial period, the WCoS in both models reaches equilibrium and starts to behave in the same way regardless of what the IRHS was set to. This suggests that the IRHS will only impact the estimated risk of mould if it starts to increase early, and will have no impact if the WCoS reaches equilibrium first.

5.2.2 COMPARING ESTIMATED MOULD GROWTH WITH OBSERVED MOULD GROWTH

The results of the typical and thermal bridge models with 60% IRHS were compared to the observed mould from the HCS. The 40% and 80% models were excluded from this comparison because there was no change in what risk of mould they estimated. Figure 14 and Figure 15 shows the results for bathroom PR-M-NI-01 and WL-NM-I-01 respectively, using the same format described in section 5.2.1.

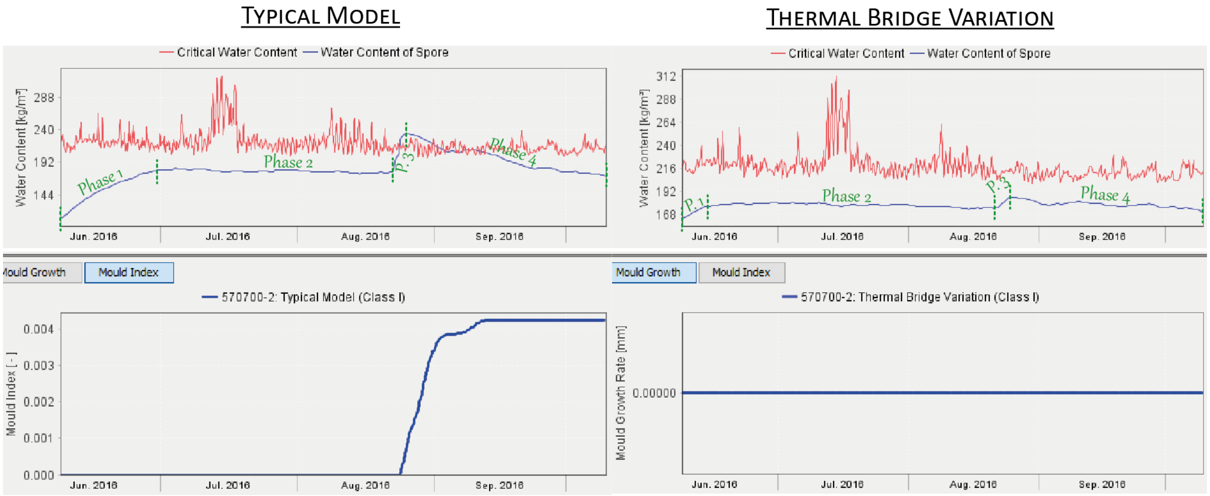

FIGURE 14 WUFI-BIO RESULTS FOR BATHROOM PR-M-NI-01

Visible mould was found in bathroom PR-M-NI-01 during the HCS. However, neither the typical nor the thermal bridge model aligned with this As established in section 4.4.4, the bathroom with mould in it should have a risk of mould greater than 3.0 to indicate that there is enough risk that enough mould to be visible to the naked eye will grow. While there is a risk in the typical models reporting here, this risk only reaches 0.004. This is not high enough for mould to start germinating. This implies that the model results do not match the mould growth in the actual bathroom. Potential reasons for this, and the effect this had on achieving research objective two are discussed in section 5.3.

The green lines in Figure 14 for bathroom PR-M-NI-01 show the WCoS broken into phases where the behaviour of the water content changes. The following is an explanation what is occurring during each phase:

- Phase 1: The WCoS is rising to reach equilibrium. This is due to the IRHS being set lower than the actual humidity. The water content reaching equilibrium before equally the critical water content and the critical water content not lowering the point of equilibrium during phase 1 suggest that no mould growth would have occur during this time.
- Phase 2: The WCoS has reached equilibrium and stays this way until phase 3 begins.

- **Phase 3:** The micro-climate changes in a way that results in the WCoS rapidly increasing, exceeding the CMC and resulting in mould growth. The micro-climate can be determined to be the cause of this rather than the construction because this change occurs in both the typical and thermal bridge models. However, the thermal bridge model's increase is significantly less.
- **Phase 4:** The WCoS slowly decreases, slowing down the rate of mould growth before lowering below the CMC and stopping mould from continuing to grow.

TYPICAL MODEL | THERMAL BRIDGE VARIATION

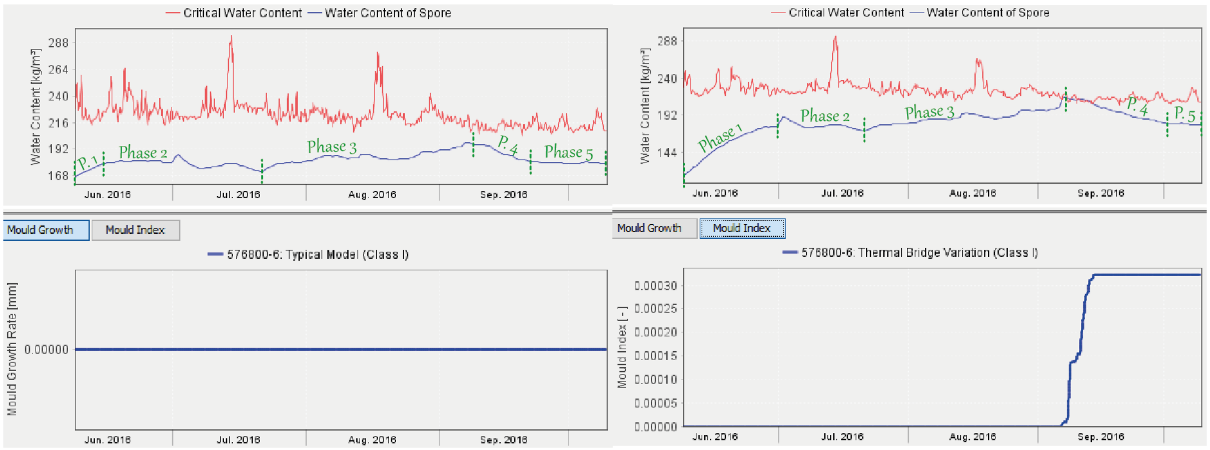

FIGURE 15 WUFI-BIO RESULTS FOR BATHROOM WL-NM-I-01

Visible mould was not found in bathroom WL-NM-I-01 during the HCS. Both models appear to align with this observation, with both estimating no (or extremely low) risk of mould. Whether this actually suggests that the model is representing no risk of mould in the actual bathroom is discussed in section 5.3.

The green lines in Figure 15 for bathroom WL-NM-I-01show the WCoS broken into phases were the behaviour of the water content changes:

- **Phase 1:** The WCoS is rising to reach equilibrium. This is due to the IRHS being set lower than the actual humidity. The water content reaching equilibrium before equally the critical water content and the critical water content not lowering the point of equilibrium during phase 1 suggest that no mould growth would have occur during this time.
- **Phase 2:** The WCoS reached equilibrium and stays in this state until phase 3 begins.

- **Phase 3:** The WCoS gradually increases. The WCoS in the thermal bridge model exceeds the CMC resulting in mould growth, while this does not happen in the typical model.
- **Phase 4:** The WCoS slowly decreases, slowing down the rate of mould growth before lowering below the threshold and stopping mould from continuing to grow in the thermal bridge model.

5.3 EXPLORING WHY ONE MODEL DID NOT ALIGN

The aim of this pilot study was to develop a methodology that could be used to produce models that simulated the risk of mould in NZ bathrooms, and test the effect of mould mitigation strategies on that risk. This was done to try and meet research objective two in section 1.3.1 and answer the following question:

Can models capable of testing mould mitigation strategies be created using HCS data and WuFi-Pro?

However, the results from bathroom PR-M-NI-01 suggest that this model does accurately reproduce the actual bathroom, but the number assumptions used made it unclear what could have contributed to this. The rest of this section discusses some major issues that are likely to have prevented the question above being answered, and why this pilot study failed to meet objective two.

5.3.1 UNCERTAINTY WITH VALIDATING THE MODELS

During the pilot study the method to validate that the models were representative of the risk of mould in the actual bathrooms was found to be simplistic and limited. The logic behind this validation was that if there was visible mould in the actual bathroom, then the model of the bathroom should show that there is a risk of visible mould. The way to check this was that the risk of mould in the model had to equal or exceed mould index 3.0 at some point within estimation period.

However, this method fails to take into account factors that could affect the risk of mould in the bathroom that could not be determined by the HCS observations. This includes the occupants' attempts to treat mould, the time it took for the HCS observed mould to grow, and whether it was still growing or if it had stagnated at the time of observation. How these situations effected observations from the HCS is unknown, and thus it cannot be determined whether these observations were accurate indicators of the risk of mould in the actual bathrooms.

This uncertainty is best explained via example. The model results from Bathroom WL-NM-I-01 appeared to align with the observations from the HCS during the pilot study. There was no visible mould observed during the HCS, and no risk of visible mould was estimated. The following is a list of scenarios that could have led to the observations in bathroom WL-NM-I-01, and possible reasons for the model being correct or incorrect:

- There is no mould issue in the HCS bathroom. The model would be correct
- There was microscopic mould that was not seen during the HCS. In this case the risk of mould in WuFi-Bio should exceed 1.0, and as was not the case the model could be wrong.
- The bathroom had a mould issue, but the occupants cleaned it before the HCS inspection. There would be a risk of visible mould in the actual bathroom but as the model suggested no mould growth it could be wrong.
- The mould had not grown enough to be visible before the HCS inspection. There is a risk of non-visible mould and there could be a risk of visible mould, but the model suggested no mould growth it would be wrong.

All of these scenarios are plausible, but which one is true cannot be distinguished using the data collected by the HCS. This seems to be a likely reason why models that can be used to test mould mitigation strategies can't be produced using HCS data. However, there were other uncertainties that could have caused the results in section 5.2.2. Before concluding whether this was the main issue, the other uncertainties discussed in the rest of this section need to be explored to see if they had an impact.

5.3.2 UNCERTAINTY WITH WUFI-BIO

As discussed in section 4.2, WuFi-Bio is subject to limitations that give it a tendency to overestimate the risk of mould, and how quickly mould starts to grow. It is unknown whether WuFi-Bio's limitations contributed to the results found in section 5.2.2, although it seems unlikely due to the results from bathroom PR-M-NI-01 being lower than 3.0. WuFi Mould Index VTT (VTT) was introduced into the study at this stage so that the impact of WuFi-Bio's limitations could be tested.

The risk of mould was estimated using both of these programs and their results were compared to see if they estimated different risks of mould. Differences between their results would indicate that the programs assumptions and limitations would have an impact on the risk of mould and indicate that this could have contributed to the results from the pilot study not aligning with the HCS.

The results from WuFi-Bio and VTT cannot be compared directly. This is because of WuFi-Bio assumes that mould growth stagnates during unfavourable conditions while VTT estimates that it decreases. This leads to WuFi-Bio generally estimating a higher risk of mould growth than VTT (Vereecken, Saelens, & Roels, 2011, p. 1940). However, whether this difference is serious enough to affect whether no mould, microscopic mould, or visible mould is estimated in the houses in this study is unknown.

The results of both programs for the same models were compared to see if there were differences between the classifications of mould they estimated. The criteria for these classifications are shown in Table 11. These criteria apply to the rest of the estimations in this study.

TABLE 11 CRITERIA FOR MOULD GROWTH CLASSIFICATION

Classification	Criteria
No Mould	Maximum mould index **<1.0**
Microscopic Mould	Maximum mould index **between 1.0 and 3.0**
Visible Mould	Maximum mould index **> 3.0**

The same method in section 4.4.4 to determine whether the models aligned with the HCS, was used for these estimations as well, despite the uncertainty identified in the Pilot Study. This remains a potential cause of the models not aligning, but there is no other possible indicator of the risk of mould that was collected during the HCS.

5.3.3 NOT KNOWING ORIENTATION OF WALLS

No information about the orientation of walls being modelled or the houses they are a part of were recorded by the HCS. There is also no reasonable way to estimate the orientation of the walls from the HCS data. A sensitivity analysis was conducted to determine if the orientation of a wall would have a significant impact on the risk of mould growth on its interior lining. A sensitivity analysis testing the difference between the four orientations listed below was conducted:

- North
- East
- South
- West

The aim of this was to test the impact this variable would have on the risk of mould and see if it could have been a contributing factor to the results in the pilot study not aligning with the HCS. Variations each with a different orientation was created for the typical and thermal bridge models of all seventeen bathrooms. The risk of mould in them was estimated using WuFi-Bio and VTT.

The results for each variation would be assigned classifications based on the criteria in Table 11. Differences between the assigned classifications would determine whether orientation could have a great enough impact to contribute to the results in the pilot study not aligning with the HCS. If all the classifications remained the same, then the impact of changing the orientation of the wall would not be great enough to change the risk of mould. This would mean that any impact caused by incorrectly estimating the orientation would be negligible, and this variable would not have contributed to the pilot study results.

If any of the classifications changed, then this would indicate that changing the orientation would have a great enough impact to affect the risk of mould in each model. This means that incorrectly estimating the orientation of the wall could have affected the results from the Pilot Study and contributed to them not aligning with HCS.

5.3.4 NOT KNOWING AMOUNT OF INSULATION

Insulation is frequently mentioned as a means to reduce the risk of mould growth, and is commonly recommended to NZ home occupiers (section 2.2). This suggests that to produce a model in WuFi-Bio that simulates the risk of mould in the actual bathroom, the presence and amount of insulation needs to be known. Whether the assumptions made about the insulation in the models represented the insulation in the actual bathrooms is unknown. For example, these assumptions did not consider the possibility that bathroom PR-M-NI-01 was renovated after 1978 or if bathroom WL-NM-I-01 exceeded the requirements of NZS 4218.

To address these issues, a sensitivity analysis testing the impact that insulation has on the risk of mould was undertaken. This tested the assumption about the presence of insulation, and also the impact of incorrectly assuming the amount of insulation. This was done by creating variations of each cross-section with different levels of insulation. The levels of insulation included and justifications for why they were included are as follows. All insulation used in these variations was fibreglass as this is commonly used in NZ construction:

- **No Insulation:** Base level for houses constructed before 1978.
- **Minimum 1978 (Total wall R-value 1.2m^2 ºC/W):** Base level for houses constructed after 1978. Tests the impact of incorrectly assuming that no insulation is present when there is insulation present.
- **90mm thick insulation (R-value between 1.81 to 2.78m^2 ºC/W):** Shown in the HIG to be a common amount of insulation used in the NZ housing stock (BRANZ, 2014, p. 65). Tests the impact of incorrectly assuming level of insulation.
- **140mm thick insulation (R-value between 2.75 to 3.71m^2 ºC/W):** Shown in the HIG to be a common amount of insulation used in the NZ housing stock (BRANZ, 2014, p. 65). Tests the impact of incorrectly assuming level of insulation.

- **180mm thick insulation (R-value between 3.49 to 4.46m^2 °C/W):** Shown in the HIG to be a common amount of insulation used in the NZ housing stock (BRANZ, 2014, p. 65). Tests the impact of incorrectly assuming level of insulation.

The aim of this was to test the impact of R-value on the risk of mould and see if it could have been a contributing factor to the results in the Pilot Study not aligning with the HCS. Variations each with a different level of insulation were created for the typical models of all seventeen bathrooms. The risk of mould in them was estimated using WuFi-Bio and VTT, and whether differences between the variations were great enough to affect the risk of mould was determined using the same method as the orientation sensitivity analysis.

5.3.5 NOT KNOWING EXTERIOR FINISH OF WALLS

No information about the finishes on the bathrooms exterior cladding was reported in the HCS, and there is also no reasonable way to estimate them. A sensitivity analysis was also conducted to determine if the exterior finish would have a significant impact on the risk of mould.

To allow this sensitivity analysis to be conducted four variations of each cross-section were created, with one representing each of the following finishes. This would allow the risk of mould to be estimated in WuFi-Bio for each type of finish, and their results could be compared to establish if the finish would have a significant impact.

- No finish
- Primer only
- Paint only
- Primer and Paint

The aim of this was to test the impact this variable would have on the risk of mould and see if it could have been a contributing factor to the results in the Pilot Study not aligning with the HCS. The hygrothermal information supplied by BRANZ was used to create materials representing each finish in WuFi-Pro. Variations each with a different finishing material was created for the typical models of all seventeen bathrooms. The risk of mould in them was estimated using WuFi-Bio and VTT, and whether differences between the variations were great enough to affect the risk of mould was determined using the same method as the orientation sensitivity analysis.

5.4 SUMMARY OF CHANGES MADE TO METHODOLOGY

Going through the process of modelling two bathrooms in WuFi-Pro and estimating the mould that would grow in them in WuFi-Bio revealed that the modelling strategy established in section 5.1.1 was insufficient. It could not take into account the impact of major assumptions such as orientation and insulation, and did not have means of validation. Reasonable assumptions could be made to account for some of the missing data while ensuring that the models remained representative of NZ houses. However, some of the unavailable data from the HCS directly impacted the ability to validate the models or did not provide enough context to make reasonable assumptions about variables that have been shown to have an impact on mould.

The following is a summary of the changes made to the modelling methodology throughout this pilot study. An improved methodology diagram is shown in Figure 16. This methodology is used for the initial data analysis in Chapter 6: to achieve research objective two.

- Model four variations with changing orientation.
- Model five variations with different levels of insulation
- Model four variations of exterior finishes
- Use house insulation guide to determine missing construction
- Run preliminary simulation to determine initial conditions
- Use NZS4218 to determine likely presence of insulation

- Run preliminary WuFi-Bio simulation to determine appropriate initial relative humidity of spore
- Determine if results from WuFi-Bio simulations show; no mould, non-visible mould, or visible mould
- Use VTT to estimate risk of mould as well, and compare to WuFi Bio (not shown in Figure 16.

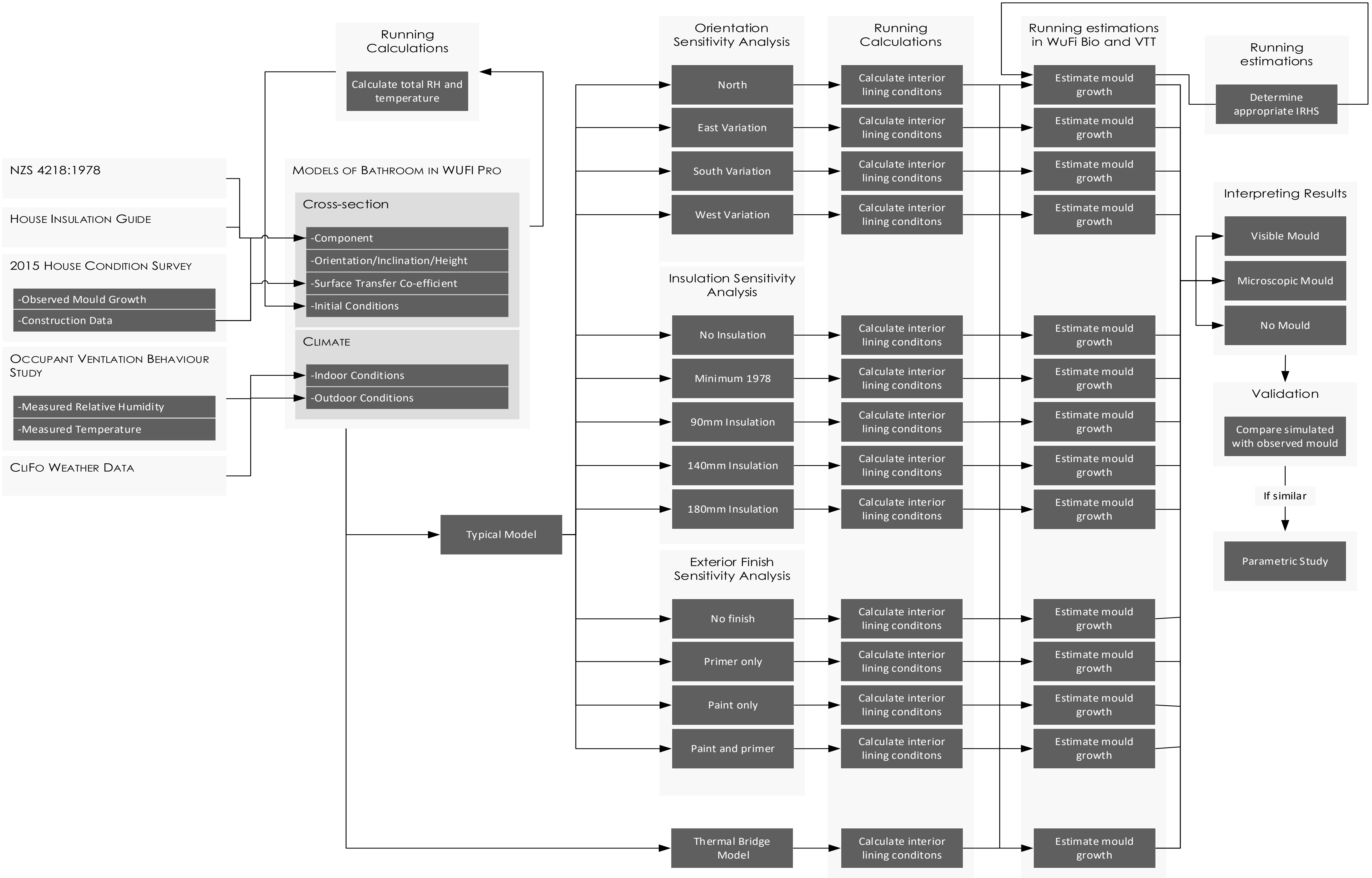

FIGURE 16 REVISED MODELLING METHODOLOGY

Chapter 6: Initial Data Analysis

An initial data analysis was conducted to test the impact of assumptions and uncertainties on the risk of mould in the models. The results from the revised methodology in Figure 16, and how they relate to the research objectives are discussed.

The results obtained during the pilot study did not align with what was observed in the actual bathrooms, however what variables contributed to this was unknown. The aim of this initial data analysis was to get closer to identifying the variable/s that prevented research objective two being met in the Pilot Study and answer the third research question:

Do the assumptions made to create the models in the previous chapter have an impact on the risk of mould?

The unknown variables tested were the impacts of WuFi-Bio's assumptions, and incorrectly assuming the orientation, insulation, and exterior finish of the walls. The seventeen bathrooms shown in Table 7 were modelled in WuFi-Pro using the modelling methodology developed throughout section Chapter 5:, and the risk of mould in them was estimated using WuFi-Bio and VTT. The cross-sections for each bathroom wall are shown in Appendix C.

Variations of each model with different orientations, levels of insulation, and exterior finishes were created as part of the modelling methodology developed throughout section Chapter 5:. This process created a total of 234 variations, with 4 orientation variations, 5 insulation variations, 4 exterior finishes variations and 1 thermal bridge variation for each bathroom. How these variations were used to determine the impact that these variables had on the risk of mould growth and the reliability of the models is discussed in sections 5.3. None of these tests were trying to prove that any one of the variations was the cause of the results from the Pilot Study not aligning, but trying to eliminate them as potential contributing factors.

6.1 WERE THE UNCERTAINTIES IMPORTANT?

This section presents the results from going through the revised methodology developed throughout the pilot study for all 17 bathrooms and their variations. These variations included representations of the bathrooms typical wall constructions as determined using the method developed in section Chapter 5:, their thermal bridges, and changes in orientation, insulation, and exterior finishes. The mould growth in each variation was estimated using WuFi-Bio and VTT resulting in 306 total estimations and results.

The results for this are presented in tables so that variations could be compared. The tables list each model with the results from each of their variations being shown along the corresponding row. All results are expressed in the peak mould index. The colours of each cell show the classification that each result was assigned based on the criteria explained in section 5.3.2 with green representing no mould, orange representing microscopic mould and red representing visible mould.

6.1.1 COMPARISON TO OBSERVED MOULD AND VTT

Two base models of each bathroom were created based on what was assumed to be their most likely constructions. The 'typical' models represent parts of the bathroom's walls where insulation or an air gap is located, and the ones labelled thermal bridge represent where a 90x45mm stud is located. The results from these models were compared to the observed mould from the HCS to validate the models using the criteria described in section 4.4.4. The results from this process and the observed mould for each bathroom are shown in Table 12.

TABLE 12 SIMULATION RESULTS FROM WUFI-BIO AND VTT COMPARED TO OBSERVED MOULD

House ID	Observed Mould	Base Models			
		WuFi-Bio		VTT	
		Typical	Thermal Bridge	Typical	Thermal Bridge
DN-NM-NI-01	No	-	-	<0.01	-
DN-NM-NI-02	No	0.05	0.02	0.03	0.02
BH-NM-I-01	No	-	-	<0.01	-
BH-NM-I-02	No	-	-	<0.01	-
BH-NM-I-03	No	-	-	-	-
NL-NM-I-01	No	0.18	0.19	0.15	0.15
BH-NM-I-04	No	-	-	<0.01	-
MT-NM-I-01	No	-	-	-	-
MT-NM-I-02	No	-	-	<0.01	<0.01
PR-M-NI-01	Yes	<0.01	-	0.01	<0.01
WL-NM-I-01	No	-	-	<0.01	-
WL-NM-I-02	No	-	-	<0.01	<0.01
WL-NM-I-03	No	-	-	<0.01	<0.01
WL-NM-NI-01	No	-	-	<0.01	<0.01
WL-NM-NI-02	No	-	<0.01	<0.01	<0.01
WL-NM-NI-03	No	-	-	<0.01	<0.01
WL-NM-NI-04	No	-	-	-	-

The risk of mould in none of the bathroom's base models was high enough to show a risk of mould germination. This can be seen by all the results in Table 12 being green. Bathrooms DN-NM-NI-02, NL-NM-I-01, PR-M-NI-01, and WL-NM-NI-02 were estimated to have a maximum mould index above zero when estimating with WuFi-Bio, and all except for bathrooms BH-NM-I-03, MT-NM-I-01, and WL-NM-NI-04 achieved the same when using VTT. However, none of these values exceeded 1.0 indicating there was no risk of even non-visible mould growing.

There was no apparent risk of mould even for bathroom PR-M-NI-01 despite having mould found in it during the HCS. Both WuFi-Bio and VTT estimated a maximum mould index of higher than 0, but these did not exceed the 3.0 needed for the risk of model to be present.

WuFi-Bio and VTT had slightly different mould risk results. VTT estimated a mould index above zero in 24 of the models compared to WuFi-Bio only estimating this in 6, but in both the index was below 1.0 suggesting no risk of even non-visible mould.

Using WuFi-Bio or VTT had no impact on the classification of mould that the models were estimated to be at risk of growing. This indicates that the limitations of WuFi-Bio likely did not contribute the results in the pilot study not aligning with the HCS.

This analysis was intended to be the main indicator of whether the models were representative of their respective bathrooms. The results do not suggest that they are. The sensitivity analyses in the following three sections would indicate if this was caused by incorrect assumptions about the orientation, insulation, or exterior finishes.

6.1.2 ORIENTATION SENSITIVITY ANALYSIS

North, east, west, and south oriented variations were created for each of the typical and thermal bridge base models shown in Table 12. Both WuFi-Bio and VTT were used to estimate the risk of mould. The results from these models were used to test the impact of incorrectly assuming the orientation of the bathroom on the risk of mould and seeing if models that could be used to test strategies could be created without this information. The results from this process and the observed mould for each bathroom are shown in Table 13.

TABLE 13 RESULTS FROM ORIENTATION VARAITONS

House ID	Observed Mould	WuFi-Bio								VTT							
		Typical Models				Thermal Bridge Models				Typical Models				Thermal Bridge Models			
		North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
DN-NM-NI-01	No	-	-	-	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	-	-	<0.01	-
DN-NM-NI-02	No	0.05	0.09	0.11	0.09	0.02	0.05	0.07	0.05	0.03	0.04	0.05	0.04	0.02	0.03	0.04	0.03
BH-NM-I-01	No	-	-	-	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	-	-	<0.01	-
BH-NM-I-02	No	-	-	-	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	-	-	<0.01	-
BH-NM-I-03	No	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NL-NM-I-01	No	0.18	0.21	0.22	0.20	0.19	0.22	0.24	0.22	0.15	0.18	0.19	0.17	0.15	0.18	0.20	0.18
BH-NM-I-04	No	-	-	-	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	-	-	<0.01	-
MT-NM-I-01	No	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MT-NM-I-02	No	-	-	-	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
PR-M-NI-01	Yes	<0.01	<0.01	<0.01	<0.01	-	-	-	-	0.01	0.01	0.02	0.01	<0.01	<0.01	0.01	<0.01
WL-NM-I-01	No	-	-	-	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	-	-	<0.01	-
WL-NM-I-02	No	-	-	-	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-I-03	No	-	-	-	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-NI-01	No	-	-	-	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-NI-02	No	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01
WL-NM-NI-03	No	-	-	-	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-NI-04	No	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

No risk of mould growth was found in any of the models when their orientations were changed, with all the results in Table 13 being green. Like their base models, bathrooms DN-NM-NI-02, NL-NM-I-01, PR-M-NI-01, and WL-NM-NI-02 had maximum mould indexes above zero when estimating with WuFi-Bio, and all except for bathrooms BH-NM-I-03, MT-NM-I-01, and WL-NM-NI-04 achieved the same when using VTT. However, none of these values exceeded 1.0 indicating there was no actual risk of mould when the model's orientations were changed.

Changing the orientation of bathroom PR-M-NI-01 had no impact on the risk of mould. VTT did estimate a slight increase of 0.01 when both its base models were changed to face south, but regardless of orientation the estimated risk of mould in the bathroom did not exceed 1.0.

The south orientated variations of bathroom PR-M-NI-01 having a slightly higher mould index was consistent amongst all other bathrooms that had a mould index higher than zero. This can be seen in bathrooms DN-NM-NI-02, NL-NM-I-01, and WL-NM-NI-02, where VTT always estimated the south facing orientations to be higher and WuFi-Bio did this for the former two. However, due to these estimations being below 1.0 no visible mould would be expected. It cannot be determined whether these differences are significant enough to suggest genuinely different risks of mould or is a result of the programs margins of error.

The differences between WuFi-Bio and VTT followed a similar trend as the base models. VTT estimated a mould index above zero in 97 of the models compared to WuFi-Bio only estimating this in 27. This further supports the finding about VTT identified in section 6.1.2, but the results in Table 13 differ in that WuFi-Bio consistently estimates a higher mould index than VTT when both estimate a value above 0. This can be seen in bathrooms DN-NI-NI-02 and NL-NM-I-01 where WuFi-Bio's estimates are higher than VTT's for all variations. It is still unknown whether these differences are of concern due to none of them exceeding mould index 1.0, but WuFi-Bio consistently being higher be indicative of significant changes at higher risks of mould.

6.1.3 INSULATION SENSITIVITY ANALYSIS

Uninsulated, insulated to 1978 minimum standards, 90mm insulation, 140mm insulation, and 180mm insulation variations were created for each of the typical base models shown in Table 12. The results from this process and the observed mould for each bathroom are shown in Table 14. The uninsulated variations are the base models for bathrooms that have 'NI' in third position in their ID's and the 1978 variations are the base models for bathrooms with 'I'.

TABLE 14 RESULTS FROM INSULATION VARIATIONS

House ID	Observed Mould	Insulation									
		WuFi-Bio					VTT				
		Uninsulated	1978	90mm	140mm	180mm	Uninsulated	1978	90mm	140mm	180mm
DN-NM-NI-01	No	-	-	-	-	-	<0.01	-	-	-	-
DN-NM-NI-02	No	0.05	<0.01	<0.01	-	-	0.03	<0.01	<0.01	<0.01	<0.01
BH-NM-I-01	No	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01
BH-NM-I-02	No	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	-
BH-NM-I-03	No	-	-	-	-	-	-	-	-	-	-
NL-NM-I-01	No	0.14	0.18	0.13	0.12	0.12	0.12	0.15	0.11	0.10	0.10
BH-NM-I-04	No	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	-
MT-NM-I-01	No	-	-	-	-	-	-	-	-	-	-
MT-NM-I-02	No	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01
PR-M-NI-01	Yes	<0.01	-	-	-	-	0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-I-01	No	-	-	-	-	-	<0.01	<0.01	<0.01	-	-
WL-NM-I-02	No	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-I-03	No	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-NI-01	No	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-NI-02	No	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-NI-03	No	-	-	-	-	-	<0.01	<0.01	-	-	-
WL-NM-NI-04	No	-	-	-	-	-	-	-	-	-	-
Total 0 Values		14	15	15	16	16	3	4	5	6	8

There was no risk of mould in any of the models when the amount of insulation in them was changed. This can be seen by all the results in Table 14 being green. Bathrooms DN-NM-NI-02, NL-NM-I-01, and PR-M-NI-01 had maximum mould indexes above zero when estimating with WuFi-Bio, and all except for bathrooms BH-NM-I-03, MT-NM-I-01, and WL-NM-NI-04 achieved the same when using VTT. However, none of these values exceeded 1.0 indicating there was no actual risk of mould when the amount of insulation in the models was changed.

Adding more insulation into bathroom PR-M-NI-01 had no impact on the classification of mould. The base model of bathroom PR-M-NI-01 was uninsulated and adding 140mm and 180mm insulation dropped the mould index to zero in VTT, with the same occurring for any amount of insulation in WuFi-Bio. This indicates that the base model was the most likely variation to show any risk of mould yet did not.

The trend shown in bathroom PR-M-NI-01 where the more insulated the bathroom the more likely it is to have a mould index of zero is consistent with the rest of the models. Variations with 180mm insulation have the most mould indexes of zero, while uninsulated variations have the fewest This can be seen in the last row of Table 14 which counts the number of variations in the corresponding column that have mould indexes of zero.

The differences between WuFi-Bio and VTT followed a similar trend as the base models. VTT estimated a mould index above zero in 60 of the models compared to WuFi-Bio only estimating this in 9. This further supports the findings about VTT identified in sections 6.1.2 and 6.1.3. This can be seen in bathroom NL-NM-I-01 where WuFi-Bio's estimates are higher than VTT's for all variations.

6.1.4 EXTERIOR FINISHES SENSITIVITY ANALYSIS

No coating, with primer, with paint, and with primer and paint variations were created of the typical base models shown in Table 12. Both WuFi-Bio and VTT were used to estimate the risk of mould. The results from these models were used to test the impact of incorrectly assuming what exterior wall coating was used on the risk of mould, and seeing if reliable models could be created without this information. The results from this process and the observed mould for each bathroom are shown in Table 15.

TABLE 15 EXTERIOR COATING SENSITVITY ANALYSIS RESULTS

House ID	Observed Mould	Exterior Coating							
		WuFi-Bio				VTT			
		Bare	Primer	Paint	Paint + Primer	Bare	Primer	Paint	Paint + Primer
DN-NM-NI-01	No	-	-	-	-	<0.01	<0.01	<0.01	-
DN-NM-NI-02	No	0.05	0.05	0.05	0.04	0.03	0.03	0.03	0.03
BH-NM-I-01	No	-	-	-	-	<0.01	<0.01	<0.01	<0.01
BH-NM-I-02	No	-	-	-	-	<0.01	<0.01	<0.01	-
BH-NM-I-03	No	-	-	-	-	-	-	-	-
NL-NM-I-01	No	0.19	0.19	0.19	0.18	0.15	0.15	0.15	0.15
BH-NM-I-04	No	-	-	-	-	<0.01	<0.01	<0.01	<0.01
MT-NM-I-01	No	-	-	-	-	-	-	-	-
MT-NM-I-02	No	-	-	-	-	<0.01	<0.01	<0.01	<0.01
PR-M-NI-01	Yes	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.01	<0.01
WL-NM-I-01	No	-	-	-	-	<0.01	<0.01	<0.01	-
WL-NM-I-02	No	-	-	-	-	<0.01	<0.01	<0.01	-
WL-NM-I-03	No	-	-	-	-	<0.01	<0.01	<0.01	-
WL-NM-NI-01	No	-	-	-	-	<0.01	<0.01	<0.01	<0.01
WL-NM-NI-02	No	-	-	-	-	<0.01	<0.01	<0.01	<0.01
WL-NM-NI-03	No	-	-	-	-	<0.01	<0.01	<0.01	-
WL-NM-NI-04	No	-	-	-	-	-	-	-	-

No mould was estimated to grow in any of the models when their exterior coatings were changed. This can be seen by all the results in Table 15 being green. Like their base models, bathrooms DN-NM-NI-02, NL-NM-I-01, PR-M-NI-01, and WL-NM-NI-02 had maximum mould indexes above zero when estimating with WuFi-Bio, and all except for bathrooms BH-NM-I-03, MT-NM-I-01, and WL-NM-NI-04 achieved the same when using VTT. However, none of these values exceeded 1.0 indicating there was no actual risk of mould when the model's exterior finish was changed.

Changing the exterior coating used on bathroom PR-M-NI-01 did not have enough of an impact to change the risk of mould. VTT did estimate a slight increase of less than 0.01 when both primer and paint were added, but regardless of the coating the estimated risk of mould in the bathroom did not exceed 3.0.

The trend shown in bathroom PR-M-NI-01 with the primer + paint variation having a slightly lower mould index was consistent amongst the other bathrooms that had a mould index higher than zero. This can be seen in bathrooms DN-NM-NI-02 and NL-NM-I-01 where VTT and WuFi-Bio estimated the variations with paint and primer would have slightly lower mould indexes.

The differences between WuFi-Bio and VTT followed a similar trend as the base models and the other sensitivity analyses. VTT estimated a mould index above zero in 97 of the models compared to WuFi-Bio only estimating this in 27. This further supports the finding about VTT identified in section 6.1.2, but the results in Table 13 differ in that WuFi-Bio consistently estimates a higher mould index than VTT when both estimate a value above 0. This can be seen in bathrooms DN-NI-NI-02 and NL-NM-I-01 where WuFi-Bio's estimates are higher than VTT's for all variations. It is still unknown whether these differences are significant due to none of them exceeding mould index 1.0.

6.2 EXPLORING ANOMALIES

The results throughout sections 6.1.1-6.1.4 suggest that neither the limitations of WuFi-Bio or incorrectly assuming the orientation, insulation, or exterior finishes contributed to bathroom PR-M-NI-01 not aligning with the HCS. However, the reason why the results did not align are still unknown. The conditions acting on the interior surface of the model that as calculated by WuFi-Pro were analysed to see if they supported visible mould growth.

This analysis was done by using the criteria for visible mould outlined in the ASHRAE 160-2009 (ASHRAE, 2009) (see section 2.1.2). The method from ASHRAE 160-2016 was not used because VTT uses that method. The relative humidity calculated by WuFi-Pro was compared to this criteria.

For visible mould to grow, the average relative humidity of air making contact with the interior surface over a 30 day period must exceed 85%.

Figure 17 shows the WuFi calculated relative humidity of the air contacting the interior surface in bathroom PR-M-NI-01 over the whole period. The blue line shows the relative humidity and the red dotted line shows the 85% threshold that the average needs to exceed for 30 days. The x-axis grids represent the start of each month.

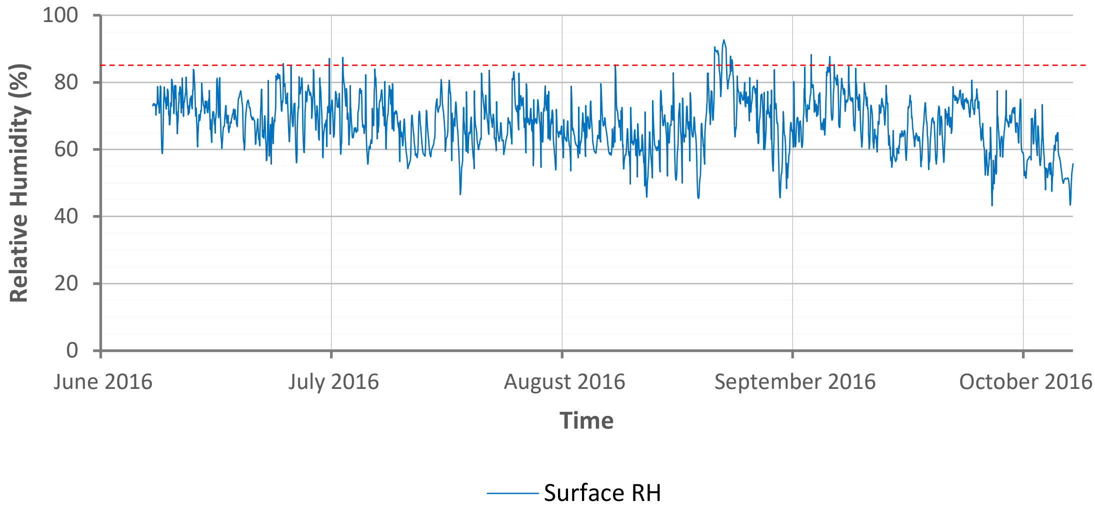

FIGURE 17 SURFACE RELATIVE HUMIDITY OF BATHROOM PR-M-NI-01 TYPICAL MODEL ESTIMATED BY WUFI-PRO

The blue line only goes over the red line (85% RH) for more than one hour in late August, and even then only stays above it for 1 to 2 days, which is less than the required 30 day period threshold. This agrees with the WuFi-Bio and VTT calculations that there was no risk of visible mould growth.

This result could have been caused by the WuFi-Pro model being incorrect. However, the assumptions that could have had the most impact were already tested previously in this chapter, and the calculations in WuFi-Pro reported no numerical errors (see section 4.1). This indicates that it is unlikely that any differences between the model and the actual bathroom would have had a great enough impact on the calculated surface conditions to stop visible mould from growing.

Another explanation is that the internal conditions measured during the Occupant Ventilation Behaviour Study (OVBS) do not represent the conditions that the mould grew in. The OVBS data used in this study was measured between June and October 2016 (Plagmann & White, 2017, p. 68), while the inspections for the HCS were conducted between May 2016 and June 2016 (White et al., 2017, p. 4). This meant that the observations from the HCS were dependent on the conditions before May 2016, not the OVBS data collection period.

The period before May (autumn) is generally warmer than between June and October (winter). Porirua, where the house with visible mould is located is exposed to extreme winds but no other extreme weather, indicating that it is usually less humid than other parts of the country (e.g. Northland, Auckland) (NIWA, 2016). Unless the occupant's moisture production habits changed between May and June, it seems unlikely that the warmer and less humid period before May would provide favourable conditions for mould, while the period after June would not. Internal condition data collected before mould was observed would be need to check this.

6.2.1 BATHROOM NL-NM-I-01

Despite visible mould being found in bathroom PR-M-NI-01, and none being found in bathroom NL-NM-I-01, bathroom NL-NM-I-01 consistently had a much higher risk of mould than all the other models. This remained true regardless of what orientation, insulation, or exterior finish was used, and these results were consistent between WuFi-Bio and VTT. This implies that this bathroom had a higher risk of mould then PR-M-NI-01 despite the HCS having found having no visible mould.

The relative humidity of the air making contact with the interior surface calculated by WuFi-Pro was compared to the same criteria (ASHRAE, 2009) used to assess PR-M-NI-01. The criteria was also expanded to test for mould germination which would allow microscopic mould to grow. This followed the same criteria as visible mould, however the relative humidity threshold the average needed to exceed was 80% rather than 85%. This was to show if this bathroom was at risk of growing visible mould even though none was observed in the HCS, and if there was a risk of microscopic mould despite the results from WuFi-Bio and VTT not exceeding 1.0.

Figure 18 shows the relative humidity of the air contacting the interior surface of bathroom NL-NM-I-01 that was calculated by WuFi-Pro. The same formatting used in Figure 17 was also used here, except a solid red line has been added to show the threshold for mould germination, and a red box has been added to show a point of interest.

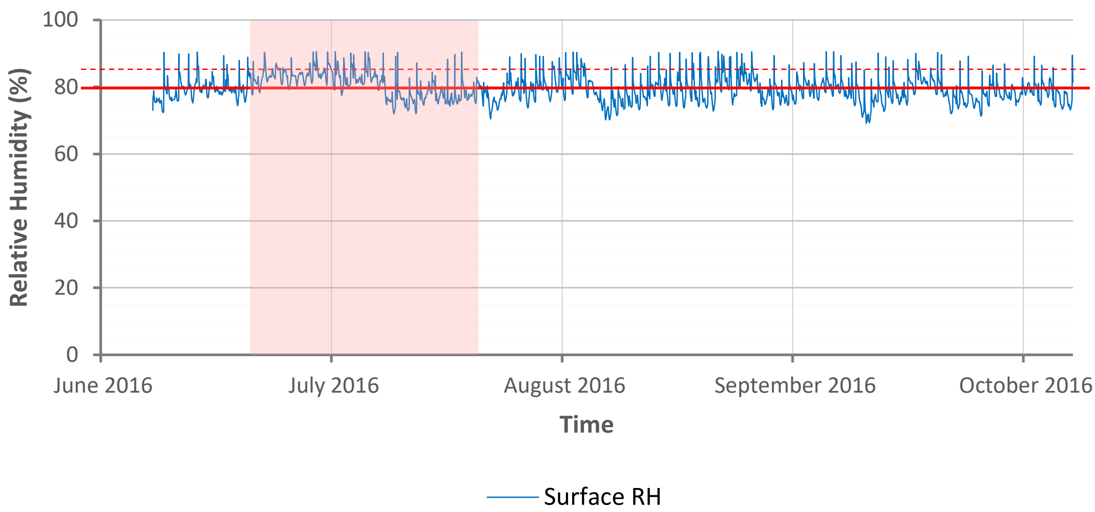

FIGURE 18 SURFACE RELATIVE HUMIDITY OF BATHROOM NL-NM-I-01 TYPICAL MODEL ESTIMATED BY WUFI-PRO

Bathroom NL-NM-I-01 has a consistently higher surface relative humidity than PR-M-NI-01, and exceeds the 85% threshold more often too. There was no 30 day period where the average relative humidity exceeded 85%, but the section highlighted in red shows a 30 day period where it exceeded 80%. This shows that germination could occur, and microscopic mould should grow, however the results from WuFi-Bio and VTT never exceeded 1.0, suggesting that there was no risk of this occurring. This discrepancy between the criteria used in this section, and WuFi-Bio and VTT is further discussed in 7.5

6.3 SUMMARY OF FINDINGS

The aim of this initial data analysis was narrow down the potential reasons why the results from the Pilot Study did not align with the observations from the HCS, and help achieve research objective two in section 1.3.1. This was done by exploring potential answers the following research question:

Do the assumptions made to produce the models have an impact on the risk of mould?

Sensitivity analyses testing the impact of incorrectly assuming what the orientation, insulation, and exterior finishes of the bathrooms were conducted due to this data not be included in the HCS. Both WuFi-Bio and VTT were used to test the impact of the changes. None of these changes resulted in the model for bathroom PR-M-NI-01 aligning with the HCS, and there was no difference between where they estimated no mould, microscopic mould, or visible mould. This implies that not knowing the missing data from the HCS and the software did not contribute to the model aligning to the HCS reports.

To confirm whether this missing data contributed the models not aligning with the HCS, full details of the orientation, insulation, and exterior finishes in the actual bathroom would need to be known and used to create the models. This would eliminate the possibility that none of the variations accurately portrayed the construction of the actual bathroom. However, the resources and time required to inspect the houses were not available so testing this could not be included in the scope of this study.

When the conditions acting on the surface of the model estimated by WuFi-Pro were explored, it showed that there was not a suitable environment for visible mould to grow. Doing the same for bathroom NL-NM-I-01 showed there was a risk that microscopic mould could grow in it, yet the results from WuFi-Bio and VTT did not align with this. The sensitivity analyses showing that the major uncertainties of the modelling process had no significant impact on the risk of mould growth.

These results suggest a strong possibility that the relative humidity and temperature data measured during the OVBS was not representative of the conditions that led to the mould observations in the HCS. However, whether this is true or not is still unknown, and cannot be tested without having condition data measured before mould was observed. Research objective two could not be met during this part of the study due to not being able to identify the cause of the models not aligning.

Chapter 7: Parametric Study

A parametric study of was conducted to test the impact of mould mitigation strategies on the risk of mould in the bathrooms shown in Chapter 3:. What strategies were tested and the attempts to emulate them are discussed.

A parametric study was conducted using the 17 bathroom models shown in Chapter 3:. The aim of this was to test if the models that had been created in Chapter 3: could still be used to assess the impact of mould mitigation strategies. If this could be achieved, then the parametric study would also be used to test what strategies were most effective at reducing the risk of mould in New Zealand homes. The research objectives for this stage of the study are as follows:

2. Establish whether representative models capable of testing the risk of mould can be created using HCS data and WUFI.
3. Determine what interventions are most effective at reducing mould in NZ bathrooms.

And the questions trying to be answered are as follows:

Can models capable of testing mould mitigation strategies be created using HCS data and WuFi-Pro?

What commonly used mould mitigation strategies are most effective at reducing the risk of mould in NZ bathrooms?

During the Pilot Study, model PR-M-NI-01 did not align with the observations from the House Condition Survey (HCS) suggesting that the models do not represent their respective bathrooms. No other method of validation could be performed using the BRANZ provided data. The results of the initial data analysis eliminated potential causes, but did not identify the actual cause(s).

This parametric study was intended to test if these models could still be used to indicate what strategies were more likely to be effective than others. It was also intended to identify issues in the process that could be used to inform future research into their actual effectiveness. This could have allowed strategies to still be tested using these models, and would contribute to establishing what strategies were most effective in the future.

This was done by emulating the common strategies used to make mould discussed in, section 7.1.1 and by generating an artificial risk of mould in the bathrooms so they could be used to test how effectively the strategies alleviated mould. Section 7.1.2 presents the strategies that were tested and how they were emulated in WuFi-Pro.

7.1 CONDUCTING THE STUDY

7.1.1 MAKING MOULD

There was no significant risk of mould in any of the models under the reported conditions and testing if the assumptions made about unknown variables were incorrect did not increase the risk of mould growth. This makes it impossible to test the impact of any mould mitigation strategies due to not knowing if they are having a significant impact or not. To address this, variations of the base models were created with the aim of generating artificial risks of mould. These variations were then used to test the impact of the mitigation strategies described in section 7.1.2

Variations were created with different parameters, and the risk of mould estimated using WuFi-Bio and VTT. The appropriate method would generate a significant risk of mould (mould index above 1.0 minimum, preferably above 3.0) in most of the bathrooms, yet still be representative of plausible scenarios in the NZ housing stock. The following are the variations that were created, with the method used to create them and why they were made explained below. Each of these changes were made individually.

- Realistically favourable conditions for mould growth.
- Unrealistically favourable conditions for mould growth.
- Using outdoor relative humidity and temperature inside.
- Removing wall tiles from the modelled wall.

Realistically favourable conditions: The internal conditions in the bathrooms were changed to be more favourable for mould growth. This was done by taking the internal conditions from bathroom NL-NM-I-01 and creating copies of the other 16 models using those conditions. These conditions were chosen because this bathroom always produced the highest mould index during the initial data analysis throughout section 6.1, and they were always in worse conditions than recommended by EECA to prevent mould growth (EECA, 2019).

Unrealistically favourable conditions: The internal conditions in the bathrooms were changed to be much more favourable for mould growth. This was done by changing the internal conditions in the models to constantly have 90% relative humidity. This was intended to create a worst case scenario where the conditions were so favourable that mould should grow regardless of what the construction or exterior conditions are. This would not be representative of plausible scenarios in the NZ housing stock, but variations that did not show a significant amount of mould would indicate that there may be faults with the models causing the low mould indexes in section 6.1.

Using exterior conditions inside: The internal conditions in the bathrooms were changed to be more favourable for mould growth. This was done by taking exterior relative humidity and temperature, and using them as internal conditions. This was intended to create a worst case scenario where the conditions were so favourable that mould should grow regardless of what the construction or exterior conditions are. This would not be representative of plausible scenarios in the NZ housing stock, but variations that did not show a significant amount of mould would indicate that there may be faults with the models causing the low mould indexes in section 6.1.

Removing tiles: Tiles were removed from the bathroom interiors if present. This was done by creating variations that had an interior surface sd-value of 0. Tiles were chosen to be removed because in ASHRAE 160-2016 the sensitivity to mould of the surface material is an important contributor to the risk of mould. The pre-set of tiles in WuFi-Pro also had a high sd-value, indicating that if they resisted moisture transfer well. This would test if bathrooms that had similar constructions and conditions, but no tiles, would be more susceptible to mould growth.

7.1.2 BREAKING MOULD

Strategies to be tested were based on what had been identified as effective as stopping mould growth in existing literature and what was frequently recommended to NZ occupants by government agencies or other trusted sources, as discussed in section 2.2. Variations of the typical base models shown in Table 12 were created in WuFi-Pro with changing parameters to emulate those strategies, and the risk of mould in them was estimated using WuFi-Bio and VTT. The effectiveness of each strategy was determined by how much, and how consistently, they reduced the risk of mould compared to the base models. A significant reduction was considered if there was a change from visible mould to microscopic mould or no mould, using the criteria established in section 5.3.2.

The following are the mould mitigation strategies that were included, while the method used to emulate them and why they were included are explained afterwards.

- Realistically unfavourable conditions for mould growth.
- Unrealistically unfavourable conditions for mould growth.
- Using an extractor fan while showering.
- Heating while showering
- Adding tiles to bathrooms without any.
- Add more insulation
- Changing interior lining

Realistically unfavourable conditions: Keeping the relative humidity below 65% and the temperature above 18ºC (EECA, 2019) to prevent mould from growing. This was done by taking the internal conditions from bathroom MT-NM-I-01 and creating variations of the other models using those conditions. These conditions were chosen because this bathroom always had an estimated mould index of zero during the initial data analysis, and it was always in better conditions than recommended by EECA to prevent mould growth (EECA, 2019). This would test the effect of managing moisture and heating to the standards recommended by to NZ occupants on the risk of mould.

Unrealistically unfavourable conditions: Keeping the relative humidity well below 65% and the temperature above 18ºC (EECA, 2019) to prevent mould from growing. This was done by changing the internal conditions in the models to constantly have 40% relative humidity and 20ºC temperature. This was intended to create a best case scenario where the conditions were so unfavourable that it should be impossible for mould to grow. This was not intended to test a specific strategy, but instead test whether there were any errors in the models. Models that showed there was a risk of mould under these conditions would indicate that there was an error or the model had not been created properly.

Using an extractor fan while showering: Ventilating by using an extractor fan or opening a window during periods of high moisture production (showering). This was done by editing the internal conditions to have a lower absolute humidity when the occupants were showering, and creating variations of the base models using these edited conditions. Showering times were identified by using the method set out in Allister Stubbe's Master of Building Science thesis (Stubbe, 2018). The formula below was created and used to change the absolute humidity during showering times. This was intended to replicate increased ventilation caused by an extractor fan removing moisture from the bathrooms more quickly and not allowing it to accumulate, resulting in the absolute humidity not increasing as much during these times. This strategy was frequently recommended to NZ home occupiers, refer to section 2.2.

$$AH_C = AH_O - 0.9\left(AH_O - \left(\frac{(M_S + M_E)}{2}\right)\right)$$

AH_C = The changed absolute humidity during the moisture event

AH_O = The original absolute humidity during the moisture event

M_S = The absolute humidity at the start of a moisture event

M_E = The absolute humidity at the end of a moisture event

EQUATION 8 FORMULA USED TO REMOVE MOISTURE EVENTS FROM HUMIDITY DATA

The formula determines what the absolute humidity would have been at the time of a shower if it was not being taken. It does this by averaging the absolute humidity from the two surrounding time steps. It then calculates the change between the measured humidity and the calculated average, and reduces the measured humidity by 90% of this change.

Heating while showering: Using a heater during periods of high moisture production (showering) was tested. This was done by editing the internal conditions to be 18ºC and recalculating the relative humidity when the occupants were showering, and creating variations of the base models using these edited conditions. Showering times were identified by using the method proposed in (Stubbe, 2018).This approach was intended to replicate occupants using heat lamps or other forms of heating while showering, and heating their bathrooms to the standards recommended by EECA (EECA, 2019). This strategy was frequently recommended to NZ home occupiers, refer to section 2.2.

Adding tiles: Tiles were added to the interior surfaces of bathrooms that did not had them. This was done by creating variations that had an interior surface sd-value of 2.0. Tiles were chosen to be added for the same reason they were removed in section 7.1.1. This would test if retrofitting existing bathrooms with tiles would help alleviate the risk of mould if other measures such as managing moisture and heating could not be reasonably taken.

Adding insulation: Retrofitting uninsulated bathrooms with insulation and insulated bathrooms with modern standards if insulation was tested. This followed the same methodology for the insulation sensitivity analysis described in section 5.3.4. This strategy was frequently recommended to NZ home occupiers, refer to section 2.2.

Changing interior linings: The effect of different interior linings that are commonly used in NZ bathrooms were tested. This was done by changing the bathrooms with plasterboard linings to hardboard, and vice versa for bathrooms with hardboard lining. Variations of the base models were created with these changes. This was intended to test whether either of the two interior linings in the bathrooms used in this study were more likely to support mould growth.

7.2 CREATING ARTIFICIAL MOULD

This section presents the results from trying to generate artificial risks of mould in the seventeen bathrooms using the process described in section 7.1.1. These results are presented in Table 16.

Each coloured cell shows the result from one variation. The colour of the cells show the classification for each result, with green showing no mould, orange showing microscopic mould, and red showing visible mould. All results are expressed in the maximum mould index that each variation reached during their estimations.

The risk of visible mould was considered significant enough for an artificial risk of mould to be generated and used to test the strategies in section 7.1.1. For a strategy to be considered effective, it would have to increase the risk of mould growth for most of the bathrooms.

TABLE 16 RESULTS FROM TRYING TO GENERATE AN ARTIFICIAL RISK OF MOULD

House ID	Observed Mould	WuFi-Bio				VTT			
		Realistic High	Unrealistic High	SEC	No Tiles	Realistic High	Unrealistic High	SEC	No Tiles
DN-NM-NI-01	No	1.17	3.53	0.02		0.65	1.63	0.02	
DN-NM-NI-02	No	0.31	4.42	<0.01		0.26	2.02	0.02	
BH-NM-I-01	No	-	<0.01	-	0.13	<0.01	<0.01	<0.01	0.10
BH-NM-I-02	No	0.02	<0.01	0.07	-	0.06	0.02	0.15	<0.01
BH-NM-I-03	No	-	-	-	-	<0.01	-	<0.01	<0.01
NL-NM-I-01	No		3.31	0.37			1.42	0.40	
BH-NM-I-04	No	0.02	0.03	0.08	-	0.06	0.07	0.16	<0.01
MT-NM-I-01	No	0.23	4.58	0.50		0.20	2.08	0.48	
MT-NM-I-02	No	0.12	3.97	0.41		0.09	1.64	0.44	
PR-M-NI-01	Yes	0.22	4.85	0.02		0.20	2.59	0.03	
WL-NM-I-01	No	<0.01	<0.01	<0.01	-	0.02	0.02	<0.01	<0.01
WL-NM-I-02	No	0.10	3.90	0.02		0.10	1.63	0.04	
WL-NM-I-03	No	0.17	4.29	0.05		0.10	1.80	0.05	
WL-NM-NI-01	No	0.15	5.16	0.01		0.16	2.92	0.03	
WL-NM-NI-02	No	0.11	3.68	0.03		0.09	1.53	0.04	
WL-NM-NI-03	No	0.12	3.34	<0.01		0.14	1.50	0.03	
WL-NM-NI-04	No	<0.01	-	<0.01	-	0.02	<0.01	<0.01	<0.01

Only changing the relative humidity in the bathrooms to 90% and estimating with WuFi-Bio consistently generated a risk of visible mould. WuFi Mould Index VTT (VTT) only estimated that non-visible mould would grow in the same variations. Replacing bathroom DN-NM-NI-01's internal conditions with the ones from bathroom NL-NM-I-01 did generate a risk of microscopic mould when estimating with WuFi-Bio, but not VTT.

None of the attempts to generate an artificial risk of mould were successful, except for the Unrealistic High variation. This variation was only included to test if there were errors in the models, and not intended to be used to test the strategies in section 7.1.2. This change would not have represented plausible scenarios in the NZ housing stock, and would have made it impossible to test any changes that affected the internal conditions (e.g. extractor fan, and heating). This was because changing the relative humidity to be constantly 90% removed any variation in the bathroom conditions, for example caused by showering.

Ideally the Realistic High variation would have been used to continue the parametric study. This variation still represented plausible scenarios in the NZ housing stock due to using observed constructions, and measured interior and exterior condition data. However, the results show that no visible mould was found in any of the bathrooms when making this change. This meant that the parametric study could not continue due to not being able to generate mould in a plausible manner.

WuFi-Bio tended to estimate a higher risk of mould than VTT when the risk of mould in the bathroom was enough to allow mould to germinate. This can be seen by comparing the results from when the air relative humidity was changed to be constantly 90%. This change increased the risk of mould in most bathrooms to be above 1.0, but WuFi-Bio consistently increased it by more. The average mould index estimated by WuFi-Bio was 3.22, while VTT averaged 1.39.

In every case in Table 16 where VTT estimated there was a risk of microscopic mould, WuFi-Bio estimated that there was a risk of visible mould. This aligns with what has been observed in previous studies (Vereecken et al., 2011, p. 1940). However, these results suggest that this difference is significant enough to affect whether there is risk of mould germination, and whether there is a risk of visible mould.

7.3 EXPLORING VTT RESULTS

Using the internal climate file from bathroom NL-NM-I-01 in the other bathrooms should have allowed mould to germinate, and it would be expected that WuFi-Bio and VTT would estimate mould indexes above 1.0. At the least, this should have happened for bathrooms that were uninsulated because their interior surfaces would likely be colder than the surfaces in the insulated bathroom NL-NM-I-01. This would have increased the relative humidity of the air contacting the surface, which is already high enough to allow mould to germinate in bathroom NL-NM-I-01 (see section 6.2.1).

The period for these estimations was 4 months, however the estimations ran in the studies found in the literature review (see section 2.3) typically exceeded 12 months, and in some cases went up to 120 months. Whether VTT showed the risk of mould accumulating over the estimation period was examined to see if running the estimations for longer would have allowed there to be a risk of mould germination or visible mould. This was only done in VTT because it assumes that the risk decreases in unfavourable conditions while WuFi-Bio does not. The risk of the mould index dropping back to zero over the estimation period would indicate that mould would not accumulate

Figure 19 shows the results from VTT for all the bathrooms that had a mould index above 0.1 for four months. Date is along the x-axis and the mould index is along the y-axis. Each coloured line shows how the risk of mould changed over the estimation period for one bathroom.

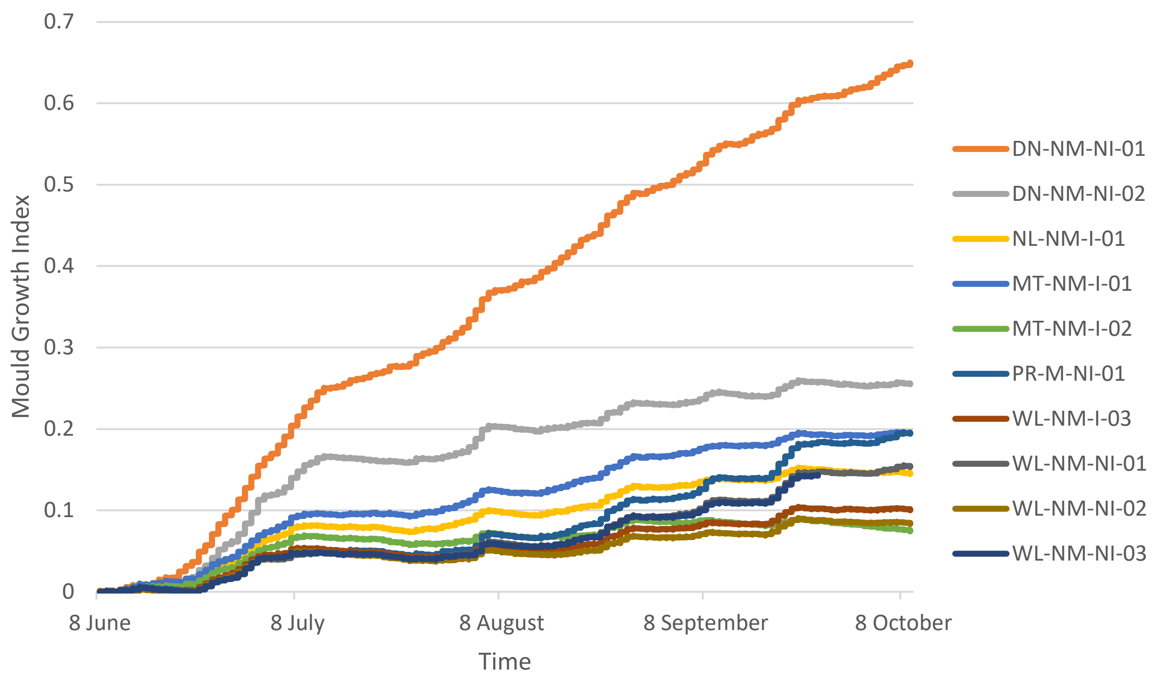

FIGURE 19 CHANGE IN MOULD INDEX FOR BASE MODELS OF BATHROOMS INCLUDED IN PARAMTERIC STUDY

All bathrooms in Figure 19 frequently have spikes in risk that make mould growth accumulate over the estimation period. The risk of mould continued to accumulate despite VTT decreasing the risk in unfavourable conditions. This suggests that a favourable environment for mould growth is being maintained.

The rate that each bathroom's risk of mould at the end of 4 months was increasing was extrapolated over 12 months. This was to see if the risk of mould would accumulate enough to a point where there was a risk of microscopic mould (mould index 1.0) or of visible mould (mould index 3.0). The rate that was used to extrapolate over 12 months was calculated by averaging the four month rate of each model, and assuming that this rate would remain constant over the 12 month period.

The results from this are shown in Table 17. Only bathroom DN-NM-NI-01 returned a risk of mould higher than 1.0. The implications and limitations of this are further discussed in section 8.2.

TABLE 17 MAXIMUM ARTIFICIAL RISK OF MOULD EXTRPOLATED OVER 12 MONTHS

Bathroom No.	Max. Mould Growth Index
DN-NM-NI-01	1.95
DN-NM-NI-02	0.78
NL-NM-I-01	0.46
MT-NM-I-01	0.59
MT-NM-I-02	0.27
PR-M-NI-01	0.59
WL-NM-I-03	0.31
WL-NM-NI-01	0.47
WL-NM-NI-02	0.27
WL-NM-NI-03	0.43

7.4 AN ABRUPT END TO THE PARAMETRIC STUDY

An attempt was made to conduct a parametric study testing the impact of mould mitigation strategies and meet research objective three in section 1.3.1. This was done to test if the models produced in this study could still be used to test strategies, despite not aligning with the HCS and not knowing the reason why. This could have indicated what strategies could be effective in NZ homes and identify which ones should be tested for their effectiveness. This could have been continued to provide guidance to home occupiers and designers about how to reduce the risk of mould in their bathrooms.

For the parametric study, artificial risks of mould had to be generated in the models to test if any changes caused by strategies were significant enough to eliminate the risk of visible mould. This had to be done in a way that still represented plausible scenarios in the NZ housing stock and make sure that the estimated effects were similar to the actual effects. However, all attempts to do this failed, with the only method consistently producing a risk of mould above 1.0 not representing plausible scenarios in the housing stock. This meant that the rest of the parametric study could not be continued due to not being able to tell whether any changes were significant enough to eliminate the risk of visible mould.

The research objectives and questions listed at the start of this chapter could not be answered. The lack of mould in the models meant that the effect of mould mitigation strategies could not be tested. The findings do suggest that models that represent the bathrooms in NZ homes could not be produced using HCS data and WuFi-Pro. However, without knowing the cause of this it cannot be determined whether it could be accounted for using the data and software in this study. Models capable of testing strategies could not be produced during this study, however the results mean it is still unknown if they could be generated using WuFi with either WuFi-Bio or VTT.

7.5 TAKING THE PARAMETRIC STUDY FURTHER

Despite the attempts to produce artificial risks of mould in section 7.2 being unsuccessful, how the models could have been used if risks mould of had been generated was explored. There was not enough time to complete this exploration in a deep manner due to the time constraints imposed on this thesis. Ultimately the results from this were inconclusive due to not knowing if they were significant or represented the strategies actual effects. However, they have been summarised here to give an example of how models that represented mould infested bathrooms could be used in future studies.

7.5.1 TESTING MOULD MITIGATION STRATEGIES

The following lists the strategies that were tested when the parametric study was taken further. Variations of each strategy was made for each bathroom and were compared to their base models:

- Add 1978 minimum insulation (uninsulated bathrooms only, refer to section 5.1.3).
- Add 90mm thick insulation (refer to section 5.1.3).
- Add 140mm thick insulation (refer to section 5.1.3).
- Add 180mm thick insulation (refer to section 5.1.3).
- Add tiles (refer to section 7.1.1).
- Using an extractor fan during showers (refer to section 7.1.1).
- Heating during showers.
- Heating overnight.
- Heating all the time.

The method for creating the insulation, tiles, extractor fan, and heating during showers variations described in section 7.1.1 was also used here. The *heating overnight* and *all the time* variations used the same method as *heating during showers*, except temperature was set to 18°C overnight and all the time respectively. The variations were also combined with each other to test what strategies worked best together. The results from this process are shown in Table 18. All the results still remained below 1.0, indicating no risk of mould germination, so whether these results represented how these strategies would act in actual bathrooms or not could not be determined.

The following presents the initial results that were obtained when the parametric study was taken further. It shows the results from creating variations of the models that showed maximum mould indexes above 0.1 when attempts were made to generate artificial risks of mould in them. Each cell represents the highest mould index estimated over the estimation period for one variation, with the corresponding row and column labels detailing what changes were made to that variation. Changes that intersect with 'base' mean that only one change was made in the variation that the cell represents. Green coloured cells show 'no risk of mould', orange shows 'mould germination/microscopic mould', and red shows 'visible mould'.

TABLE 18 TESTING THE EFFECT OF MOULD MITIGATION STRATEGIES AND COMBINING THEM

Model Variations	Bio						VTT					
	Base	Tiles	Fan	Heating - Shower	Heating - Night	Heating - Full	Base	Tiles	Fan	Heating - Shower	Heating - Night	Heating - Full
DN-NM-NI-01												
Base	1.17	-	0.76	0.70	0.16	<0.01	0.65	-	0.52	0.46	0.08	0.01
Insulation - 1978 Min	0.32	-	0.16	0.17	0.02	-	0.28	-	0.17	0.15	0.01	<0.01
Insulation - 90mm	0.21	-	0.10	0.08	<0.01	-	0.19	-	0.10	0.06	<0.01	<0.01
Insulation - 140mm	0.17	-	0.07	0.08	-	-	0.15	-	0.07	0.06	<0.01	<0.01
Insulation - 180mm	0.15	-	0.06	0.08	<0.01	-	0.13	-	0.06	0.06	<0.01	<0.01
Tiles			-	-	-	-			-	-	-	-
Fan				0.37	0.04	<0.01				0.32	0.04	<0.01
DN-NM-NI-02												
Base	0.31	-	0.16	0.14	<0.01	-	0.26	-	0.15	0.16	0.14	0.02
Insulation - 1978 Min	0.18	-	0.08	0.07	-	-	0.17	-	0.08	0.06	<0.01	<0.01
Insulation - 90mm	0.13	-	0.05	0.05	-	-	0.13	-	0.07	0.04	<0.01	<0.01
Insulation - 140mm	0.11	-	0.04	0.04	-	-	0.11	-	0.06	0.04	<0.01	<0.01
Insulation - 180mm	0.10	-	0.04	0.04	-	-	0.10	-	0.06	0.03	<0.01	<0.01
Tiles			-	-	-	-			-	-	-	-
Fan				0.05	-	-				0.07	0.01	<0.01
NL-NM-I-01												
Base	0.18	-	0.07	0.08	<0.01	-	0.15	-	0.07	0.05	<0.01	<0.01
Insulation - 90mm	0.13	-	0.05	0.06	<0.01	-	0.11	-	0.05	0.04	<0.01	<0.01
Insulation - 140mm	0.12	-	0.04	0.05	<0.01	-	0.10	-	0.05	0.03	<0.01	<0.01
Insulation - 180mm	0.12	-	0.04	0.05	<0.01	-	0.10	-	0.05	0.03	<0.01	<0.01
Tiles			-	-	-	-			-	-	-	-
Fan				<0.01	-	-				0.03	<0.01	<0.01
MT-NM-I-01												
Base	0.23	-	-	0.12	<0.01	-	0.20	-	-	0.09	<0.01	<0.01
Insulation - 90mm	0.13	-	0.08	0.08	<0.01	-	-	-	0.07	0.06	<0.01	<0.01
Insulation - 140mm	0.12	-	0.06	0.07	<0.01	-	-	-	0.06	0.04	<0.01	<0.01
Insulation - 180mm	0.11	-	0.05	0.06	<0.01	-	-	-	0.05	0.04	<0.01	<0.01
Tiles			-	-	<0.01	-			<0.01	<0.01	<0.01	-
Fan				0.02	-	-				0.03	<0.01	<0.01
MT-NM-I-02												
Base	0.12	0.01	0.04	0.05	-	-	0.09	<0.01	0.05	0.03	<0.01	<0.01
Insulation - 90mm	0.11	0.01	0.04	0.05	-	-	0.09	<0.01	0.05	0.03	<0.01	<0.01
Insulation - 140mm	0.11	<0.01	0.04	0.05	-	-	0.08	<0.01	0.05	0.03	<0.01	<0.01
Insulation - 180mm	0.11	<0.01	0.03	0.05	-	-	0.09	<0.01	0.05	0.03	<0.01	<0.01
Tiles			<0.01	-	-	-			<0.01	<0.01	-	-
Fan				<0.01	-	-				0.02	<0.01	<0.01
PR-M-NI-01												
Base	0.22	-	0.07	0.11	0.02	<0.01	0.20	-	0.09	0.11	0.01	<0.01

Model Variations	Bio						VTT					
	Base	Tiles	Fan	Heating - Shower	Heating - Night	Heating - Full	Base	Tiles	Fan	Heating - Shower	Heating - Night	Heating - Full
Insulation - 1978 Min	0.12	-	0.04	0.06	<0.01	-	0.11	-	0.04	0.03	<0.01	<0.01
Insulation - 90mm	0.11	-	0.03	0.05	<0.01	-	0.10	-	0.04	0.03	<0.01	<0.01
Insulation - 140mm	0.10	-	0.03	0.05	<0.01	-	0.09	-	0.04	0.03	<0.01	<0.01
Insulation - 180mm	0.10	-	0.03	0.05	<0.01	-	0.09	-	0.04	0.03	<0.01	<0.01
Tiles			-	-	-	-			-	-	-	-
Fan				0.02	0.02	-				0.03	0.01	<0.01
WL-NM-I-03												
Base	0.12	<0.01	0.04	0.06	<0.01	-	0.10	0.02	0.04	0.03	<0.01	<0.01
Insulation - 90mm	0.12	<0.01	0.04	0.05	<0.01	-	0.10	0.01	0.04	0.03	<0.01	<0.01
Insulation - 140mm	0.12	<0.01	0.04	0.05	<0.01	-	0.09	<0.01	0.04	0.03	<0.01	<0.01
Insulation - 180mm	0.11	<0.01	0.04	0.05	<0.01	-	0.09	<0.01	0.04	0.03	<0.01	<0.01
Tiles			<0.01	-	-	-			0.02	<0.01	-	-
Fan				<0.01	-	-				0.02	<0.01	<0.01
WL-NM-NI-01												
Base	0.15	-	0.05	0.07	<0.01	-	0.16	-	0.06	0.07	<0.01	<0.01
Insulation - 1978 Min	0.10	-	0.03	0.04	<0.01	-	0.10	-	0.04	0.03	<0.01	<0.01
Insulation - 90mm	0.09	-	0.03	0.04	-	-	0.09	-	0.04	0.03	<0.01	<0.01
Insulation - 140mm	0.09	-	0.03	0.04	-	-	0.09	-	0.04	0.03	<0.01	<0.01
Insulation - 180mm	0.09	-	0.09	0.04	-	-	0.09	-	0.09	0.03	<0.01	<0.01
Tiles			-	-	-	-			-	-	-	-
Fan				0.01	-	-				0.02	<0.01	<0.01
WL-NM-NI-02												
Base	0.11	<0.01	0.03	0.05	<0.01	-	0.09	0.02	0.04	0.03	<0.01	<0.01
Insulation - 1978 Min	0.11	<0.01	0.03	0.05	<0.01	-	0.10	0.02	0.04	0.03	<0.01	<0.01
Insulation - 90mm	0.11	<0.01	0.03	0.05	<0.01	-	0.08	0.01	0.04	0.03	<0.01	<0.01
Insulation - 140mm	0.11	<0.01	0.03	0.05	<0.01	-	0.08	<0.01	0.04	0.03	<0.01	<0.01
Insulation - 180mm	0.11	<0.01	0.03	0.05	<0.01	-	0.08	<0.01	0.04	0.03	<0.01	<0.01
Tiles			0.03	0.05	<0.01	-			0.04	0.03	<0.01	<0.01
Fan				<0.01	-	-				0.02	<0.01	<0.01
WL-NM-NI-03												
Base	0.12	-	0.03	0.05	<0.01	-	0.14	<0.01	0.05	0.06	<0.01	<0.01
Insulation - 1978 Min	0.09	<0.01	0.03	0.04	<0.01	-	0.10	0.02	0.04	0.03	<0.01	<0.01
Insulation - 90mm	0.09	<0.01	0.03	0.04	<0.01	-	0.10	0.02	0.04	0.03	<0.01	<0.01
Insulation - 140mm	0.09	<0.01	0.03	0.03	-	-	0.09	0.01	0.04	0.03	<0.01	<0.01
Insulation - 180mm	0.09	<0.01	0.03	0.03	<0.01	-	0.09	<0.01	0.04	0.03	<0.01	<0.01
Tiles			-	-	-	-			<0.01	<0.01	<0.01	-
Fan				<0.01	-	-				0.02	<0.01	<0.01

7.5.2 CHANGING CLIMATES

The bathrooms were put into different climates by using .epw files created by NIWA for the external conditions. The aim of this was to explore how the models could be used to test the impact NZ's different climate zones would have on the risk of mould. Each file represented a typical year of weather data for the location. The blue dots in Figure 20 show where each station was located, and key next to the map presents what area the files from those weather stations represent. One set of variations using all 18 locations were created for each bathroom (18 x 9 = 162 model runs), and the risk of mould was estimated for each using WuFi-Bio and VTT.

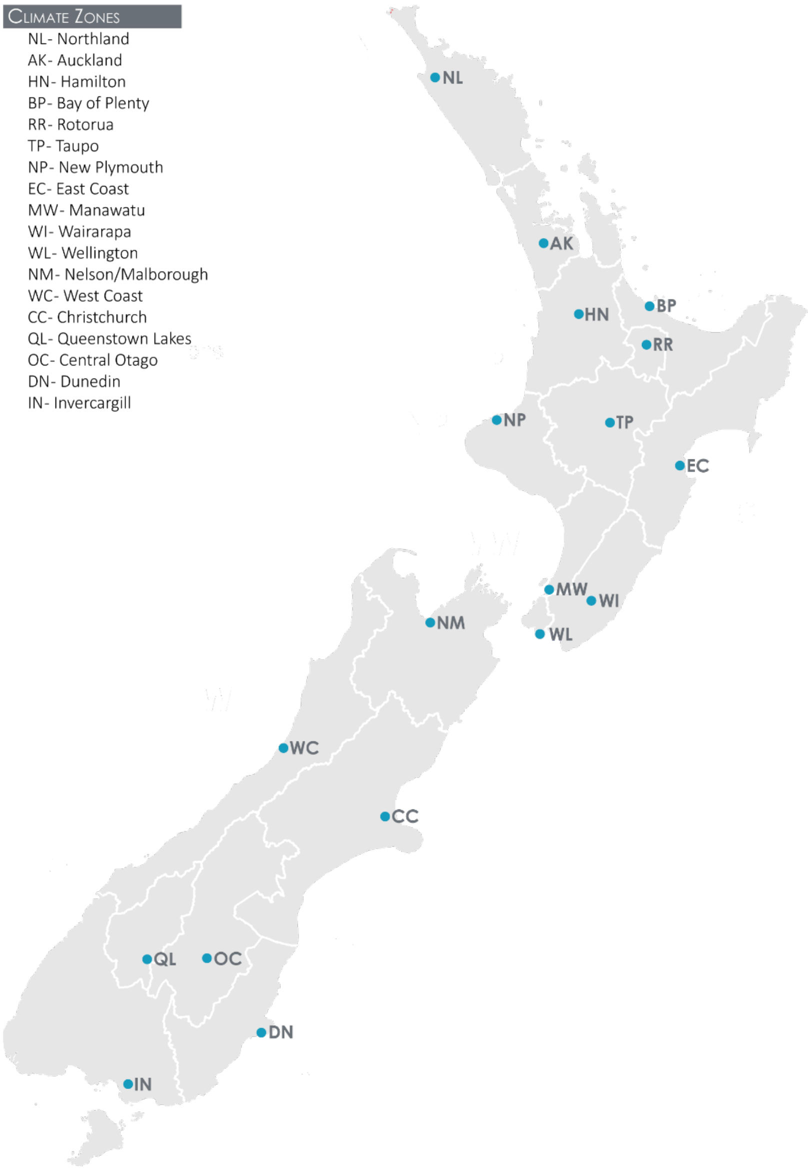

FIGURE 20 LOCATIONS OF WEATHER STATIONS USED TO COLLECT DATA FOR WEATHER FILES

The results from this are shown in Table 19 and Table 20. Ultimately the results were inconclusive due to all of them being below 1.0, and not being able to distinguish if different climates had a great enough impact to reduce the risk of mould from visible to microscopic, or microscopic to no risk. However, going through this process did identify that the method described above did not consider the impact that changing the external climate would have on the internal climate. This issue could not be explored further due to the time constraints imposed on this thesis, however the implications this could have on future studies and how it could be accounted for are further discussed in section 9.3.

The following tables show the results from testing different climates. Each cell represents one variation and all results are represented in the maximum mould index estimated over the estimation period. Green coloured cells show 'no risk of mould', orange shows 'mould germination/microscopic mould', and red shows 'visible mould'.

TABLE 19 PRELIMINARY CLIMATE RESULTS FOR CONTINUATION OF PARAMETRIC STUDY USING WUFI-BIO

House ID	Observed Mould	WuFi-Bio																		
		Base Model	NL	AK	HN	BP	RR	TP	NP	EC	MW	WI	WL	NM	WC	CC	QL	OC	DN	IN
DN-NM-NI-01	No	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-
DN-NM-NI-02	No	0.05	-	-	<0.01	-	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.03	0.05	0.05		0.03
BH-NM-I-01	No	-	0.25	0.11	0.03	0.04	-	<0.01	0.03	<0.01	-	-	-		-	-	-	<0.01	-	-
BH-NM-I-02	No	-	0.04	0.01	<0.01	<0.01	-	-	<0.01	<0.01	-	-	-		-	-	-	-	-	-
BH-NM-I-03	No	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-
NL-NM-I-01	No	0.18	0.09	0.11	0.20	0.14	0.20	0.23	0.13	0.15	0.16	0.22	0.16		0.21	0.25	0.32	0.38	0.23	0.26
BH-NM-I-04	No	-	0.05	0.01	<0.01	0.01	-	-	<0.01	<0.01	<0.01	-	-		-	-	-	-	-	-
MT-NM-I-01	No	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-
MT-NM-I-02	No	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-
PR-M-NI-01	Yes	<0.01	-	-	<0.01	<0.01	0.03	0.04	<0.01	-	0.01	0.02		<0.01	0.02	0.01	0.09	0.17	0.03	0.04
WL-NM-I-01	No	-	0.14	0.01	<0.01	-	-	-	-	-	-	-		-	-	-	-	-	-	-
WL-NM-I-02	No	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-
WL-NM-I-03	No	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-
WL-NM-NI-01	No	-	-	-	-	-	-	-	-	-	-	<0.01		-	-	<0.01	<0.01	0.02	-	<0.01
WL-NM-NI-02	No	-	-	-	<0.01	-	<0.01	<0.01	-	-	-	<0.01		<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
WL-NM-NI-03	No	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-
WL-NM-NI-04	No	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-

TABLE 20 PRELIMINARY CLIMATE RESULTS FOR CONTINUATION OF PARAMETRIC STUDY USING VTT

House ID	Observed Mould	VTT																		
		Base Model	NL	AK	HN	BP	RR	TP	NP	EC	MW	WI	WL	NM	WC	CC	QL	OC	DN	IN
DN-NM-NI-01	No	<0.01	-	-	-	-	<0.01	<0.01	-	<0.01	-	-	-	-	-	-	<0.01	<0.01		<0.01
DN-NM-NI-02	No	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.03	0.04		0.02
BH-NM-I-01	No	<0.01	0.30	0.18	0.04	0.07	-	<0.01	0.05	0.02	<0.01	<0.01	<0.01		<0.01	<0.01	-	0.02	<0.01	-
BH-NM-I-02	No	<0.01	0.05	0.03	0.02	0.01	-	<0.01	<0.01	0.01	<0.01	<0.01	<0.01		-	<0.01	-	<0.01	<0.01	-
BH-NM-I-03	No	-	<0.01	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-
NL-NM-I-01	No	0.15	0.06	0.08	0.17	0.10	0.18	0.21	0.11	0.11	0.13	0.19	0.14		0.19	0.21	0.28	0.32	0.21	0.25
BH-NM-I-04	No	<0.01	0.09	0.03	<0.01	0.04	-	<0.01	<0.01	0.02	<0.01	<0.01	<0.01		<0.01	<0.01	-	<0.01	<0.01	-
MT-NM-I-01	No	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-
MT-NM-I-02	No	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
PR-M-NI-01	Yes	0.01	<0.01	<0.01	0.02	0.01	0.04	0.05	0.02	<0.01	0.03	0.02		0.01	0.03	0.02	0.05	0.13	0.04	0.04
WL-NM-I-01	No	<0.01	0.16	0.02	0.02	<0.01	-	<0.01	<0.01	<0.01	-	<0.01		<0.01	-	<0.01	-	<0.01	<0.01	-
WL-NM-I-02	No	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-I-03	No	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-NI-01	No	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01	0.01	0.01	0.04	<0.01	0.01
WL-NM-NI-02	No	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-NI-03	No	<0.01	-	<0.01	<0.01	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
WL-NM-NI-04	No	-	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	-	<0.01		<0.01	<0.01	<0.01	-	<0.01	-	-

Chapter 8: Exploring the Models

This section explores potential explanations for why the models created throughout this study did not align with the HCS, or what is commonly observed in NZ buildings. Potential explanations discussed earlier in the thesis are expanded upon, and what would be needed to resolve them are discussed.

The aim of this study was to use WuFi and data from the 2015 House Condition Survey (White et al., 2017) (HCS) to test what mould mitigation strategies were most effective in NZ residential bathrooms. Selected, monitored bathrooms from the HCS were modelled and model variations with changing parameters were created to emulate those strategies. Research questions two and three in section 1.4 focused on testing whether models capable of doing this could be made. However, the simulation results did not align with the conditions observed during the HCS monitored bathrooms.

This can be seen by the results from the pilot study in section 5.2 and the parametric study in section 7.2. During the pilot study, no risk of visible mould was found in the one bathroom of the seventeen which had visible mould. During the parametric study, the attempts to artificially grow mould only showed a risk of microscopic (non-visible) mould in one of the bathrooms. Considering the results are not aligning with what has been observed in the HCS, it cannot be determined if the data that was available and WuFi-Bio/VTT could be used to test the effect of mould mitigation strategies.

The results suggested that the risk of mould was consistently lower than expected based on what was observed. The one bathroom with mould found in the HCS should have had a maximum mould index of at least 3.0, yet with both programmes it was below 0.01. The attempts to generate an increase the risk of mould were expected to produce mould indexes at least above 1.0 and possibly above 3.0, yet all except one was below 1.0.

The research objectives for this thesis were not met due to the simulation results not matching the observed results, meaning it was not possible to draw conclusions from the models. The rest of this section will discuss possible explanations for this, what was done to try and resolve them, and what limitations prevented them from being resolved. The implications these explanations could have on the HCS and OVBS, and future research is further discussed in Chapter 9:.

8.1 DID PRESENCE INDICATE RISK?

A single spot observation was used during the HCS to assess mould in the bathrooms. This gave no indication to what state the mould was in e.g. if was still growing or stagnated, how long it had been growing, nor where it was growing e.g. external wall, roof, etc. Differences in what state mould was in could lead to similar observations during the HCS, but differences in what WuFi-Bio and VTT estimated.

The consequences of only having one spot measurement of visible mould can be seen in the results of the pilot study. Bathroom WL-NM-I-01 did not have any mould found in it during the HCS, and the results from the pilot study showed there was no risk of mould in this bathroom. However, it was still unclear whether the model emulated the actual risk of mould in the bathroom or not. This made it impossible to validate the models because of the lack of HCS data indicating how mould grew.

The following is an example of how this could have affected the results in this study. The first statement proposes a hypothetical scenario that suggests that the model aligns with what was observed during the HCS. The next four points are scenarios that could be true based on the observation and how they would produce different results.

Visible mould was observed in the HCS, the mould index estimated by WuFi Bio exceeded 3.0, and mould continued to accumulate after that point.

1. If the mould had been growing over a short period of time (<4 months), the mould index would exceed 3.0 within the estimation period and the statement would be true
2. If the mould had been growing for a longer period of time (>4 months), then the mould index would not exceed 3.0 within the estimation period and the statement be false.
3. If the mould was still growing, then the mould index would not drop below 3.0 for the remainder of the estimation period and the statement would be true.
4. If the mould was no longer germinating, then the mould index would drop below 3.0 before the end of the estimation period, and the statement would be false.

All of these scenarios are plausible. However, only having observations of the mould at one time meant that it cannot be determined which scenario, if any, represents the actual risk of mould in the bathroom. This uncertainty meant that even if WuFi Bio or VTT showed a risk of visible mould when mould was observed during the HCS, it couldn't be determined if the estimated risk of mould growth was similar to the actual risk of mould growth.

When this uncertainty is applied to bathroom PR-M-NI-01, it is unclear whether the model is mimicking the risk of mould growth in the bathroom or not. There are multiple scenarios that could have resulted in this result. For example, the mould in the bathroom could have taken longer than 5 months to accumulate, or it may have grown a long time ago but has remained stagnant due to improved internal conditions. Without knowing what state the mould is in, it cannot be determined which scenario is true.

The rate of mould growth, or at least whether it was still growing or not, would need to be known to remove this uncertainty. This could be achieved by performing a longitudinal measurement of the coverage of mould at two suitably separate points in time. Change, or lack of change, would indicate the state of the mould.

8.2 NOT ENOUGH TIME FOR RISK TO ACCUMULATE

While the HCS reported on what was found in the bathroom at the time of inspection, OVBS recorded temperature and humidity data for approximately 6 months, but in general the WuFi estimation period was limited to four months due to limited usable data.

Previous studies that have used WuFi typically use a period between twelve to thirty-six months (refer to section 2.2). WuFi Bio and VTT also require a minimum period of twelve months to use their signal light system (see section 4.3) to assess whether the risk of mould is low enough to be considered acceptable (Fraunhofer IBP, 2018, p. 21, Fraunhofer IBP, 2011). Running the WuFi Bio or VTT estimations for just five months may not have allowed the risk of mould to accumulate enough to exceed mould index 1.0 or 3.0. If this were the case, even if the models accurately replicated the risk of mould, the risk would still appear lower than it should.

Some evidence suggesting this is shown in section 7.3. The VTT results from trying to generate an artificial risk of mould show that the risk was still accumulating by the end of the estimation period. Extrapolating this over twelve month's only led to a risk of mould germination in one of the seventeen bathrooms (see section 2.3.7).

However, this method assumed that the rate that the risk of mould increased remained constant over the three-year period. This did not consider how it would change during times of the year where conditions for mould growth were less favourable, such as summer.

Only running four-month long estimations could have contributed to bathroom PR-M-NI-01 not aligning with the HCS, and no risk of mould being estimated in the parametric study. However, the method used to find evidence for this in section 7.3 was limited due to not being able to estimate how the risk of mould would change between the periods that were not included in the estimations. The estimations would need to be run for a longer period to test this, ideally for at least 12 months using internal data monitored for this period.

8.3 DATA FROM OVBS NOT BEING REPRESENTATIVE

As discussed in section 6.2, it is possible that the internal condition data taken from OVBS was not representative of the conditions that led to mould observations during the HCS.

This could have led to the results in the pilot study not aligning with the observations from the HCS. Determining whether mould was more likely to grow before May 2016 than the period used for the OVBS would help indicate whether the previous statement was true. Mould being more likely to grow would give a potential explanation for mould being observed in bathroom PR-M-NI-01 during the HCS, but none being found during the pilot study.

Evidence for this is shown in section 6.2, where the conditions acting on the interior surface of bathroom PR-M-NI-01 were assessed. Using the method proposed by Riordan (Riordan & Tsongas, 2016, p. 43), the risk of visible mould was manually assessed using the surface relative humidity from OVBS data. This showed that the conditions acting on the wall were not suited for mould germination, despite visible mould being found in the HCS. This suggests that the mould observed in the HCS must have grown under different conditions from the OVBS.

It is important to note that it was the surface conditions calculated by WuFi-Pro that indicated this, and not the measured data from the OVBS. Inaccuracies in the WuFi-Pro model could have led to the difference between the HCS and the risk estimation based on OVBS. However, as no change in the risk of no mould or visible mould was shown in the sensitivity analyses in Chapter 6: and WuFi-Pro returned no numerical errors (see section 4.1) suggest that this is not the case.

Unfortunately, the conditions before May 2016 are unknown and a reasonable assumption about what they might have been be could not be made. It could be assumed that mould was less likely to grow before May 2016 due to the June to October period typically having colder exterior conditions. However, it is unknown how dependent the internal conditions in the bathrooms used in this study are on external conditions.

Due to lack of information, this is a limitation that could not be addressed within the scope of this study.

Chapter 9: Discussion

This section discusses the findings from this thesis and the implications they could have on the wider field of research about mould, and what future research could be done.

9.1 Lack of data

Chapter 8: discussed potential reasons for why the models did not align with the observations from the HCS, and why artificial mould could not be generated in the parametric study. Three of the potential explanations could not be explored further due to not enough data being available from the HCS and OVBS. This indicates longer time-series data is required to produce models that emulate the risk of mould in bathrooms, and more information about how mould grows in the bathrooms is needed to validate models.

While not directly related to mould growth or WuFi-Bio, BRANZ has conducted various studies utilising WuFi-2D to explore the behaviour of moisture and effect of ventilation in wall cavities. Of particular interest are two experimental studies; one conducted by McNeil and Bassett (2007), and another one conducted by McNeil, Bassett, Overton, and Kehrer (2009). The former measured moisture recovery rates in walls with different water management systems while the latter measured the drying rates of timber framing in walls. What these studies have in common is that they both created models in WuFi-2D of the walls in their respective studies, calculated moisture removal using those models, and compared those results to what they measured in their experiments.

Both studies produced results that aligned with measurements, but only by having a better understanding of how moisture behaved in the buildings they studied. They achieved this by collecting more data to inform their models than what was used in this thesis. This included quarter hourly internal conditions (humidity and temperature), wall surface temperatures, external climate conditions (wind speed, direction, solar radiation), all of which were measured on site (McNeil & Bassett, 2007, p. 3). Some material properties were also measured at BRANZ while others were used from WuFi's database (McNeil et al., 2009, p. 5). Ultimately models that aligned with existing buildings were produced, but only by measuring all influential variables on site, and in a controlled environment to reduce the number of unknown variables.

WuFi products are used throughout the NZ construction industry to assess building envelope designs, but it is unclear how well users understand the programs and whether they have access to enough data to create a representative model. At the very least users of the programs would need access to more data than what was used in this thesis, (just hourly air relative humidity and temperature) to produce valid models of how moisture behaves in a building envelope design. Ideally, they would have access to similar data that was measured during the two previously discussed BRANZ studies. A survey investigating how WuFi users in the NZ construction industry use WuFi products could give insight into how effectively (or ineffectively) they are being used, and what consequences this could pose to NZ buildings.

9.2 RECOMMENDATIONS

The HCS was a single spot study, while the OVBS was a short-term longitudinal study that did not focus on mould growth. Attempts were made using data from these studies to produce models of bathrooms that could be used to test the impact of mould mitigation strategies. This data was used outside of the intended scope of the original studies to see if these models could be made, and it not, what the limitations were that prevented them from being made. The following section summarises what other data was found to be required and discusses what further research could be done if this data was obtained.

Visual spot measurements were used to assess mould in the HCS, and only four months of relative humidity and temperature data could be used from the OVBS. This created limitations that made it difficult to tell what contributed to the results in the pilot study and initial data analysis not aligning with the HCS. These limitations included not knowing where mould was growing, being unable to distinguish whether no mould or microscopic mould was growing, and not knowing what measures the occupants had previously taken to address this. The following lists how the methodology in the HCS and OVBS could been different in order to collect the required data identified in this thesis.

1. Take photos of mould growth and the entire surface that it is growing on.
2. Take spot measurements of the mould growth at two separate points of time.
3. Record the occupants cleaning habits and attempts to alleviate mould.
4. Record the location(s) of the mould, and whether the ceiling/roof and what walls are exposed to the exterior.

9.2.1 PHOTOS

Photos of the mould observed during the HCS were taken, but they could not be accessed for analysis until near the end of the thesis. It was also unknown where mould was growing in the bathrooms. This made it impossible to known which surface should have been modelled in WuFi-Pro so that a direct comparison between the model and the real bathroom could be made. This meant that the models could not take into account mould growing on other surfaces than what was modelled.

This could be addressed by taking contextual photos of the surfaces with on mould while the houses are being inspected. This would allow the location of any mould to be identified and the appropriate surface could be modelled in WuFi-Pro. It would also give a better indication of the amount of mould in the bathrooms than the 5-point scale used in the HCS.

The 1-6 Viitanen mould index scale used for estimating the risk of mould establishes a level of coverage on the surface in question, with each integer of the scale representing a higher level of coverage determined by measuring the growth on material samples in controlled conditions. Taking photos of mould so that they can be used to determine the coverage, or directly measuring the coverage on site, would allow this coverage to be compared to the mould index results from WuFi-Bio or VTT.

A comparison like this could be used to explore whether the material sensitivity classes that VTT and ASHRAE 160 use actually represent NZ materials, and whether WuFi-Bio and VTT in their current state are suitable to be used in the NZ context. This comparison could also be used to test if the presence of mould in a bathroom is an accurate indicator of the risk of mould (see section 8.1), but only if data about whether the mould is still growing and occupants attempts to clean it is also collected.

9.2.1 MULTIPLE SPOT MEASUREMENTS

The HCS was a snap-shot of mould growth, and only recorded the presence of mould at one point in time. This gave no indication of the rate that the mould was growing at, or if the mould was still growing at all. This made it impossible to determine whether the models emulated the risk of mould in the actual bathrooms, even when a bathroom that had no mould found in the HCS also showed no estimated risk of mould (see section 5.3.1). As this study progressed, it became clear that comparing the estimated risk of mould to a single spot observation was not a sufficient method to validate the models in this study.

Identifying whether any observed mould was still growing or stagnated could allow a more suitable validation method to be tested. This could be done by taking multiple spot measurements of the area or coverage of observed mould while internal condition data is being collected, and using the difference between these measurements to determine how rapidly mould is growing. The rate of mould growth could be compared to how the risk of mould estimated by WuFi-Bio or VTT changes throughout the estimation period. This could be used to further explore whether comparing an estimated risk of mould to the presence of mould is a suitable means of validation by eliminating the uncertainty about whether the observed mould in the bathrooms had stagnated.

9.2.2 CLEANING

How long the mould observed in the HCS had been allowed to accumulate for was unknown. This made it difficult to determine if the observed mould was representative of the actual risk of mould. It was also unknown whether the occupants made attempts to alleviate or clean any mould before the HCS inspection. If cleaning attempts had been made, then bathrooms may have had a high risk of mould despite not having any observed during the HCS. If attempts were not made, then bathrooms with a low risk of mould may have still have mould observed in them due to it being allowed to accumulate over a long period of time.

Information about the occupants cleaning habits and other attempts made to alleviate mould growth would need to be collected to address this issue. Having this information would make it easier to figure out why the risk of mould in a model would not be aligning with the mould observed during the HCS.

This information could also be used to determine a suitable period that the calculations are run for. It could be assumed that the presence and risk of mould resets to zero when a surface is cleaned. This could be used as the starting point for the calculations and the next time the surface is cleaned could be the end point. This could be used to explore how the risk of mould changes between cleanings, and how changing the time between cleanings would affect this. However, a full year's worth of internal condition data, as discussed in section, would be needed to have the necessary control over the time period of the calculations needed to do this.

9.2.3 SURROUNDING ROOMS

Data about the rooms (or the exterior) surrounding the bathroom was not collected during the HCS. This made it impossible to determine which walls were exterior and whether there was a storey above the bathroom. Bathroom ceilings could not be modelled due to not knowing if they were exposed to exterior conditions. The risk of mould on the ceilings could not be assessed and it would have made it impossible to validate the models if mould was shown to be growing on the ceilings when a photo was taken.

Whether the walls and ceilings are exposed to external conditions would need to be recorded. This would allow the ceilings in the bathrooms to be modelled and would allow the more robust validation method to be used if photographs of the mould were also taken.

Not knowing this was also the main reason why 3-D models in WuFi Plus could not be made. A pilot study modelling bathrooms in 3-D would need to be conducted to confirm what other information would be needed. Creating a 3-D model of the bathrooms would allow all surfaces to be tested for risk of mould, make it easier to compare to the real bathrooms, and identify which surfaces were most at risk.

9.2.4 PURPOSE DESIGNED EXPERIMENTS

Chapter 8: and this section discusses how limited data prevented exploration into what caused the models created in this study to not align with the HCS observations. Most of the data identified throughout these sections falls outside the intended scope of the HCS and OVBS, so implementing changes to future versions of these studies may not be practical. For example, taking multiple spot measurements (see section 9.2.1) of all 560 houses in the HCS would increase time, resource requirements, and costs for an already large-scale study. A dedicated study, with the intent of testing mould mitigation strategies, would need to conducted to achieve the original objectives of this thesis (see section 1.3.1), rather than relying on already existing data.

The biggest issue that prevented the research objectives for this thesis being achieved was being unable to produce models that aligned with the observations. Thus, establishing what data would be needed to produce models on NZ bathrooms models would be the first aim of any future research, starting from the issues identified in Chapter 8: and this section.

This could be achieved through a purpose designed experiment monitoring conditions and mould growth in bathrooms, potentially utilising a controlled test building. The internal air conditions in selected bathrooms could be monitored and recorded for at least 12 months (see section 8.2), with spot measurements and photos of any mould growth taken at regular intervals. Inspections of the houses could determine their constructions, and models created in a 3-D hygrothermal program such as WuFi-Plus.

The risk of mould in the models could be assessed using WuFi-Bio or VTT, and their results could be compared to the mould growth found from the spot measurements. This could test if WuFi-Bio or VTT are realistically estimating the risk of mould, and that it is estimating that the risk is highest where mould is observed. A comparison like this would be more comprehensive than the validation used in this thesis, be more capable of exploring whether the presence of mould is an indicator of the risk of mould and be more capable of producing results that align with observations.

A case study like the experiment above could also be conducted on an existing bathroom, ensuring that the internal conditions in the bathroom are plausible. Ideally the occupants of these houses would not interfere with any mould growth by not cleaning it. Establishing models that emulate the risk of mould in the actual bathrooms first would be ideal, and then the effect of occupants cleaning habits could be tested using those models. However, asking occupants to allow mould to grow in their bathrooms could be an unreasonable request and may pose of health risk. Surveys recording the occupants cleaning habits could be conducted instead, or a study such as this could be used as a follow-up to the previously designed experiment to test the impact of occupants' cleaning habits.

9.3 EXPLORING CHANGING CLIMATES FURTHER

The climate variations created as an exploration beyond the parametric study in section 7.5.2 did not consider the impact that changing the external climate would have on the internal climate. This could have resulted in the model results not representing the impact that different external climates would have on the conditions that dictated the risk of mould.

With the data that was used in this study, it was also unknown how dependent the internal climate was on the external climate. This could also change between bathrooms due to lower R-values of building envelopes allowing more heat exchange between the exterior and interior.

Any future studies that would attempt to use similar models to explore the effect of different climates on the risk of mould would need to determine the relationship between the internal and external climate the building envelope created. They would then need to change these conditions accordingly to suit the new climate. The following method is an example of what could be used to do this, but it would need to be tested. This testing could not be completed due to the time constraints imposed on this thesis.

1. The increases in humidity and temperature associated with showers could be removed by lowering them to the average of their two surrounding time steps. Showering times could be identified using the method proposed in Alister Stubbe's Master of Building Science thesis (Stubbe, 2018).
2. The internal and external absolute humidity could be plotted on a scatter graph to establish the mathematical relationship between the two sets of data (assuming there was a relationship). The same could be done for the temperature
3. The interior absolute humidity and temperature could be recalculated using the formula established in the previous step, and the external humidity and temperature data from one of the typical weather files.
4. The humidity and temperature could be increased during showers by the same amount they were reduced by in step 1.
5. The new internal conditions file could be used to create a variation of the original model. This could be done for each climate zone.

9.4 LIMITATIONS WITH THE STUDY

The following lists the limitations that the study results, which could not be taken into consideration either due to time or resource constraints, or limitations in the available data or software:

Small sample size: The study initially intended to test mould mitigation strategies in NZ houses, however only seventeen houses were included. This small sample size means this study cannot be considered a representative sample of the NZ housing stock. It is possible common types of houses were not included, and thus the impact of strategies on this portion of the housing stock have not been tested.

Surface mould only: This study could only assess the risk of surface mould growing on interior linings. This was because not information was known about the presence of interstitial mould in the bathrooms, nor was any data collected on the moisture and temperature conditions inside the bathrooms' walls.

Amount of mould: This study could not consider specific quantities of mould, only whether there was a risk of mould germination, or visible mould. This was due to the presence of mould only being visually assessed rather than measured during the HCS.

Chapter 10: Conclusions

How the results obtained from this study contribute to achieving the research objectives in section 1.3.1 and recommendations for future action.

This research used data from 17 bathrooms in the 2015 BRANZ House Condition Survey, and the associated OVBS, with wall models created in the commercially available WuFi Pro software programme. WuFi-Bio and VTT were used to estimate the risk of mould. The purpose of this was to explore if representative models could be used to test the effect of mould management or mitigation strategies. The models could then be used to test whether the mould management recommendations being provided to home occupiers were sufficient, and if not, whether suitable alternatives could be generated. This would provide guidance to occupiers and designers about how they could reduce mould in their homes/designs and help reduce the mould in NZ homes. The following discusses whether this research met the research objectives outlined in section 1.3.1 and summarises areas where future research could be conducted.

10.1 RESEARCH OBJECTIVE ONE

Research objective one aimed to establish what mould mitigation strategies were being recommended to NZ home occupiers. Publicly available material from government agencies and building research organisations was examined to achieve this. The intent was to then test whether they were sufficient to alleviate mould in bathrooms using the models developed in this thesis. This would help establish whether the correct information was being provided to home occupiers, and would indicate whether changes needed to be made to compensate for new homes increasing air-tightness (McNeil et al., 2015, p. 56).

The four sources found that provided guidance were the MBIE, HNZ, EECA, and BRANZ. Their consensus was that existing mould should be removed via cleaning or disposing of infected material, with ventilating during showers, heating during showers, and insulating used as means of prevention. EECA provided more performance-based criteria, recommending that the indoor relative humidity and temperature should be kept below 65% and above 18°C respectively. Due to the results from the simulations not aligning with the observations from the HCS, the results from testing these strategies were inconclusive, and it could not be determined whether these recommendations are sufficient.

10.2 RESEARCH OBJECTIVE TWO

Research objective two aimed test whether HCS data and WuFi-Bio could be used to create models of NZ bathrooms, and their risk of mould align with what HCS observations. This was done through a pilot study which was intended to develop a modelling methodology, and an initial data analysis testing the impact of assumptions from the modelling methodology. The intent of this was to ensure that the estimated effects of the mould mitigation strategies identified in research objective one emulated how they would affect the risk of mould in actual bathrooms.

Models representing 17 NZ bathrooms were created during this study, but their results did not align with what was observed in the HCS. The short simulation period due to OVBS monitoring only five months of internal condition data coupled with the HCS recording of the observations of mould not clearly indicating the quantity or location of mould, are likely explanations. However, the lack of data created did not provide a clear enough understanding of the conditions that lead to the mould observed in the HCS to establish the cause of the models not aligning.

An experimental study would need to be conducted in a controlled environment where enough data could be collected to develop an understanding of the conditions that lead to mould growing in the modelled bathroom/s. Such a study would need to collect internal condition data for over 12 months, take multiple spot measurements of the coverage of any mould that forms, and collect enough information about the construction of the bathroom to build a 3-D model. This would be more capable of testing what variables may contribute to results not aligning with observations and could be used to test the effect of strategies it results that align could be achieved.

10.3 RESEARCH OBJECTIVE THREE

Research objective three aimed to test the effectiveness of the mould mitigation strategies identified for research objective one, using the method established in research objective two. Attempts were made to test the effectiveness of mould mitigation strategies recommended to home occupiers and used in other countries. If successful the results would have shown whether the strategies being communicated to home occupiers were sufficient to combat the mould issue. If they were not, strategies used in other countries could have been tested and used to provide guidance to occupiers and designers.

However, the failure of the models to match the observed mould made it impossible to explore the effects of mould mitigation strategies. Attempts to generate, by artificially high levels of absolute humidity and temperature, a high risk of mould did succeed but could not be used to test the effect of strategies. The short simulation period based on four months of internal condition and single spot observations of mould are likely explanations, but the actual reasoning could not be determined.

10.4 Research objective four

Research objective four aimed to develop a hierarchy of recommendations, based on the findings from research objective three, that could be used to communicate effective strategies to home occupiers and designers. This would have allowed occupiers to determine what strategies would be the most appropriate for their situation. It would have also allowed designers to prioritise what systems and controls they implement into their designs to allow occupiers to execute those strategies. Due to not being able to test strategies, as discussed in section 7.4, this hierarchy could not be established.

10.5 Summary

Going through the process of modelling in WuFi-Pro 17 existing NZ bathrooms, and trying to use them to test mould mitigation strategies, revealed how difficult it can be to produce results that emulate what is observed in the housing stock. The main cause of difficulty identified in this thesis was a lack of data that made it difficult to explore what variables caused the estimated results to not align with what was observed in the HCS. Subsequently the programs and data used could not help determine what mould mitigation strategies would be best to help address mould growing in NZ houses.

Even with access to a dataset as comprehensive as the HCS, and measured internal data from the OVBS, models with results that aligned could not be produced. This highlights the difficulties with trying to use WuFi-Pro in the NZ context, outside of a controlled experimental environment where all unknown variables are minimal. The less data used to inform a model, the more unknown variables that could contribute to results not aligning with observations, and the more potential for the effects of interventions to differ from their actual effects on mould.

WuFi-Pro is a tool that can be used effectively when enough time-series data is known about bathroom heat and moisture. However, generally information like this is not available in NZ unless the user has the resources to measure it themselves. Trying to use this to conduct a parametric study on houses from the HCS large-scale survey but with a maximum of 4 months of data (as was attempted in this thesis) is not practical.

Using WuFi-Bio in a more controlled environment, where a better understanding of how heat and moisture behave on a bathroom’s interior surfaces can be developed, such as a case study or experiment (see section 9.2.4). This would be a better method of testing mould mitigation strategies rather than identifying trends throughout multiple houses. Future research monitoring the conditions experienced in bathrooms and using the programs in controlled environments would help determine how they can be used to assess and further develop effective mould mitigation strategies aimed at reducing the mould in NZ bathrooms.

Chapter 11: References

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Chapter 12: Appendices

APPENDIX A: ARTICLE SUMMARY SHEET EXAMPLE

The following is an example of the full-text screening sheet that was used to assess the found articles in the systematic literature review in section 2.3. The assessment sheet that was used for most studies from the *U.S. NHLBI Study Quality Assessment Tools* (NHLBI, n.d.) is shown in Figure 21.

TABLE 21 SUMMARISING TOOL FOR ARTICLES

Title:	**Effect of façade impregnation on feasibility of capillary active thermal internal insulation for a historic dormitory – A hygrothermal simulation study**
Author(s):	Finken, G. Bjarløv, S. Peuhkuri, R.
Date:	2016
Journal:	Construction and Building Materials
Country:	Denmark
Included:	**Yes** – Used WuFi Bio to test the mould risk potential and drying times of capillary active/hydrophilic insulation and the effect of adding façade impregnation
Aim:	Explore the moisture performance of capillary active/hydrophilic insulation as a means of addressing moisture issues created by internal insulation.
Methodology:	1. Three internal insulation systems based on active/hydrophilic insulating materials were modelled in WuFi-Pro. 2. The models were typical representations of Copenhagen buildings, using weather data measured from a weather station close to Copenhagen, and using EN15026 was used for moisture load. 3. Moisture behaviour of all walls was calculated for 10 years. 4. The risk of mould in the models was assessed using WuFi-Bio.
Key Findings:	Capillary active/hydrophilic insulation could be used to improve hygrothermal performance of historic facades, but only if another form of rain load protection is added. This was because there was a risk of moisture accumulation behind the façade.

Criteria	Yes	No	Other (CD, NR, NA)*
1. Was the study question or objective clearly stated?			
2. Was the study population clearly and fully described, including a case definition?			
3. Were the cases consecutive?			
4. Were the subjects comparable?			
5. Was the intervention clearly described?			
6. Were the outcome measures clearly defined, valid, reliable, and implemented consistently across all study participants?			
7. Was the length of follow-up adequate?			
8. Were the statistical methods well-described?			
9. Were the results well-described?			

Quality Rating (Good, Fair, or Poor)
Rater #1 initials:
Rater #2 initials:
Additional Comments (If POOR, please state why):

*CD, cannot determine; NA, not applicable; NR, not reported

FIGURE 21 CASE STUDY ASSESSMENT TOOL USED DURING SYSTEMATIC LITERATURE REVIEW (NHLBI, N.D.)

APPENDIX B: RESULTS FROM GOVERNMENT AGENCIES

Table 22 summarises the results from screening government agency websites in section 2.2. It shows all the agencies that related to buildings that were selected in step one of the screening method, and when they were eliminated from the review. Green cells indicate that the agency met the requirements for that step, while blank cells show when they were removed from the review process. The Building Research Association of New Zealand was found from the Google search in step five, which is why it is italicised.

TABLE 22 RESULTS FROM SCREENING GOVERNMENT AGENCIES

Agency	Step 2	Step 3	Step 4	Step 5
Energy Efficiency and Conservation Authority				
Fire Emergency New Zealand				
Genesis Energy				
Health Promotion Agency				
Housing New Zealand				
Health Quality and Safety Commission New Zealand				
Health Research Council of New Zealand				
Ministry of Health				
Meridian Energy Limited				
Ministry of Housing and Urban Development				
Heritage New Zealand				
Ministry of Business, Innovation, and Employment				
Transpower				
Earthquake Commission				
Electricity Authority				
Tenancy Services				
Building Research Association of New Zealand				

APPENDIX C: WUFI-PRO MODELS

The following shows the base models created in WuFi-Pro of the 17 bathrooms used in this study. The left side of the images in the rest of this section show the boundary with the external climate, while the right shows the interior. The top section of each model shows the typical (insulated, or uninsulated) model, and the bottom shows the thermal bridge (where framing and no cavity are) model. Each layer of colour represents the materials used in the wall construction, with a legend for these colours shown underneath.

Each model is accompanied by a table detailing the material data that was used for the models. The data is shown as the raw entries entered into WUFI, and due to this the thermal conductivity is shown in them rather than thermal resistance. After the completion of this thesis, it was realised that the thermal bridge models for some of the insulated wall constructions were modelled incorrectly. The timber stud sections should all be 90mm thick, but in some of them have been modelled thinner to align with the thickness of the insulation used.

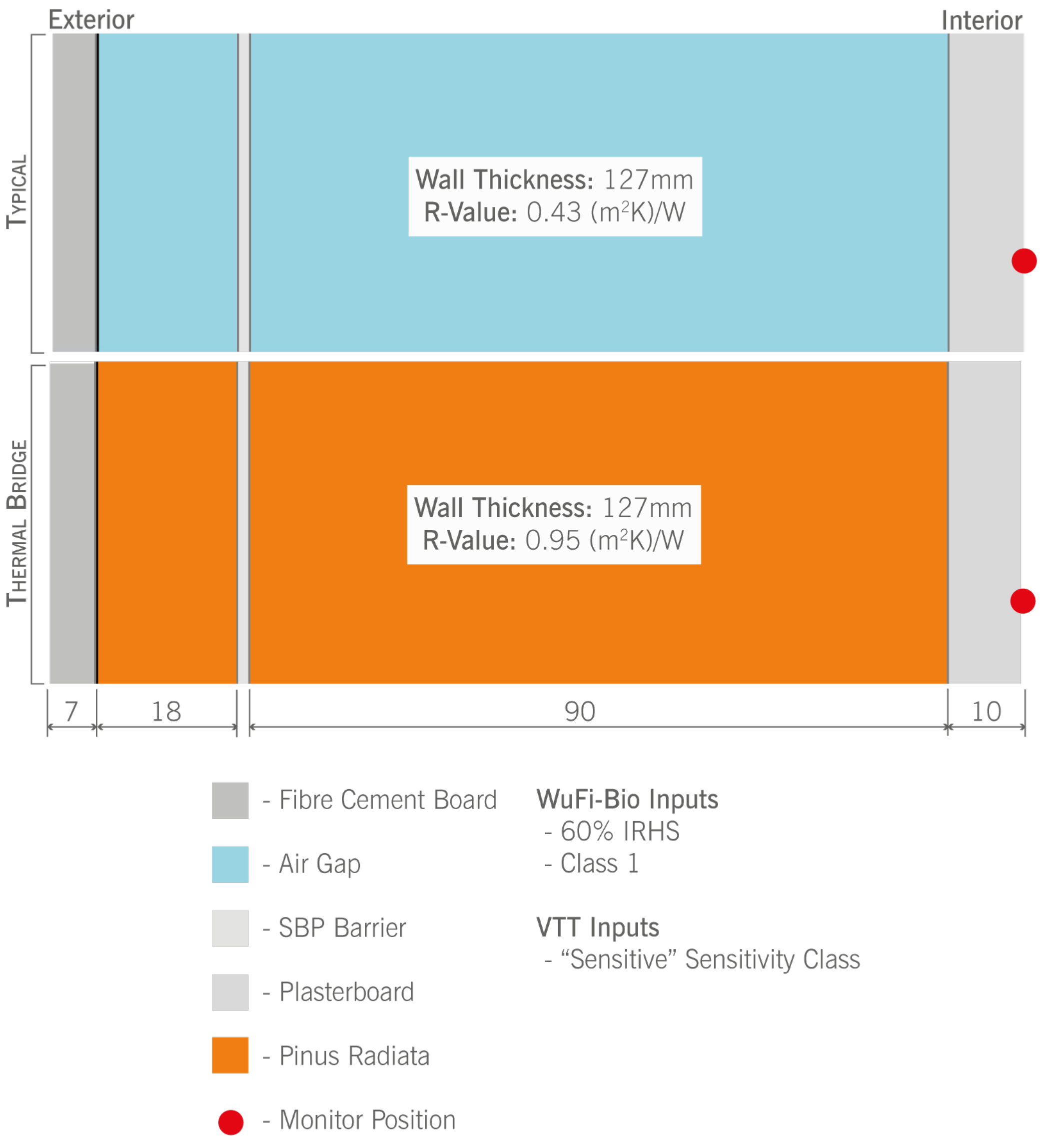


FIGURE 22 WUFI-PRO MODEL: DN-NM-NI-01

TABLE 23 MATERIAL DATA FOR MODEL DN-NM-NI-01

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
		Typical	
Fibre Cement Board	0.0075	0.13	83.3
Cladding Cavity	0.018	0.13	0.56
SBP Barrier	0.001	2.3	49.3
Wall Cavity	0.09	0.523	0.17
Plasterboard	0.01	0.16	7.03
		Thermal Bridge	
Fibre Cement Board	0.0075	0.13	83.3
Timber Cavity Batten	0.018	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.09	0.13	200-10
Plasterboard	0.01	0.16	7.03

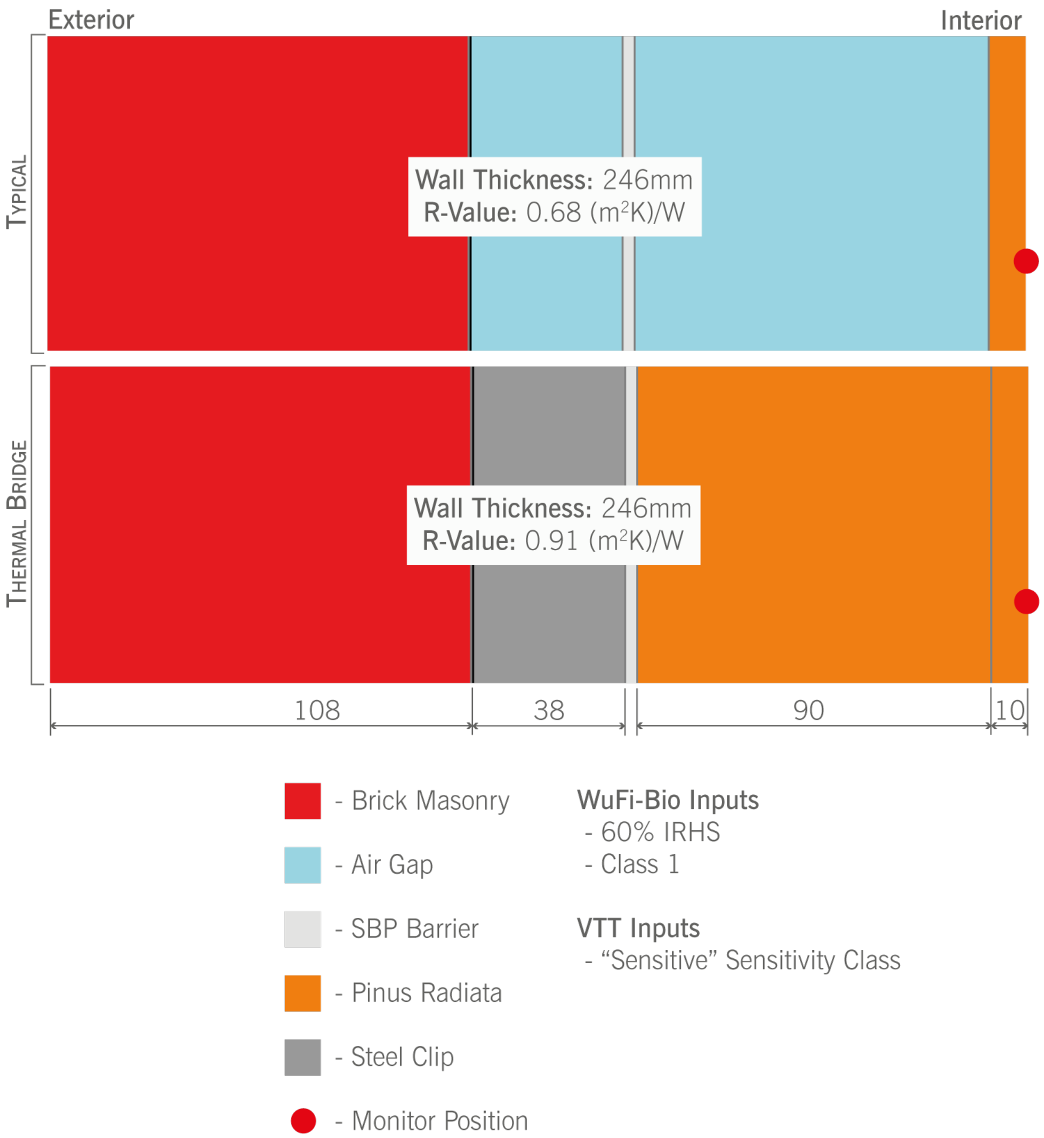


FIGURE 23 WUFI-PRO MODEL: DN-NM-NI-02

TABLE 24 MATERIAL DATA FOR MODEL DN-NM-NI-02

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
Typical			
Brick Masonry	0.108	0.6	10
Cladding Cavity	0.38	0.13	0.56
SBP Barrier	0.001	2.3	49.3
Wall Cavity	0.89	0.523	0.17
Matchlining	0.01	0.13	200-10
Thermal Bridge			
Brick Masonry	0.108	0.6	10
Steel Clip	0.38	46	6400
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.89	0.13	200-10
Matchlining	0.01	0.13	200-10

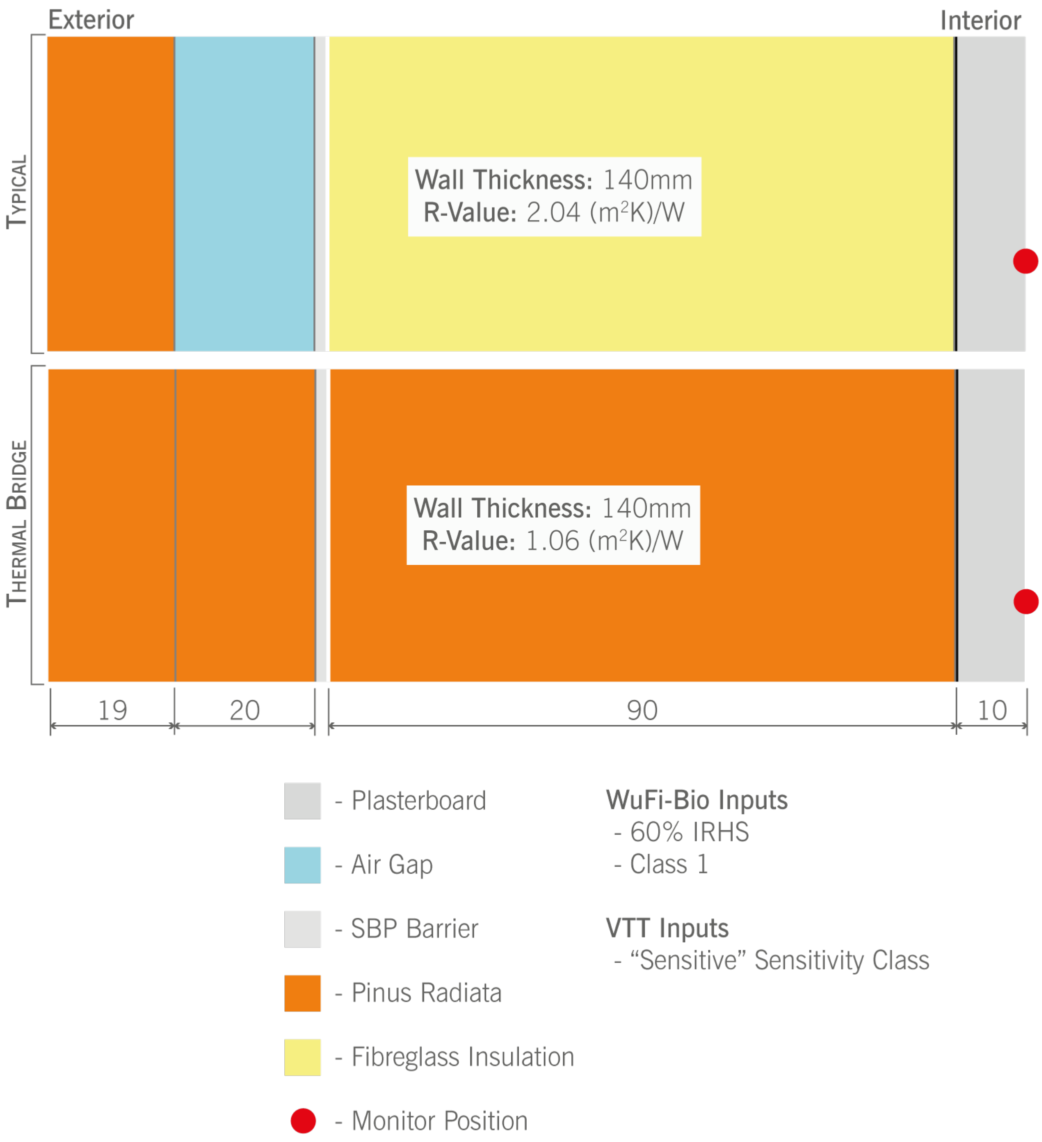


FIGURE 24 WUFI-PRO MODEL: BH-NM-I-01

TABLE 25 MATERIAL DATA FOR MODEL BH-NM-I-01

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
		Typical	
Timber Weatherboards	0.019	0.13	200-10
Cladding Cavity	0.02	0.13	0.56
SBP Barrier	0.001	2.3	49.3
Fibre Glass Insulation	0.045	0.054	1.3
Plasterboard	0.01	0.16	7.03
		Thermal Bridge	
Timber Weatherboards	0.019	0.13	200-10
Timber Cavity Batten	0.02	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.045	0.13	200-10
Plasterboard	0.01	0.16	7.03

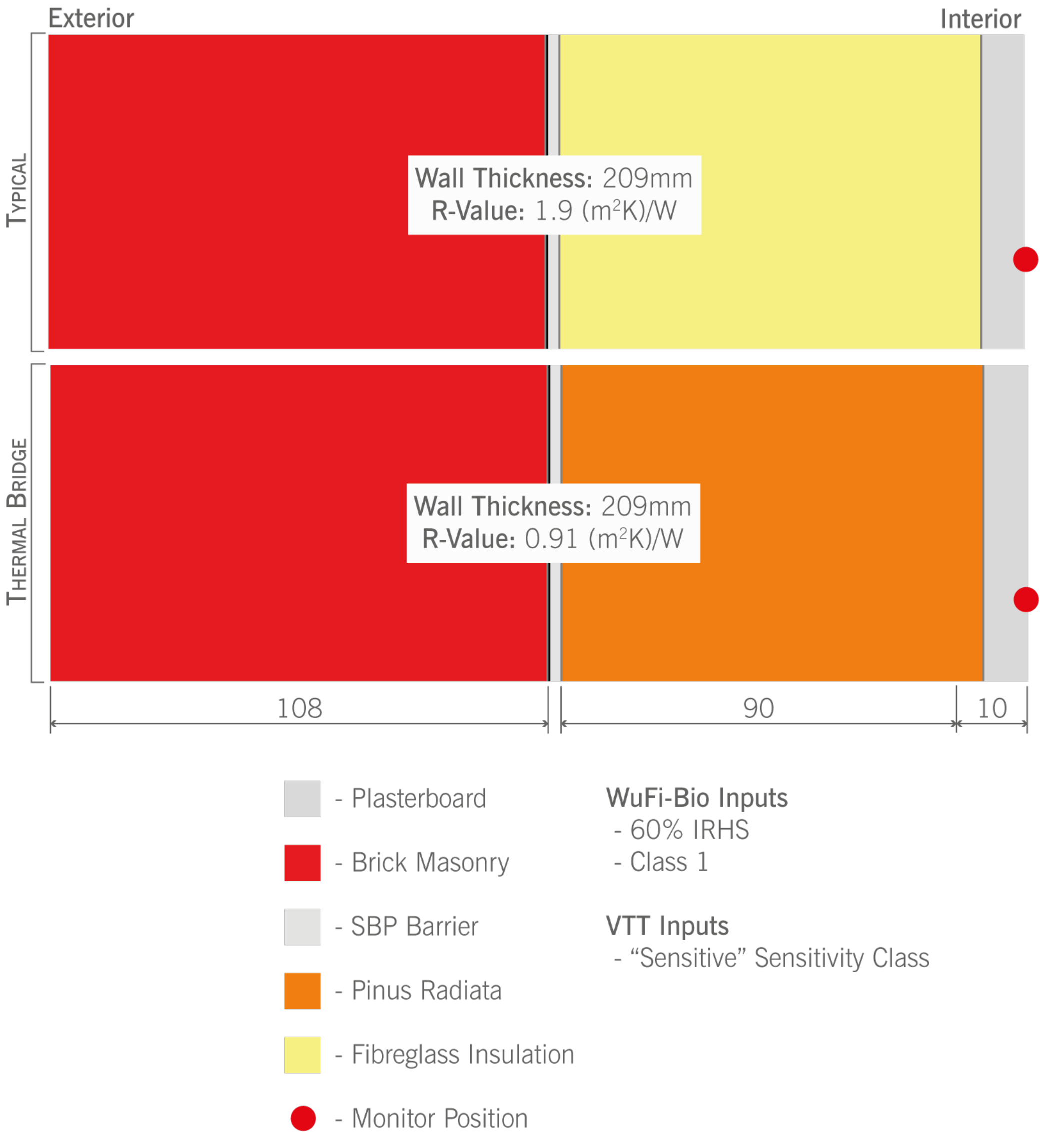


FIGURE 25 WUFI-PRO MODEL: BH-NM-I-02

TABLE 26 MATERIAL DATA FOR MODEL BH-NM-I-02

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
Typical			
Brick Masonry	0.108	0.6	10
SBP Barrier	0.001	2.3	49.3
Fibre Glass Insulation	0.055	0.054	1.3
Plasterboard	0.01	0.16	7.03
Thermal Bridge			
Brick Masonry	0.108	0.6	10
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.055	0.13	200-10
Plasterboard	0.01	0.16	7.03

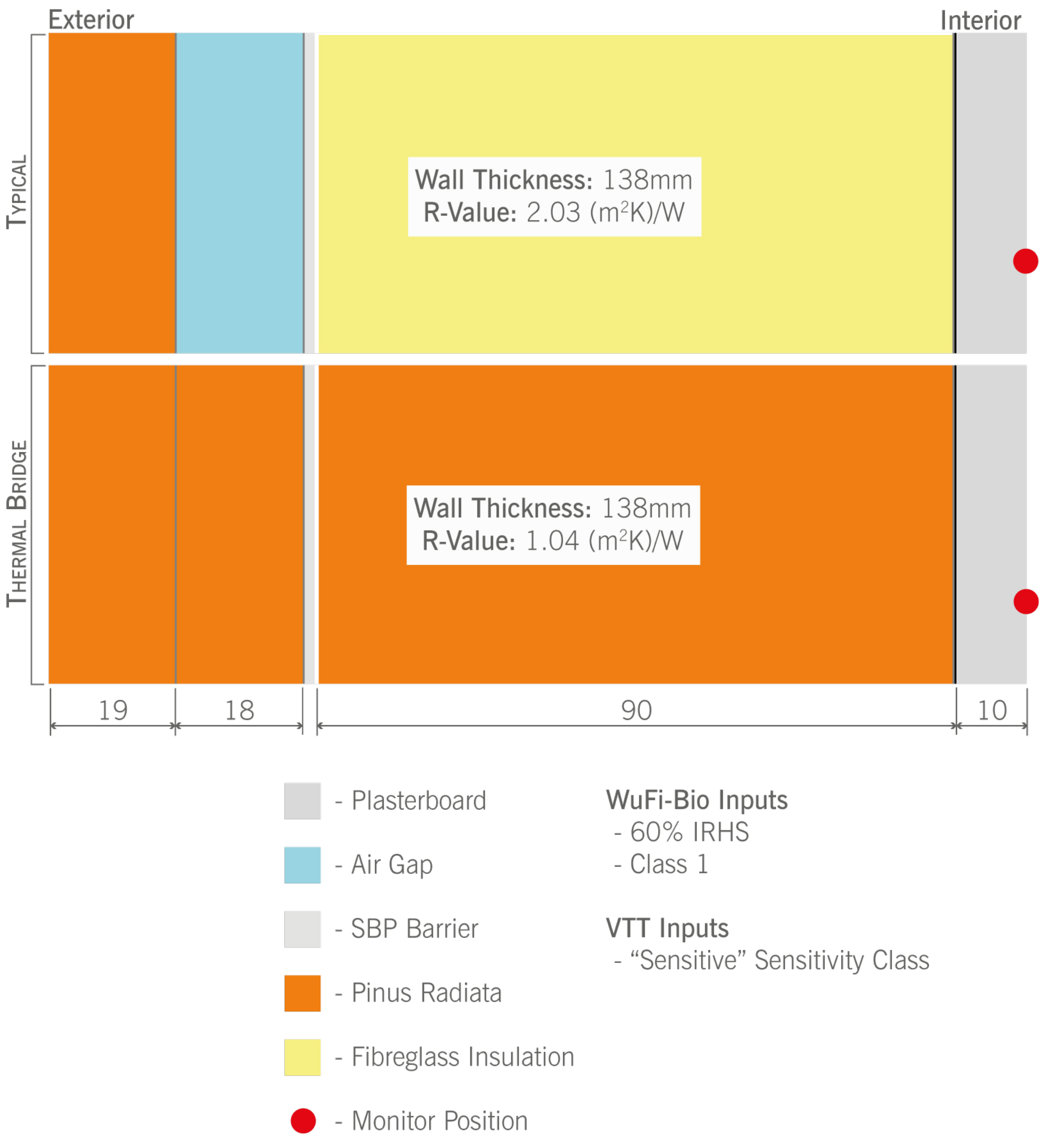
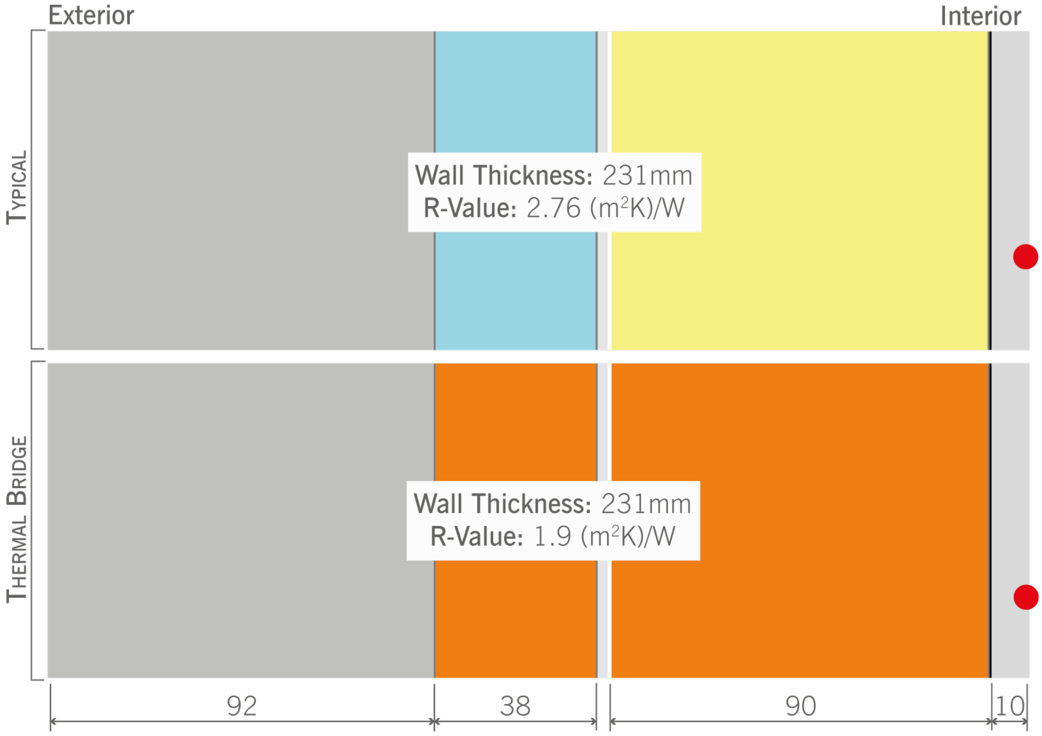


FIGURE 26 WUFI-PRO MODEL: BH-NM-I-03

TABLE 27 MATERIAL DATA FOR MODEL BH-NM-I-03

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
Typical			
Timber Weatherboards	0.019	0.13	200-10
Cladding Cavity	0.018	0.13	0.56
SBP Barrier	0.001	2.3	49.3
Fibre Glass Insulation	0.05	0.054	1.3
Plasterboard	0.01	0.16	7.03
Thermal Bridge			
Timber Weatherboards	0.019	0.13	200-10
Timber Cavity Batten	0.018	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.05	0.13	200-10
Plasterboard	0.01	0.16	7.03



- Plasterboard
- Air Gap
- SBP Barrier
- Pinus Radiata
- Fibreglass Insulation
- Aerated Concrete Block
- Monitor Position

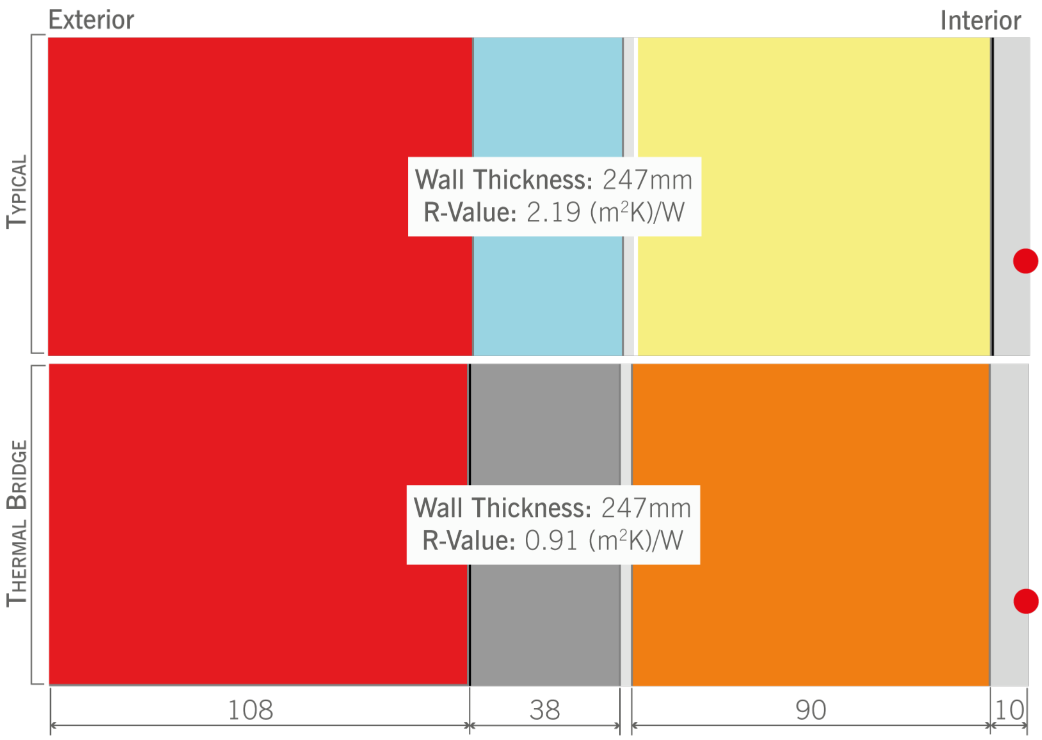
WuFi-Bio Inputs
- 60% IRHS
- Class 1

VTT Inputs
- "Sensitive" Sensitivity Class

FIGURE 27 WUFI-PRO MODEL: NL-NM-I-01

TABLE 28 MATERIAL DATA FOR MODEL NL-NM-I-01

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
		Typical	
Concrete Block	0.092	0.1	7.9
Cladding Cavity	0.38	0.13	0.56
SBP Barrier	0.001	2.3	49.3
Fibre Glass Insulation	0.01	0.054	1.3
Plasterboard	0.01	0.16	7.03
		Thermal Bridge	
Concrete Block	0.092	0.1	7.9
Timber Cavity Batten	0.38	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.01	0.13	200-10
Plasterboard	0.01	0.16	7.03



- Brick Masonry
- Air Gap
- SBP Barrier
- Pinus Radiata
- Steel Clip
- Fibreglass Insulation
- Plasterboard
- Monitor Position

WuFi-Bio Inputs
- 60% IRHS
- Class 1

VTT Inputs
- "Sensitive" Sensitivity Class

FIGURE 28 WUFI-PRO MODEL: BH-NM-I-04

TABLE 29 MATERIAL DATA FOR MODEL BH-NM-I-04

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
Typical			
Brick Masonry	0.108	0.6	10
Cladding Cavity	0.38	0.13	0.56
SBP Barrier	0.001	2.3	49.3
Fibre Glass Insulation	0.04	0.054	1.3
Plasterboard	0.01	0.16	7.03
Thermal Bridge			
Brick Masonry	0.108	0.6	10
Steel Clip	0.38	46	6400
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.04	0.13	200-10
Plasterboard	0.01	0.16	7.03

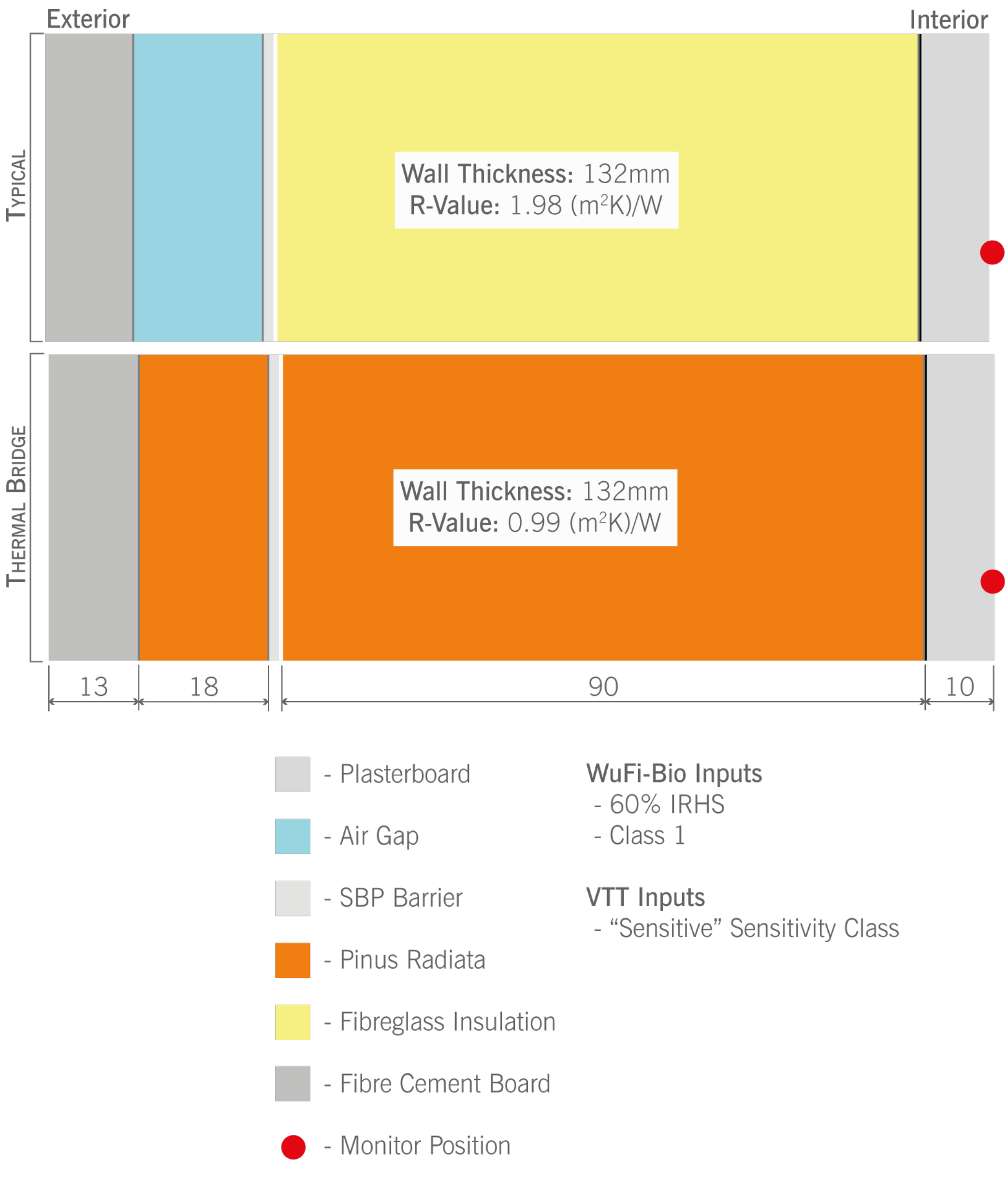


FIGURE 29 WUFI-PRO MODEL: MT-NM-I-01

TABLE 30 MATERIAL DATA FOR MODEL MT-NM-I-01

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
		Typical	
Fibre Cement Board	0.013	0.13	83.3
Cladding Cavity	0.018	0.13	0.56
SBP Barrier	0.001	2.3	49.3
Fibre Glass Insulation	0.05	0.054	1.3
Plasterboard	0.01	0.16	7.03
		Thermal Bridge	
Fibre Cement Board	0.013	0.13	83.3
Timber Cavity Batten	0.018	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.05	0.13	200-10
Plasterboard	0.01	0.16	7.03

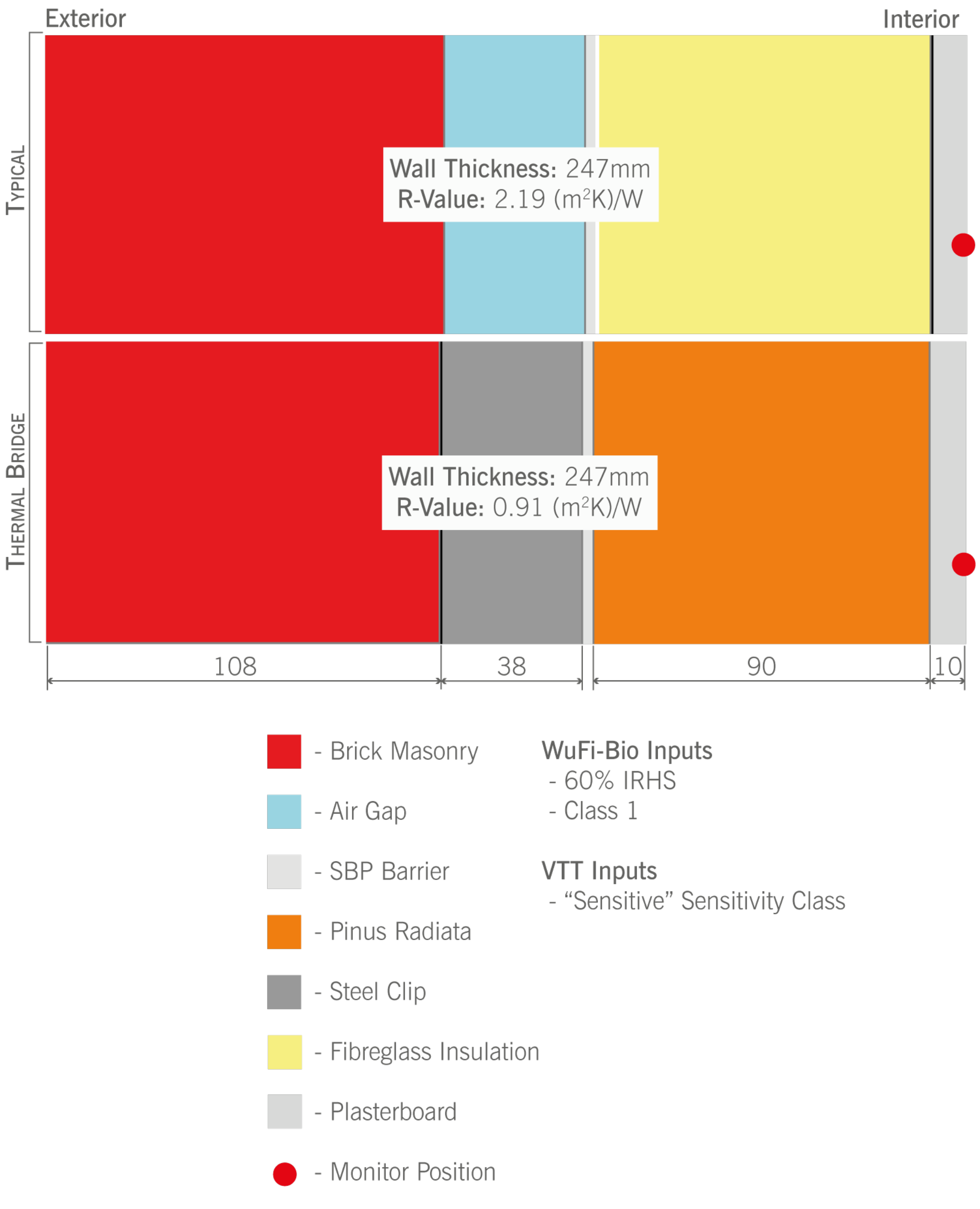


FIGURE 30 WUFI-PRO MODEL: MT-NM-I-02

TABLE 31 MATERIAL DATA FOR MODEL MT-NM-I-02

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
		Typical	
Brick Masonry	0.108	0.6	10
Cladding Cavity	0.38	0.13	0.56
SBP Barrier	0.001	2.3	49.3
Fibre Glass Insulation	0.04	0.054	1.3
Plasterboard	0.01	0.16	7.03
		Thermal Bridge	
Brick Masonry	0.108	0.6	10
Steel Clip	0.38	46	6400
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.04	0.13	200-10
Plasterboard	0.01	0.16	7.03

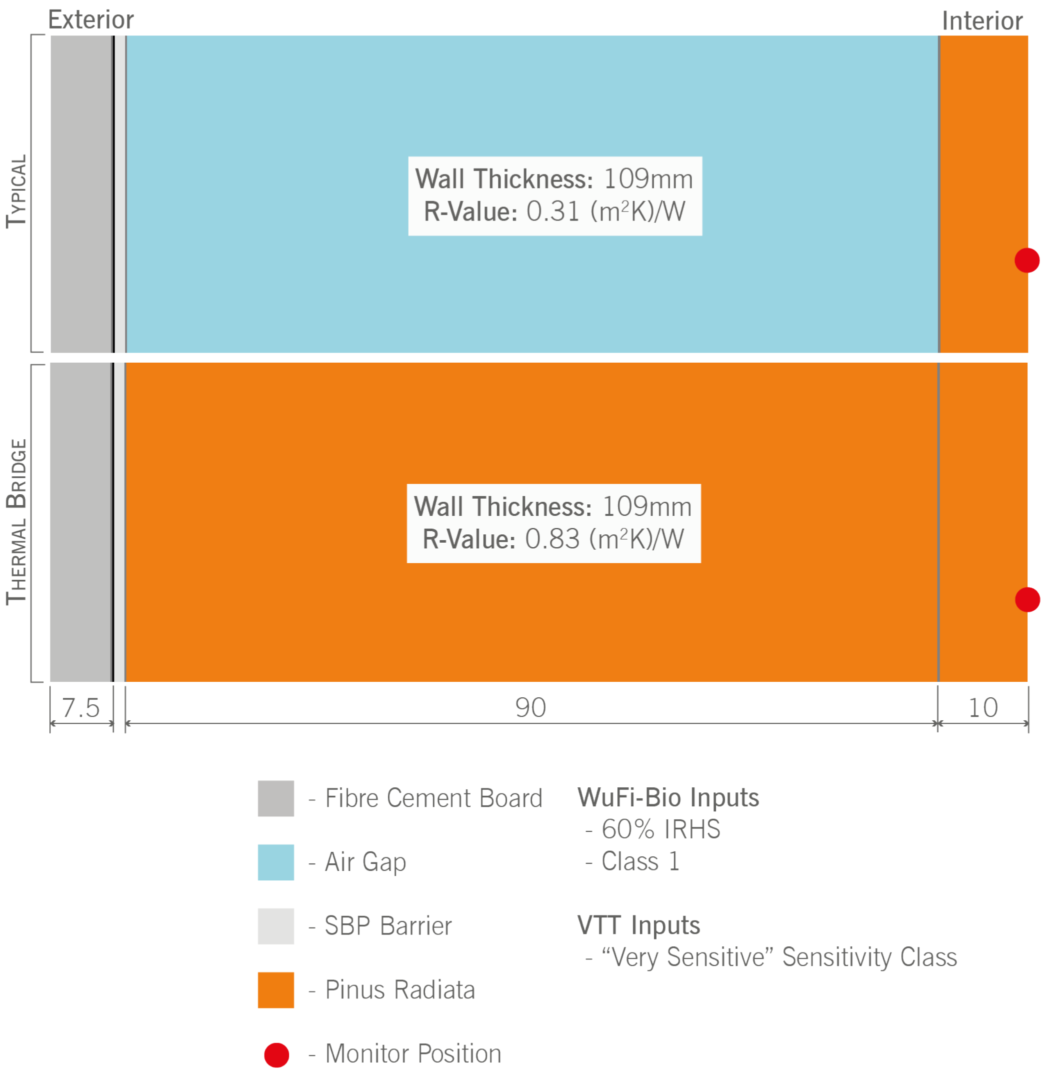


FIGURE 31 WUFI-PRO MODEL: PR-M-NI-01

TABLE 32 MATERIAL DATA FOR MODEL PR-M-NI-01

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
Typical			
Fibre Cement Board	0.0075	0.13	83.3
SBP Barrier	0.001	2.3	49.3
Wall Cavity	0.09	0.523	0.17
Matchlining	0.01	0.13	200-10
Thermal Bridge			
Fibre Cement Board	0.0075	0.13	83.3
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.09	0.13	200-10
Matchlining	0.01	0.13	200-10

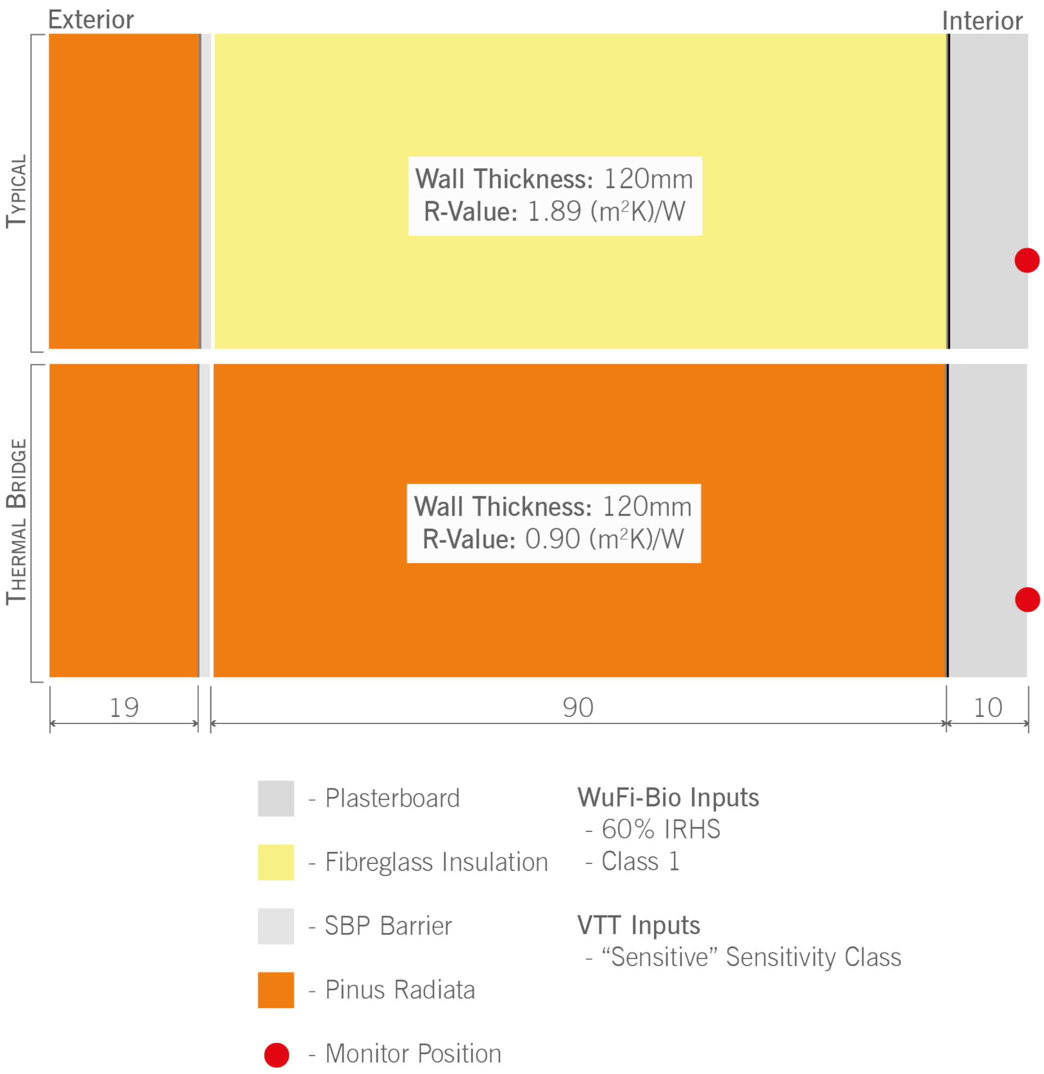


FIGURE 32 WUFI-PRO MODEL: WL-NM-I-01

TABLE 33 MATERIAL DATA FOR MODEL WL-NM-I-01

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
Typical			
Timber Weatherboards	0.019	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Fibre Glass Insulation	0.055	0.054	1.3
Plasterboard	0.01	0.16	7.03
Thermal Bridge			
Timber Weatherboards	0.019	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.055	0.13	200-10
Plasterboard	0.01	0.16	7.03

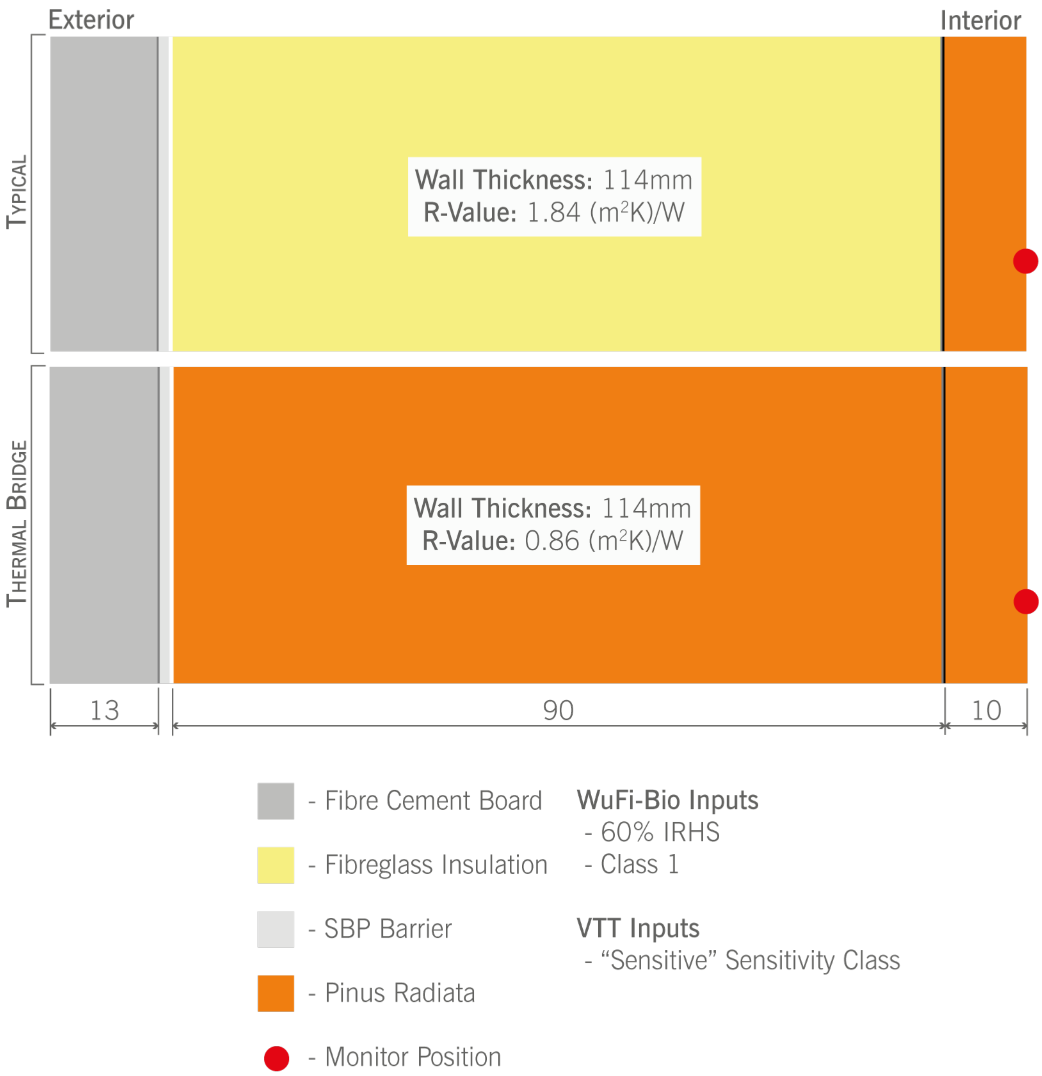


FIGURE 33 WUFI-PRO MODEL: WL-NM-I-02

TABLE 34 MATERIAL DATA FOR MODEL WL-NM-I-02

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
		Typical	
Fibre Cement Board	0.013	0.13	83.3
SBP Barrier	0.001	2.3	49.3
Fibre Glass Insulation	0.06	0.054	1.3
Matchlining	0.01	0.13	200-10
		Thermal Bridge	
Fibre Cement Board	0.013	0.13	83.3
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.06	0.13	200-10
Matchlining	0.01	0.13	200-10

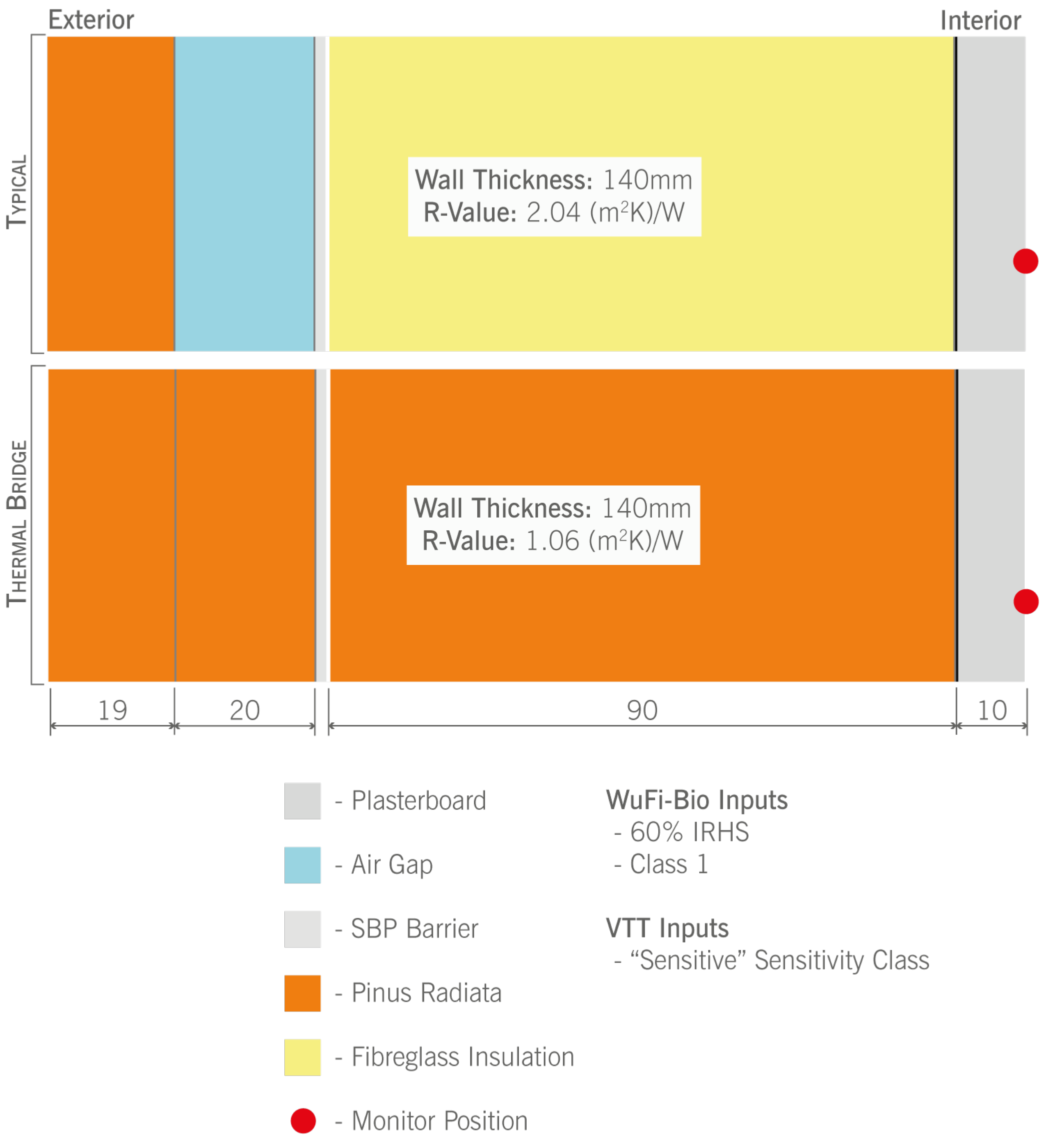


FIGURE 34 WUFI-PRO MODEL: WL-NM-I-03

TABLE 35 MATERIAL DATA FOR MODEL WL-NM-I-03

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
Typical			
Timber Weatherboards	0.019	0.13	200-10
Cladding Cavity	0.018	0.13	0.56
SBP Barrier	0.001	2.3	49.3
Fibre Glass Insulation	0.05	0.054	1.3
Plasterboard	0.01	0.16	7.03
Thermal Bridge			
Timber Weatherboards	0.019	0.13	200-10
Timber Cavity Batten	0.018	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.05	0.13	200-10
Plasterboard	0.01	0.16	7.03

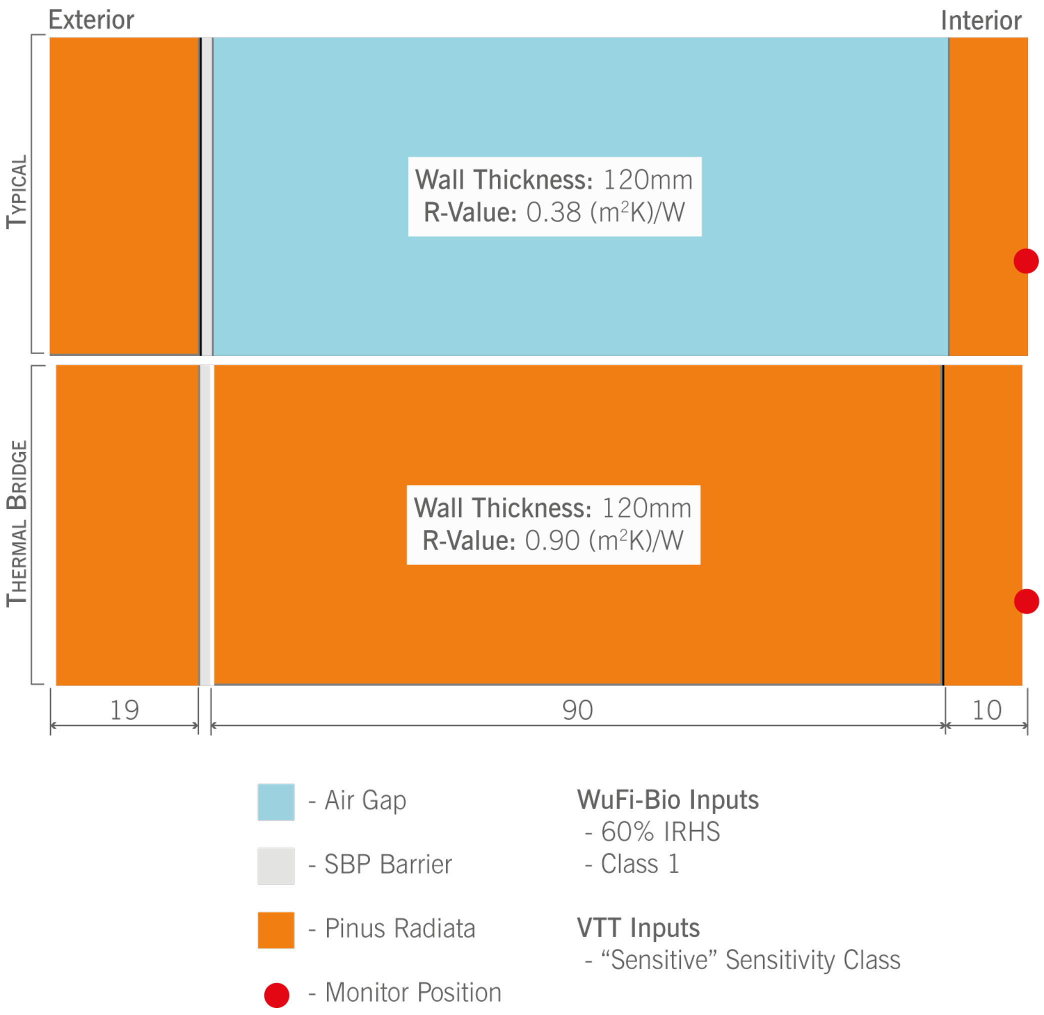


FIGURE 35 WUFI-PRO MODEL: WL-NM-NI-01

TABLE 36 MATERIAL DATA FOR MODEL WL-NM-NI-01

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
Typical			
Timber Weatherboards	0.019	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Wall Cavity	0.09	0.523	0.17
Matchlining	0.01	0.13	200-10
Thermal Bridge			
Timber Weatherboards	0.019	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.09	0.13	200-10
Matchlining	0.01	0.13	200-10

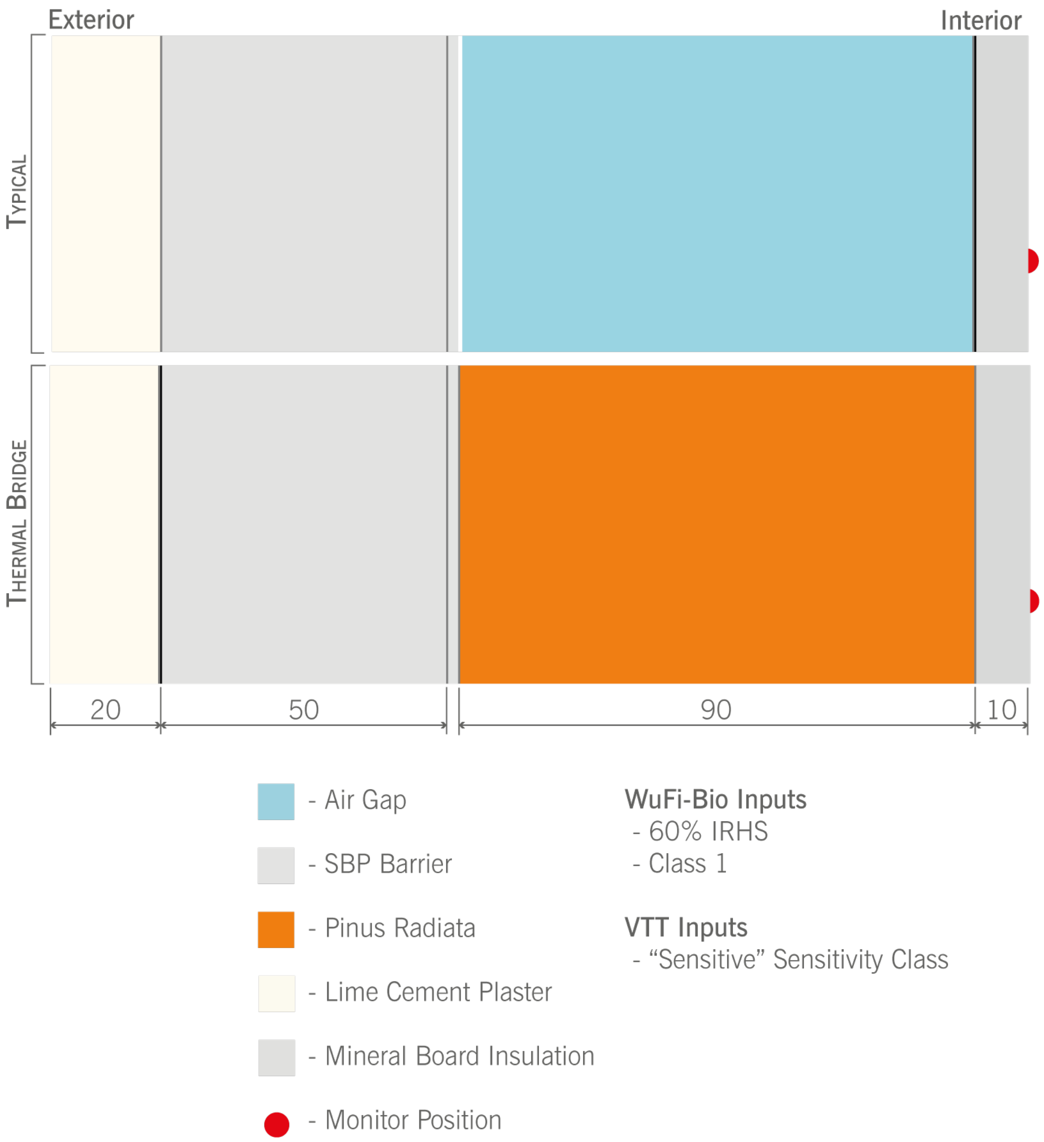


FIGURE 36 WUFI-PRO MODEL: WL-NM-NI-02

TABLE 37 MATERIAL DATA FOR MODEL WN-NM-NI-02

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
Typical			
Cement Lime Plaster	0.02	0.8	19
Mineral Insulation Board	0.05	0.043	3.4
SBP Barrier	0.001	2.3	49.3
Wall Cavity	0.09	0.523	0.17
Plasterboard	0.01	0.16	7.03
Thermal Bridge			
Cement Lime Plaster	0.02	0.8	19
Mineral Insulation Board	0.05	0.043	3.4
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.09	0.13	200-10
Plasterboard	0.01	0.16	7.03

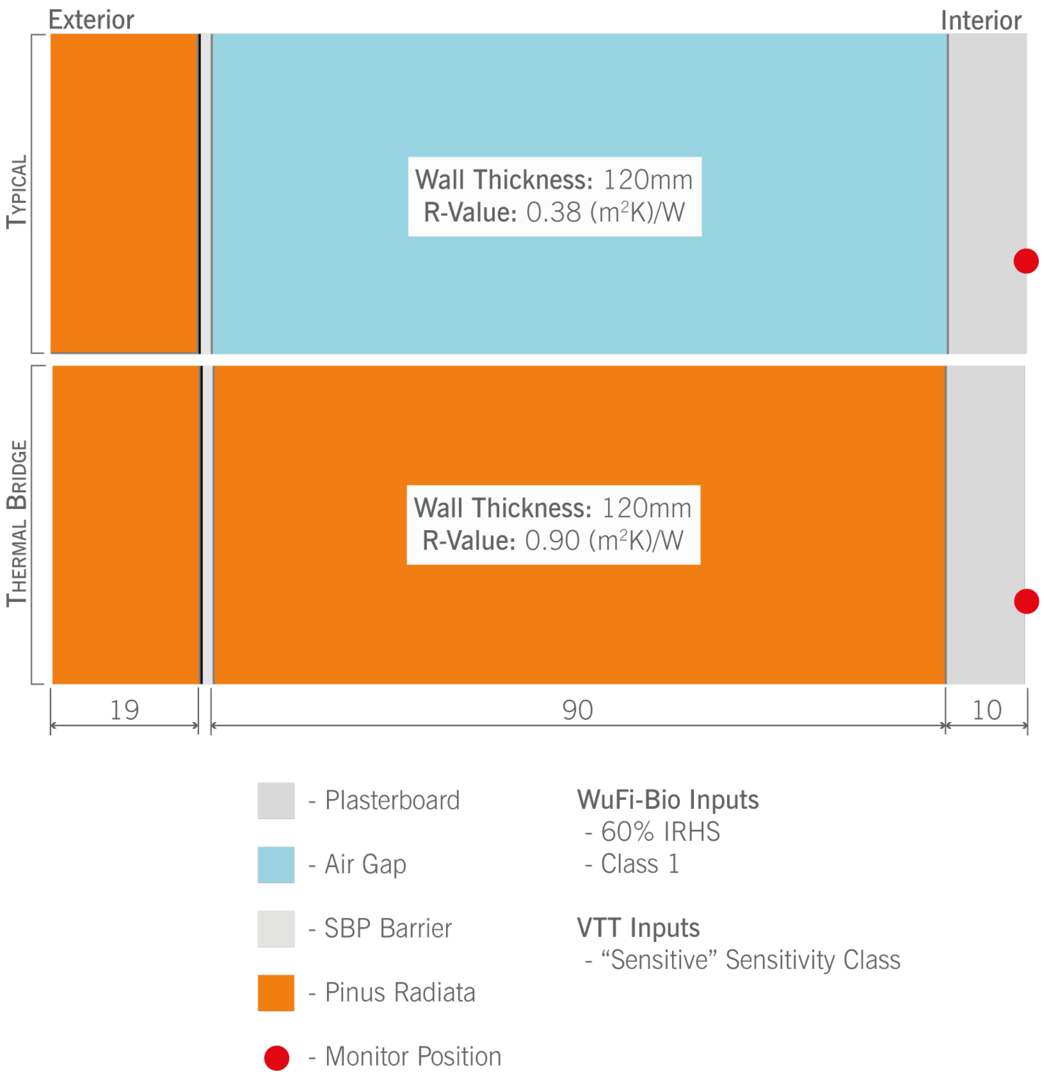


FIGURE 37 WUFI-PRO MODEL: WL-NM-NI-03

TABLE 38 MATERIAL DATA FOR MODEL WN-NM-NI-03

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
Typical			
Timber Weatherboards	0.019	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Wall Cavity	0.09	0.523	0.17
Plasterboard	0.01	0.16	7.03
Thermal Bridge			
Timber Weatherboards	0.019	0.13	200-10
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.09	0.13	200-10
Plasterboard	0.01	0.16	7.03

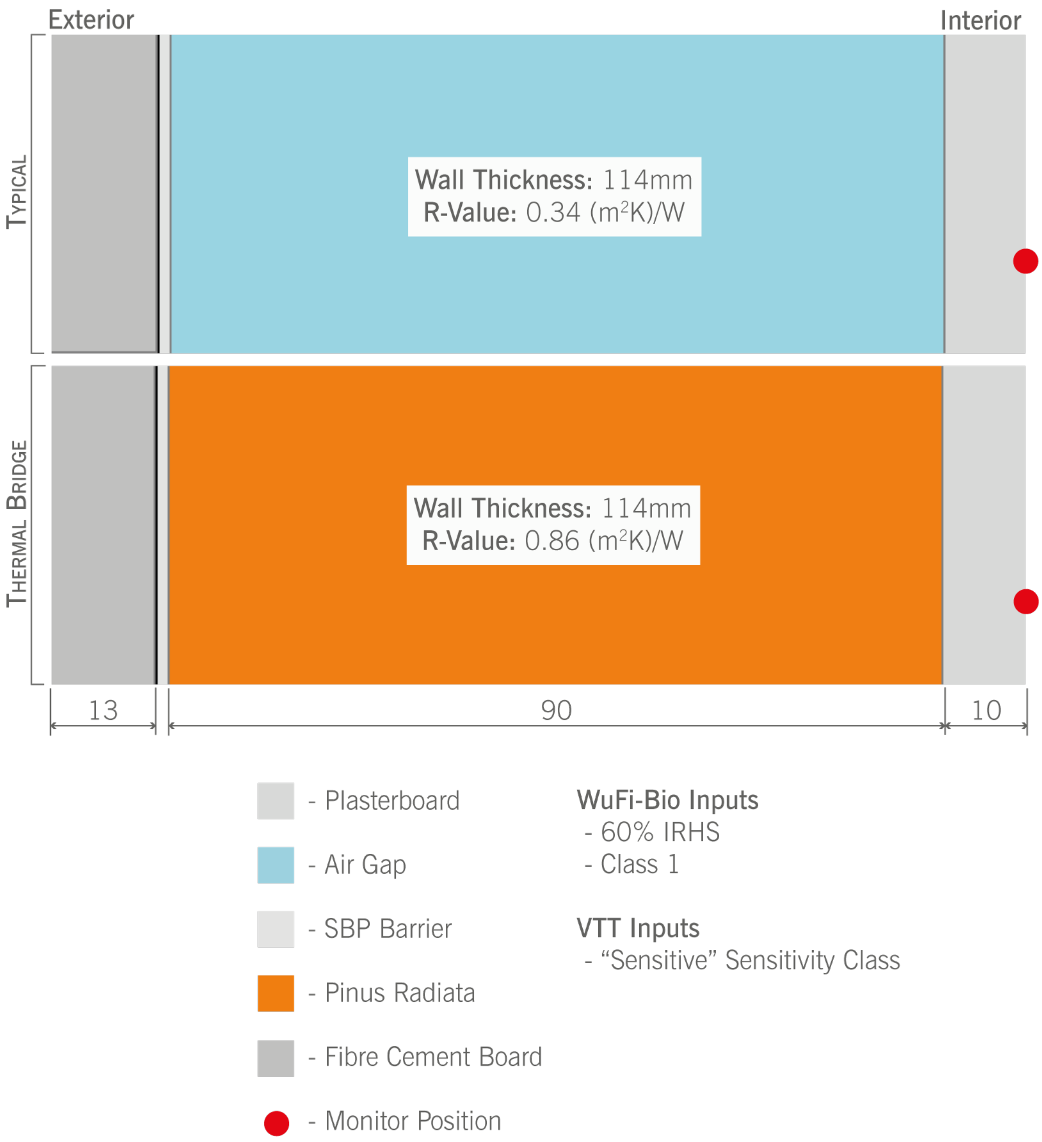


FIGURE 38 WUFI-PRO MODEL: WL-NM-NI-04

TABLE 39 MATERIAL DATA FOR MODEL WN-NM-NI-04

Material	Thickness (m)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance (-)
Typical			
Fibre Cement Board	0.013	0.13	83.3
SBP Barrier	0.001	2.3	49.3
Wall Cavity	0.09	0.523	0.17
Plasterboard	0.01	0.16	7.03
Thermal Bridge			
Fibre Cement Board	0.013	0.13	83.3
SBP Barrier	0.001	2.3	49.3
Timber Stud	0.09	0.13	200-10
Plasterboard	0.01	0.16	7.03