Developing an Optimized Sustainability Assessment Tool for Building Information Modelling (BIM) Systems - Incorporation of Hygrothermal Modelling into BIM

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Abstract

The analysis of the New Zealand (NZ) housing indicated that a notable percentage of dwellings is energy-inefficient, cold, mouldy, and damp which is likely to cause significant health-related issues. Research has suggested that this longstanding problem is rooted in potential systemic failures. However, apart from energy modelling, sustainability assessment possesses a minimal presence in the used BIM tools. Although the necessity to improve building hygrothermal performance is increasingly recognized, the information and mechanisms on how to efficiently employ hygrothermal modelling in the design process are still missing. This study offers a new perspective on understanding the relationship between BIM and sustainability. It introduces innovations through analysing hygrothermal relations in buildings and specifying requirements for integration of hygrothermal modelling into BIM.

The necessary movement in the building industry needs to follow the socio-cultural development into the second-tier thinking levels towards an integral system. Therefore, this study presents an alternative perspective from which we look at the challenging task of how to build better and healthier houses. From this integral perspective, the design and construction process and its end-product, buildings, form open systems that interact with other systems and the environment. The holistic approach to sustainability pertains with the whole project by applying systems engineering methodologies to the design and construction process.

This thesis gradually explores the research objectives from an individual to a collective level. An experimental and numerical study on real houses (individual level) delivers new data which demonstrate the fundamental importance of hygrothermal modelling during the design process. The collective level examines general requirements for incorporation of hygrothermal modelling into BIM and system approach to the design of houses. In an interdisciplinary and systematic approach grounded in integral thinking, this thesis focuses on possible BIM innovation and its implementation strategy. The hygrothermal modelling integration into BIM enables competent decisions about environmental impact of new buildings and retrofits to prevent unintended moisture related problems. Suggested solutions inevitably require a restructuration and continual transformation of the whole design and construction process to progressively eliminate design defects and leaky house syndrome in NZ.

The proposed Complex Integral Design New Zealand (CIDNZ) system accommodates the capacity to integrate diverse perspectives in a unified and flexible framework. The findings of the influence of various materials and construction types on indoor relative humidity levels enhance the practical knowledge. The research results demonstrate the benefits of hygrothermal modelling and the decisive use of hygroscopic materials to sustainable design in NZ. This thesis contributes to knowledge firstly by instigating integral thinking into the design process. Secondly, by applicating the systems approach to buildings and complex construction processes that are seen as elements of environmental systems. The proposed CIDNZ focuses on people by respecting a broad spectrum of human needs. Consequently, the design process might shift the forefront from prevailing aim for cheap and fast built to long-term energy and cost-efficient, durable, and healthy buildings.

Keywords: hygrothermal modelling; BIM interoperability; sustainability assessment; system approach; complex integral design

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List of Acronyms

0H	Null Hypothesis
AEC	Architecture, Engineering, and Construction
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
API	Application Programming Interface
AQAL	All Quadrants, All Levels
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEAM	Building Environmental Assessment Methods
BEM	Building Energy Model
BEM	Building Energy Modelling
BES	Building Energy Simulation
BEST	Building Energy Software Tools
BIM	Building Information Modelling
BRANZ	Building Research Association of New Zealand
BREEAM	Building Research Establishment's Environmental Assessment Method
CAD	Computer-Aided Design
CE	Circular Economy
CFD	Computational Fluid Dynamics
CIDNZ	Complex Integral Design New Zealand
CO_2	Carbon dioxide
CPM	Critical Path Method
CPU	Central Processing Unit
CV(s)	Co-dependent variable(s)
DNA	Deoxyribonucleic acid
DV	Dependent Variable
EECA	Energy Efficiency and Conservation Authority
EMPD	Effective Moisture Penetration Depth
EPS	Extracellular polysaccharides
EVA	Earned Value Analysis
GBC	Green Building Council
GBCs	Green Building Councils
gbXML	Green Building XML schema
GIS	Geographical Information Systems
HAM	Heat, Air, and Moisture

HAMT	Heat, Air, and Moisture Transfer
HVAC	Heating, Ventilation and Air Conditioning
IAPWS	International Association for the Properties of Water and Steam
IAQ	Indoor Air Quality
IBP	Institute for Building Physics
IBPSA	International Building Performance Simulation Association
IDDS	Integrated Design and Delivery Solutions
IEQ	Indoor Environmental Quality
IFC	Industry Foundation Classes
IPD	Integrated Project Delivery
ISD	Integral Sustainable Design
IVs	Independent Variables
LBMS	Location Based Management System
LCA	Life Cycle Analysis
LEED	Leadership in Energy and Environmental Design
LOB	Line Of Balance
LPS	Last Planner System
MBC	Moisture Buffering Capacity
MBV	Moisture Buffering Value
MgO	Magnesium oxide
MVD	Model View Definitions
MVOCs	Microbial Volatile Organic Compounds
NESAQ	National Environmental Standards for Air Quality
NZ	New Zealand
NZGBC	New Zealand Green Building Council
PGD	Proper Generalised Decomposition
PVC	Polyvinyl chloride
RH	Relative Humidity
RNA	Ribonucleic acid
RTA	Residential Tenancies Act
TMPD	Theoretical Moisture Penetration Depth
UMBV	Ultimate Moisture Buffering Value
VOCs	Volatile Organic Compounds
VTT	Technical Research Centre of Finland Ltd
WHO	World Health Organization
WHRS	Weathertight Homes Resolution Service
WUFI	Wärme Und Feuchte Instationär (heat and moisture transiency)

WV	Water Vapour
WVTR	Water Vapour Transmission Rate
XML	eXtensible Markup Language

Attestation of Authorship

"I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning."

Auckland, 07.07.2020

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Chapter 1 Introduction

High relative humidity (RH) and water intrusion affect housing in New Zealand (NZ). A recent BRANZ study revealed that cold and damp are common issues of NZ houses (Pollard, 2018). From 83 measured homes across the country, 84% of the bedrooms have not reached the WHO recommended benchmark of 18 °C (World Health Organization, 2018) from which some houses had only 12 °C. Consequently, mould growth is estimated in 50% of NZ houses (Plagmann, 2018). Energy Efficiency and Conservation Authority (EECA) estimated that about two thirds of the NZ housing stock are not insulated and inadequately heated (Bennett et al., 2016).

A large portion of NZ houses is energy-inefficient, unhealthy, cold, mouldy, and damp (X. Li et al., 2019). Data from the 2018 General Social Survey shows over a third of NZ homes are too cold (bellow 18 °C) in winter and too warm in summer. Inhabitants of 45% of the households with the recorded temperature lower than 16 °C could see their breath inside during winter. About 10% of total dwellings, constructed between 1992 and 2008 by the use of monolithic cladding, contributed significantly to the building failure known as "leaky building syndrome" (Shi et al., 2017). In 2009 the NZ Government accepted PricewaterhouseCoopers's consensus forecast that around 42,000 dwellings built between 1992 and 2008 could have been affected, which would incur total economic costs of an estimated $11.3 billion (Williamson, 2009). However, time showed that the weathertightness failures had been underestimated and they occur in dwellings with all cladding types (Knox & Star, 2015). Therefore, questions remain: Why the leaky homes crisis exists in NZ over 20 years? Why has the valuation period for the Government's Financial Assistance Package Scheme been set at the next 20 years until 2038 (New Zealand Government, 2018b)? Does it mean that the leaky homes are still being built?

According to the Weathertight Homes Resolution Service (WHRS) claims statistics, more than 7,000 claims have been lodged annually in the last five years (New Zealand Government, 2020). However, these statistics relate only to claims that have met the eligibility criteria set out in the Weathertight Homes Resolution Services Act 2006 (New Zealand Government, 2019c). Another analysis of building failures estimated that among NZ dwellings built between 1985 and 2014, 27% (about 174,000) are ‘very likely to leak’ (Knox & Star, 2015). The newly estimated remediation costs are exceeding $47.7 billion (Dyer, 2019).

The change of the Residential Tenancies Act in 2016 made a declaration of the level of insulation an obligatory part of the tenancy agreement (New Zealand Government, 2019b). These changes led to improved insulation of approximately 180,000 properties by 2019, which has been projected to save 129 lives per year and $114.6 million per year in avoided healthcare costs (BRANZ, 2018). The data indicates the scale of the impact of housing quality on economy and health.

The risks associated with poor quality of houses contain diverse issues connected with dampness, mould, and even rotting of building structure. Newly published research suggests that the problem is much broader than initially thought and is rooted in potential systemic failures (Duncan & Ward, 2017). Duncan and Ward (2017) argue that no building pathology system exists in NZ. Therefore, the industry hardly learned from past mistakes which partly led to today’s unsatisfactory situation in housing quality. Therewith, this study is dedicated to the elimination of sick building syndrome and leaky house syndrome, and generally to the improvements of hygrothermal performance and quality of buildings.

Hygrothermal analysis constitutes a part of the science called either Building Physics in Europe or Building Science in North America. Building physics is a relatively new science (since the 1930s) which is based mainly on experimental studies and empirical experience in the building industry (Bomberg, 2012). The fact is that little to no building physics has been taught to architectural students at the Universities in New Zealand (Rosemeier, 2010). The consequence of this situation is that even newly built houses are often not performing well. Although numeric calculation in the field of statics, construction and energy engineering are standard, the evaluation of hygrothermal processes of building constructions are not common. This research brings new knowledge in the field of construction in New Zealand with the intention to encourage not only building science but the whole building industry to use hygrothermal assessment appropriately wherever technical decisions about buildings are made.

1.1 Background

Design of low or zero energy sustainable buildings is a complex task which requires a broad scale of knowledge from different fields. The technology of the house moved far beyond the traditional house equipment (similarly to a modern car), the climate is changing, and the transition into the fourth industrial revolution is bringing new technology into the design process of houses. Therefore, a new approach to building design is necessary to pursue the fast changes. The holistic design process requires a total paradigm shift in thinking and applying new technology. The investigation of the influence of different building materials on indoor RH levels, as described in this thesis, represents a part of a complex holistic design process. Other components of the holistic design process are, for example, the elaboration of building structure, durability, weathertightness, energy efficiency, moisture-related issues, indoor air quality, lighting, human aspect, and impact on the environment. The movement in the architecture, engineering, and construction (AEC) industry needs to follow the socio-cultural development into the second-tier thinking levels towards an integral system by adding the human aspect (Sepers, 2017). The same integrated design paradigm, where the whole design team engages with these factors, needs to be applied by new built and retrofits (Bomberg, Gibson, et al., 2015).

1.2 Rationale and Significance of the Study

With a fast-growing population of NZ, there is an urging need for more homes, especially in agglomeration areas, such as Auckland, Christchurch, and Wellington. Using consented dwellings and population growth as indicators of the balance between housing supply and demand in Auckland, for example in the year ended June 2016, there was a surplus of demand for housing potentially 6,000 dwellings (Stats NZ, 2017). These figures, combined with the fact that many of NZ houses do not provide a healthy indoor environment, indicate the importance of the housing sector in the NZ economy. There is a significant need for improvements in the quality and durability of NZ homes because the housing is becoming increasingly important to people’s health due to demographic and climate changes (World Health Organization, 2018).

Despite the fact that the research on measured building moisture and respiratory or allergic health effects is limited, associations are strong (Mendell et al., 2018). Newly published NZ study by Ingham et al. (2019) emphasizes the impact of housing quality on the health of children:

> A dose–response relationship exists between housing quality measures, particularly dampness–mould, and young children's acute respiratory infection (ARI) hospitalisation rates. Initiatives to improve housing quality and to reduce dampness–mould would have a large impact on ARI hospitalisation. (p. 849)

Asthma and other respiratory diseases affect 700,000 people in NZ and cost more than $7 billion every year; asthma in NZ affects one in eight adults and one in seven children (Barnard & Zhang, 2018).

The analysis of the NZ housing awoke the research idea. The subject was used for this study because of an existing gap in knowledge of how to enable BIM (Building Information Modelling) to participate in a design process that pursues a holistic approach. Apart from energy modelling, sustainability assessment has a minimal presence in the used BIM tools. To be able to take responsibility for our future, there is a significant requirement for accountability and the ability to quantify the ecological, social, and economic value of projects. For example, what is the impact of improvements in the indoor environment on health issues, such as asthma, chronic headaches, or burnout syndrome, and their macroeconomic costs? Consequently, how can these building components have their environmental impact factored into the BIM process?

This research concentrates on understanding the consequences of underestimating hygrothermal relations in NZ buildings and specifying requirements for integration of hygrothermal modelling into BIM. Consequently, the research contributes to an understanding of why our current buildings are not always performing well and aims to provide a framework for acceptable solutions and tools for designers to design warmer, drier, and healthier houses. The thesis intends to find conditions and requirements for BIM enabling assessment of construction projects in different stages regarding hygrothermal relations, calculations, and optimization. The necessity to improve building hygrothermal performance is increasingly recognized, but the information on how to efficiently use the moisture buffering capacity in the design process is still missing. Design and construction process of energy-efficient and comfortable houses require the evaluation of indoor moisture and regulation of excessive indoor humidity and temperature extremes. Simplifying the problematic of building performance to thermal insulation and airtightness only, is not the solution to the problem. With new technologies and materials used in the construction, the complexity of dwellings is growing. This situation requires a new interdisciplinary approach to the design process.

Therefore, in an interdisciplinary and systematic approach relating to construction engineering, architecture, building physics, biology, building biology, chemistry, psychology, and environmental studies the thesis focuses on BIM innovation and its implementation strategy. It is essential to consider carefully both how buildings are designed and the choice of materials used (Sacks et al., 2018). This thesis aims to evaluate the risks of underestimating hygrothermal relations in buildings and suggest possible solutions to design energy efficient, healthy, and durable buildings. Suggested solutions are based on restructuration of the whole design and construction process, which is aiming to find answers to the questions in the time when they are needed, and prevent the building performance design defects. In this sense, the thesis is likely to enhance the existing knowledge by introducing integral thinking to the design process of sustainable houses.

1.3 Research Focus

This research focuses on possible ways how to improve the quality of houses in NZ, particularly hygrothermal performance. As the construction industry is increasingly complex and new technologies develop and are being incorporated in diverse stages of the construction process, modelling gains on significance. This research's intention is to demonstrate that broadening of BIM in terms of sustainability assessment of materials applied during the early stage of design might prevent moisture related problems and improve the durability and quality of construction. Consequently, negative impacts on the environment, human's health, and life cycle costs of a building can be minimized, energy efficiency and indoor air can be improved.

The problematic of energy-inefficient, unhealthy, cold, mouldy, and damp houses in NZ couldn't be solved with the same approach as it was created. A radical change in thinking is necessary because as Albert Einstein has already said: "Problems cannot be solved by the same level of thinking that created them" (as cited in German in Stahlbaum, 2020). Therefore, the second part of the thesis focuses on the paradigm shift in the architectural design process.

The research focus is depicted by research aim, objectives, and questions.

1.4 Research Aim, Objectives, and Questions

The aim of this research is to understand firstly the relationship between BIM and sustainability assessment of materials during the early design stages of housing, focusing on moisture related issues in New Zealand. Secondly, the research aim is to understand the design process from a systemic point of view.

In order to achieve the research aim, the following objectives have been identified:

- Examine the hygrothermal performance of New Zealand housing construction, focusing on internal envelope materials.
- To identify the challenges associated with undertaking effective hygrothermal assessments during the early design stage of housing in New Zealand.
- Specify requirements for integration of hygrothermal simulation into BIM to improve building sustainability.
- To develop a framework for designers to provide warmer, drier, and healthier houses for the New Zealand context.

To achieve the research aim and objectives, the following questions, as shown in Table 1, are guiding the study:

Table 1

Research Questions

Research Objectives	Research Questions
1. Examine the hygrothermal performance of New Zealand housing construction, focusing on internal envelope materials.	What levels of RH are reached in occupied NZ houses by different internal envelope materials?
	What is the impact of different building materials used on the indoor side of walls on the hygrothermal performance of a building?
	How do RH levels differ in NZ houses based on the presence/absence of airtightness membranes?
2. To identify the challenges associated with undertaking effective hygrothermal assessments during the early design stage of housing in New Zealand.	What are the most significant impacts of high humidity on NZ housing?
	What are the requirements for undertaking an effective hygrothermal assessment of houses during the early design stage?
	Which physical qualities of building materials influence hygrothermal performance most significantly?
3. Specify requirements for integration of hygrothermal simulation into BIM to improve building sustainability.	How can building sustainability be improved based on effective hygrothermal simulation?
	What are the requirements for integration of hygrothermal modelling into BIM?
	How can a BIM-integrated hygrothermal simulation tool improve the building performance?
	How can a BIM-integrated hygrothermal simulation tool reduce errors affecting the hygrothermal performance of buildings?
	How can a BIM-integrated hygrothermal simulation tool increase hygrothermal efficiency?
4. To develop a framework for designers to provide warmer, drier, and healthier houses for the New Zealand context.	How can integral principles be applied to determine potential building performance weakness during the design stage?
	Considering building physics, what are the major differences of the design process, including hygrothermal simulation compared to the traditional design process?
	What factors have the most influence on hygrothermal performance of houses in NZ?
	What are the steps to design warmer, drier, and healthier houses for NZ context?

1.5 Research Scope

The research area will be explored gradually from an individual (in the form of two test houses) to a collective level. The latter will examine general requirements for incorporation of hygrothermal modelling into BIM and system approach to the design of houses. The first part of the thesis will focus on data collection to test the hypothesis. It will provide analysis and comparison of quasi-experiment and simulation data for two test houses located in Auckland, New Zealand. The experiment ran from January 9th, 2018 till February 19th, 2018.

The collective level of the thesis will cover two stages - rational and integral. The rational stage is based on the analysis of interoperability requirements between BIM and hygrothermal modelling. It will lead to a description of possible ways how to incorporate hygrothermal modelling into BIM. The integral stage depicts a completely different type of the collective level because it is not exclusive. In contrary, the integral stage of thinking understands the importance of each of the previous stages in the development of knowledge (Gallifa, 2019). This level is holistic and all inclusive. From this level the necessary changes in the design process of houses will be discussed.

1.6 Key Assumptions of the Study and Hypothesis

Based on building physics knowledge about hygrothermal relations in buildings, the researcher proposed the following hypothesis:

"If materials used in the building envelope have a significant influence on the hygrothermal performance of the building, then the design of sustainable buildings cannot be done without hygrothermal modelling."

The hypothesis guided the direction of the research process and dictated quite precisely its nature. The formulation of the thesis indicates the used systemic approach with analytical quality. This research performed an in-field experiment and hygrothermal simulation to test the validity of the first statement - namely, "Materials used in the building envelope have a significant influence on the hygrothermal performance of the building."

After a rigorous literature review, the researcher developed a conceptual framework. A conceptual framework is representing the context of the concept that the study is based on. This study concept is based on two main pillars. The first part uses a classical approach of testing the hypothesis with experiment (quasi-experiment) and simulation. The two testing methods have been chosen deliberately in order to determine the impact of different materials on indoor RH and to demonstrate the significance of hygrothermal modelling integration into Building Information Modelling (BIM). Data gained from testing the hypothesis have been analysed using statistical methods. From the results of the analysis have been drawn conclusions supporting the hypothesis. The hypothesis has been confirmed.

The second part of the conceptual framework is of paradigm change of thinking in architecture, engineering, and construction (AEC) industry. Deductive reasoning in a systemic approach with analytical quality has been used for the development of the conceptual framework, as shown in Table 2.

Table 2

Deductive Reasoning of the Conceptual Framework

	Statements (or Conclusions)	Reasons (or Justifications)
1	Hygrothermal modelling simulates the real hygrothermal performance of buildings.	It is validated by comparison of quasi-experiment and simulation results.
2	Hygrothermal performance of low energy and sustainable buildings might be optimized.	If hygrothermal modelling simulates the real hygrothermal performance of buildings, then the hygrothermal performance of low energy and sustainable buildings might be optimized.
3	Materials used in the building envelope have a significant influence on the hygrothermal performance of the building.	Tested by quasi-experiment and hygrothermal modelling.
4	Design of low energy and sustainable buildings cannot be done without hygrothermal modelling.	If materials used in the building envelope have a significant influence on the hygrothermal performance of the building, then the design of sustainable buildings cannot be done without hygrothermal modelling.

The thesis is likely to reveal the reasons for necessary interoperability between hygrothermal modelling and BIM. Consequently, a part of the thesis constitutes an evaluation of requirements for hygrothermal simulation and suggested incorporation of the hygrothermal model into BIM. The researcher selected two examples of software - Revit representing BIM and WUFI Plus a whole building hygrothermal simulation model.

Construction is a complex process which influences the environment and society. The optimization of such a process often lies in the reorganization of existing procedures and using known methods in a new way. Consequently, the proposed design process has the capacity to integrate differentiations/different perspectives, such as outdoor conditions or intended use of the building, in a unified framework. Therefore, the thesis structure follows a logical construct which leads from a rational to an integral stage. The chapters and the two main parts of the thesis are linked together by the intention to find answers on how to optimize a sustainability assessment tool for BIM systems and its practical application in the AEC industry. The study focuses on the development of a framework for designers to provide warmer, drier, and healthier houses for the NZ context.

The framework will lead to a conscious balancing of equal outcome (freedom to choose what people like) with equal opportunity (economic and environmental factors). Therefore, the suggested framework will allow for sustainable development in harmony with changes in perspectives. An example of changing perspectives is the influence of the energy crisis. By the time the energy crisis arose, the energy saving perspective had brought a new reality into house design. The AEC industry focused on super insulated houses with only energy in view; by some extremes ignoring the natural and psychological human needs for the healthy indoor environment or natural full spectrum light. The influence of the indoor environment on health was seen as non-existing or limited because the science was unable to prove the causal relationship between them. However, an increasing number of evidence-based studies indicated the implications of the quality of housing for people's health. For this reason, official bodies, such as WHO acknowledged that healthy housing besides providing shelter from the elements and from excess moisture, mould, pests, and pollutants "… supports a state of complete physical, mental and social well-being" (World Health

Organization, 2018, p. 2). Therefore, this study is about the perspective from which we look at the task of how to build better, healthier, warmer, and safer houses. This thesis is of paradigm change of thinking in new, occupant centred design.

1.7 Limitations

The researcher is aware of the limitations of this study on both levels of the research scope. On the individual level, the limitations related to the accuracy of any data. In the quasi-experiment, the limited accuracy originated in the quality of available technical equipment and uncontrollable factors, such as weather. In the simulation, some input data, such as laboratory tested hygrothermal properties of used materials have been unknown. Therefore, the study had to rely on estimated or software's library data. The major challenge of the experiment has been technical malfunctions of one humidifier occurring during the validation process of the testing. Consequently, the original quasi-experiment design had to be changed from simultaneous to switching mode which resulted in different weather conditions by each setting. The research was limited to indoor RH measurements. However, a complete assessment of the hygrothermal performance of the house/compartment inclusive in-wall RH measurements would be required to guide design decisions. From this reason, the researcher is not taking the assessment of airtightness in the conclusions.

Other experienced limitations are of model predictions of RH development by using a classic diffusive model. These limitations are well known because these models neglect some phenomena, such as nonequilibrium behaviour between water vapour and bound water, or transport by air convection (Busser et al., 2019). The comparison of measured and simulated data demonstrated this limitation, especially due to the use of hygroscopic fibrous materials. Additionally, as existing models rely on input data which are man-prepared, the results are influenced by the quality of such data (Antretter & Pallin, 2019). The program output and its interpretation often require deeper knowledge in physics and material characteristics. Therefore, the researcher is aware of the necessary condition of successful incorporation of hygrothermal modelling into the design process, which is an adequate education for building professionals.

On the collective level, the thesis is limited to a specification of requirements for integration of hygrothermal simulation into BIM and a proposal of a framework for designers.

1.8 Thesis Contribution and Overview

The thesis is likely to contribute to the existing knowledge in multiple ways. The findings of the research confirmed the hypothesis: “If materials used in the building envelope have a significant influence on the hygrothermal performance of the building, then the design of sustainable buildings cannot be done without hygrothermal modelling.” Therefore, the proposed integration of hygrothermal modelling into BIM will enable optimization of the house design in the stage when the costs for changes are the lowest. Consequently, building sustainability and quality of houses might be improved.

With the analysis of hygrothermal performance of NZ houses, the thesis reveals that hygrothermal modelling might assist the sustainable design. The findings of RH development in real houses, which demonstrate the influence of different materials in diverse construction types (existence or non-existence of airtightness membrane), are bringing new knowledge in the NZ context.

The suggested integration of scientific achievements, available tools, and partial knowledge into the design process of houses in a holistic way - named Complex Integral Design New Zealand (CIDNZ) - is likely to change the outcome (quality of houses). The proposed framework is introducing a new perspective on how to design warmer, drier, and healthier houses for the NZ context. CIDNZ encourages architectural and engineering design to gradually develop in an integrative and interdisciplinary way. The design process will change the perspective from originally cost-oriented view (cheap and fast built) to energy-efficient, zero-energy buildings without negative influence on the environment. Therefore, the future housing (created by the CIDNZ principles) will be durable, less disturbing to the natural habitat, less polluting the environment, constructed from high quality, recyclable or reusable materials, and have healthy indoor air. The proposed CIDNZ framework is flexible, allowing the addition of new perspectives. It focuses on people by respecting a broad spectrum of human needs, inclusive physical, psychological, social, and spiritual.

Therefore, the housing will enhance humans' individual and social lives and be adaptive to changing needs.

This thesis consists of two major parts. The structure of the first part (chapters 2 – 7) follows a traditional, classical approach to thesis from the evaluation of the existing knowledge in related fields to the examination of selected problems. This thesis chose moisture related problems and building materials' influence on indoor RH. The data collection consists of quasi-experiment in real houses with real time measurements and simulation of the same settings. Data have been validated by comparison of measurements and simulation results for existing house setting without any changes. Data implementation, analysis, and interpretation of results served to test the hypothesis and demonstration of the complexity of moisture related problems in buildings. After a description of requirements for interoperability between BIM and hygrothermal modelling, the findings are discussed.

The theoretical knowledge applied and further developed in experimental studies led to the demonstration of significance and feasibility of purposeful choice and placement of building materials to design and build healthier and sustainable houses. The findings have been translated into requirements for data needed for modelling of different variants of projects, permitting early-stage identification and prevention of environmental weak points. The idea is to apply BIM in stages, allowing for competent decisions regarding environmental impact and sustainability of new buildings and retrofits/rebuild to prevent unintended moisture related problems during construction and whole life cycle of the building. A theoretical perspective, such as a conceptual framework for allowing interoperability through the BIM platform guides the study.

Therefore, the second part of the thesis (Chapter 8) offers a new look out of existing situation in the AEC industry. This part consists of defining the new set of operations CIDNZ, which likely lead to healthy housing. Consequently, the integration of this system approach will happen gradually through a transformation process.

Chapter 2 Research Methods

In this chapter, the researcher intends to debate research methodology and set a philosophical background of the research. The structure of the chapter is conceived in terms of general research methods and narrowed to the research method used by this research. The chapter first examines the philosophical position of research in relation to ontology and epistemology. This includes the description and brief characteristics of major philosophical theories, such as positivism, interpretivism, phenomenology, critical realism, constructivism, relativism, empiricism, and rationalism. This overview of the theory is followed by research strategy analysis inclusive influences of different factors on research. A comprehensive depiction of research design styles, such as survey, experiment, quasi-experiment, archival analysis, history, case study, and simulation, represent the next part of this chapter. The last part of the theoretical explanation is dedicated to available reasoning methods for research in the evaluation of theory. The whole chapter leads to the description of the methodology of this research, where reasons for the chosen research strategy and style are explained. After this sequence, the chapter focuses on experiment and simulation design, and methodology of literature review. In the summary, the significant points of this chapter are summarized.

2.1 Philosophical Position of Research

Research is defined as "… the systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions" (Lexico powered by Oxford [Lexico], n.d.) . Research is a cognitive process often influenced by ontological and epistemological beliefs (Bercht & Wijermans, 2018; Davies & Fisher, 2018). Although the ontological and epistemological beliefs might not always be conscious, they have a significant influence on the process and results of the research. Therefore, consideration of philosophical position and methodology constitutes the crucial segments of every scientific research. Despite some critics, the dominant philosophical position of science is positivism, followed by its oldest opponent interpretivism, and constructivism. Off cause, these are not the only philosophical theories today, but they represent the mainstream to which scientists have to position themselves methodologically (Gorski, 2013). As every philosophy has its position regarding to ontology and epistemology, this chapter provides an overview of the philosophical studies and theories.

2.1.1 Ontology and Epistemology

Ontology is a term which Lexico (n.d.) describes as:

1. "The branch of metaphysics dealing with the nature of being.
2. A set of concepts and categories in a subject area or domain that shows their properties and the relations between them."

In philosophy, ontology represents the study of the nature of being, in other words, the study of existence. Ontology focuses on questions about what does exist, to what does it belong, about objectivity, and meaning of existence. Ontology, in the sense of proving something in existence, is the oldest form of philosophy. It served very good in natural sciences. Objectivism is an ontological position introduced by Ayn Rand that asserts that certain phenomena exist independently and separately from human knowledge or perception (Peikoff & Ward, 1991). Objectivism has its origin in realism and essentialism (Lakoff, 1987). Objectivism asserts that the world is real and structured, and that there is an objective reality. Constructivism is an alternative ontological position which states that the reality exists in the mind so it depends from our construction of the knowledge (Jonassen, 1991). Constructivism has its origin in rationalism and empiricism (Mahoney, 2004).

Epistemology is a branch of philosophy studying the nature of thought, in other words, it is the study of knowledge. Epistemology is defined as: "The theory of knowledge, especially with regard to its methods, validity, and scope, and the distinction between justified belief and opinion" (Lexico, n.d.). The epistemological perspective influences research in two ways; defining the researcher's world view and informing the research design (Chism et al., 2008).

Since humans have always been concerned with knowledge and thoughts, many epistemological theories have been developed. The dominant epistemological theories could be distinguished according to their relationship to foundationalism and if they are explanatory or constitutive (Smith et al., 1996). Examples of epistemological theories are foundationalism, coherentism, pragmatism, rationalism, empiricism, positivism, realism, and reductionism.

2.1.2 Positivism, Interpretivism, and Phenomenology

Positivism is a philosophical theory which is deeply rooted in natural science and mathematics. Despite the name, positivism has nothing in common with "positive thinking". Positivism philosophical ideology was formulated by the French philosopher August Comte (1798-1857) (Hjørland, 2005). The positivist perspective assumes that there is an absolute truth, that everything that exists can be proven by scientific methods or logical reasoning, and that there is a clear division between facts and values (Chism et al., 2008). From the ontological perspective, the researcher is separated from reality. From the epistemological view, the reality, which is objective, exists beyond the mind (Weber, 2004). Everything that is unverifiable is false or does not have any meaning.

Positivism believes that scientific knowledge exists in universal laws and exception-less statements that make a prediction and control of the future events possible (Gorski, 2013). According to Smith et al. (1996) positivism was the leading, scientific epistemological position especially in the early 20th century but since the late 1980s, the pure positivist theory has been rejected by most philosophers. However, positivist way of thinking represents a dominant form of orthodoxy and is still the prevalent theory, especially in natural sciences (Gorski, 2013). Even in social science, the dominance of neopositivism is based on the argument that neopositivism is uniquely scientific (Jackson, 2015).

One of the reasons for the prevailing influence of positivism is the ability to practically guide the research process with a clear and understandable status. No other philosophy has been able to position itself as an "invisible philosophy of science". Another reason for the prevailing influence of positivism might be a deficiency of clear terminology in the philosophy of science (Hjørland, 2005). Postpositivism, although being successful in criticizing positivism such as reflectivist theories, still believes in objective reality.

Interpretivism represents a philosophical theory which is in contrast with positivism. However, interpretivists distinguish between natural and social sciences. Natural sciences according to interpretivism may be governed by general laws, but social sciences are governed by meanings. Therefore, the methods and aims used by interpretivism in social sciences are strongly dissimilar from the methods and aims used in natural sciences (Gorski, 2013). Many of the qualitative research studies are based on the interpretivist perspective (Chism et al., 2008). Interpretivism's metatheoretical assumption about ontology is based on the idea that the researcher and reality are inseparable and interdependent. The epistemology of interpretivism can be best described by a belief that knowledge is intentionally constituted through social construction of the reality (Weber, 2004).

Phenomenology has its origin in the work of Brentano (Poli, 2017) and is defined as

> … a radical, anti-traditional style of philosophising, which emphasises the attempt to get to the truth of matters, to describe phenomena, in the broadest sense as whatever appears in the manner in which it appears, that is as it manifests itself to consciousness, to the experiencer. (Moran, 2000, p. 4)

Phenomenology aims to understand phenomena without any impositions from existing knowledge or beliefs posed a priori on experience. In this sense, a phenomenological study focuses on the essence of an experience. Phenomenology was seen as radicalization of empiricism by Husserl (2012) who added to two generally accepted spheres of consciousness a third one. The two spheres are: material, factual sphere called unity of things, and formal sphere called unity of essence. The "unity of things" and the "unity of essence" are connected through mind only. Husserl believed that there is a third sphere of absolute consciousness where intuition and experiences add to knowledge. The sphere of absolute consciousness could be reached by using the method of phenomenological reduction (Husserl, 2012). The Husserl's theory of absolute consciousness is further developed by new theories, such as morphogenetic fields theory (Beloussov & Gordon, 2018; De Luca Picione & Freda, 2016) and morphomechanics (Ermakov, 2018). Phenomenology as philosophy underpins every qualitative research (Merriam, 2002). Although this research is based on logical positivism, the researcher positions herself into supporting this statement. The logical positivism serves the research well, however, to find solutions to environmental issues, the research recommends a holistic and integral approach. The researcher believes that morphogenetic fields theory and holistic approach might be applied to design and architecture as well. Especially in solving of environmental questions, holistic approach to sustainability opens a door for new resolutions. An example of new ways in architecture represents an atmospheric approach to design. The atmospheric approach might be detected in air design, meteorological architecture, and atmospheric preservation (Corbo, 2018).

2.1.3 Critical Realism, Constructivism, and Relativism

Constructivism is a theory developed by Piaget and Inhelder (1967). Constructivism is based on the idea that knowledge and reality are constructed through personal experience, and that they are never staying the same as they are constantly formed and transformed by means of personal experience (Ackermann, 2001). In other words, researchers are in the role of actors while participating in the research process. Reality is a social construction and is an interpretation of human sense making. This view is inspired by the philosophical position of phenomenology (Edvardsson et al., 2011). Constructivism has several differently interpreted meanings. Some versions of constructivism accede that social life is linguistically compiled (Gorski, 2013). However, they all have one philosophical position in common: knowledge is being constructed, is based on interaction, and is under constant state of revision (Bryman, 2016). According to constructivism, social structures do not have active causal powers (Harré, 2001). Constructivists maintain the idea that the subject (researcher) and the object (investigated phenomena) separation is not possible, nor the complete distinction between theory and practice. In this sense, researchers cannot be deemed to be objective or value neutral (Peters et al., 2013). Research commences "conversations" within a "community" of scholarship based on assumptions. Constructivism constitutes not only a theory but methodology as well (Mir & Watson, 2000).

Bryman (2016) writes in his description of constructionism that constructionism is often referred to as constructivism. However, these two terms are not interchangeable, as there are differences between these two theories. Constructionism is a theory of learning developed by Seymour Papert on the basis of Piaget's constructivism. Constructionism adds to constructivism that learning happens by conscious engagement of learner into expressing of ideas, in other words learning by doing (Ackermann, 2001).

Realism is often seen as the opposite of constructivism. According to realism, the world is real and not constructed. Everything that we perceive with our senses is real and exists. Knowledge and truth are based on the real world, and do not depend on constructions nor change by culture or history. On the scale of theories there are different realism theories (Hunt, 2016). Naive realism asserts that reality is almost exactly represented by current theories (Peters et al., 2013).

Critical realism adopted a transcendental realist ontology and an eclectic realist/interpretivist epistemology (Easton, 2010). Critical realism is a philosophical theory devised by Roy Bhaskar, in collaboration with Margaret Archer, Mervyn Hartwig, Tony Lawson, Alan Norrie, and Andrew Sayer (Gorski, 2013). Although constructivism and critical realism are opposite, they have some similarities as they both are anti-positivist (Kwan & Tsang, 2001), non-reductionist, and share a common notion of ontological realism in relation to the existence of natural phenomena (Mir & Watson, 2000). Differences between critical realism and constructivism are distinctive in their relation to epistemological relativism where knowledge is seen as concept-dependent and fallible. Epistemological relativism is accepted by critical realism but not blindly accepted by constructivism (Kwan & Tsang, 2001). Critical realism and constructivism differ from each other in asserting if social structures and practices have causal powers in the social world. Critical realists agree but constructivists disagree with such causal powers. Critical realism asserts an underlying order of things, which is independent from mind and is graspable by research, particularly in relation to the natural world (Peters et al., 2013). Critical realism introduced an ontological stratification by which the reality is represented by various layers or ‘‘strata’’ in the natural and social worlds. Ontology is layered into three levels: the real (phenomena generating mechanisms), the actual (occurring events), and the empirical (experience of these events) (Bhaskar, 2008). The social reality depends on people and concepts, but there is an unfolding objective world order which is structured in a hierarchy of interacting domains and strata (Hartwig, 2015). In the early 2000s developed a new philosophy — complex integral realism which is a pollination of three integrative metatheories, such as Roy Bhaskar's critical realism, Ken Wilber's integral theory, and Edgar Morin's complex thought (Marshall, 2016). Integral theory (see p.21) contains some aspects of critical realism and quantum mechanics (Wilber, 2019). Case studies often benefit from accepting critical realism as their core philosophical position (Easton, 2010).

Relativism is an epistemological term used to describe ideas about the relation of truth and observer, which is seen as relative. Relativists argue that beliefs influencing human behaviour are relative to the social value system and norms (Ryan et al., 2002). Especially in social science by describing methodological approaches is the word "relativism" often used by scholars without clarity about the possible meaning of relativist position on the scientific knowledge (Jackson, 2015). The reason why prevailing neopositivist theory is against relativism might be a profound misunderstanding of methodological diversity and its consequences as Jackson (2015) argues: "The danger is not relativism; the danger is the potential myopia produced by a methodological and theoretical monoculture" (p. 21). Grounded theory, discovered by Glaser and Strauss in 1967 (Glaser et al., 1968, p. 364), represents an example of a compromise between extreme empiricism and complete relativism (Glaser & Strauss, 2017).

2.1.4 Empiricism and Rationalism

Empiricism and rationalism are two philosophical concepts about the nature of knowledge, and therefore, they belong to the field of epistemology. Empiricism is the view where knowledge is gained by observation and by sensing the world directly with our senses. Empiricism as a concept has been used already by Aristotle (384-322 BC) and generally played an important role to the history of science, as various scholars have preferred empirical testing of knowledge to just cognitive experiments or rational calculation (Hjørland, 2005). The inclination of scientific investigations to "value free" science has beaconed to positivism which is one of the most significant philosophical movement in the last two centuries (Ryan et al., 2002). Despite this fact, as with every philosophical theory, empiricism is criticized by some scientists. One of the most known philosophers who criticized empiricism was the American philosopher Wilfrid Sellars (Sellars et al., 1997).

Empiricism is often contrasted with rationalism. Rationalism is the philosophical view where knowledge arrives from logic and a certain kind of intuition - an immediate knowing something to be true without deduction. Already the Greek philosopher Plato (429-347 BC) emphasized mind's rational abilities and logical intuition. However, the term "rationalism" has been first used by the French philosopher-mathematician Rene´

Descartes (1596–1650) while defining his world view (Ryan et al., 2002). Rationalism in its extreme form does not accept any experiences because sense perceptions are not provable without preliminary concepts. Geometry represents an example of science which is possible to construct without any observations (Hjørland, 2005).

However, in practice almost all philosophers and scientists use a combination of empiricism and rationalism. Rationalism and empiricism both play a role in science, though they correspond to different branches of science. Rationalism corresponds mostly to mathematical analysis, whereas empiricism corresponds to experiments and observation. Of course, the best route to knowledge combines rational contemplation and empirical observation. Rationalists and empiricists agree on that; they just disagree on which one is more important (Hjørland, 2005). Rationalism in the twentieth century has been epitomized by logical positivism, which attempts to unite rationalism and empiricism (Smith, 1986). Constructivism is another effort to combine empiricism and rationalism. For a description of constructivism see the previous section, Critical Realism, Constructivism, and Relativism.

Controversies between rationalists and empiricists were resolved to some extent by Immanuel Kant (1724–1804) who tried to show that empiricism and rationalism were both true in their own ways. Metaprinciples, as a part of Kant's philosophy, allow us to establish a relation to and sense of the world what we experience. People learn about the world from observations, but observations are also based on specific ways of innate reasoning. This way Kant agreed with rationalism that knowledge is proceeded by thinking mind and that way reality is mentally constructed. Kant's transcendental idealism was not the final solution to the debate between empiricism and rationalism but definitely influenced many social thinkers (Ryan et al., 2002).

2.1.5 Integral Theory

Integral theory is a school of philosophy which seeks to joint "… assets of premodern, modern and postmodern thinking systems; and helps in going beyond the nowadays syncretism of many perspectives" (Gallifa, 2019, p. 15). The word "integral" originated from late Latin integralis, from integer "whole" and signifies "Necessary to make a whole complete; essential or fundamental" with attributes, such as "Having or containing all parts that are necessary to be complete", and/or "Included as part of a whole rather than supplied separately" (Lexico, n.d.) . Integral theory started in the 1970s with the publication of The Spectrum of Consciousness (Wilber, 1993) and was further developed by the work of Ken Wilber (Wilber, 2000a, 2000b, 2019) and other philosophers and thinkers (Gallifa, 2019; Grof, 2016; Marshall, 2016; Murphy, 2011).

The core of the integral theory builds on the foundations of evolutionary theory, expending the theory from the exterior forms of reality (matter and organisms) to the interior spaces of reality, namely in the development of culture and consciousness. A comprehensive map of human potentials distills the major human growth components into five factors, namely quadrants, levels, lines, states, and types. Wilber, in his "all quadrants, all levels" (AQAL) approach defines nine altitudes of development containing three states of consciousness (tiers) and introduces four quadrants of reality. The grid of the quadrants, along the axes of interior-exterior and individual-collective, offers four complementary perspectives upon which all human knowledge and experience might be placed (Wilber, 2000a). The individual perspective refers to the interior-individual (thoughts, emotions, state of mind, perceptions, etc.) and the exterior-individual (aspect of individual as subject and object, or aspect of depth and surface). The collective perspective refers to the interior-collective (cultural, e.g. shared values, language, relationships, cultural background, etc.) and the exterior-collective (social, e.g. system, networks, technology, government, etc.) (Wilber, 2014a).

The four quadrants jointly represent a holon. The integral thinking uses the concept of the holon where holons are complete entities or unities of consciousness seen as whole/part. Each holon is made up of smaller holons and also incorporated in larger holons (Wilber, 2000a). Every holon contains four dimensions: agency, communion, self-transcendence, and self-dissolution or self-immanence (Gallifa, 2019). The agency, named by Wilber "deep structure" is the tendency of each holon to be whole, structuring, and optimized. The communion dimension is evolutionary and represents the holon's tendency to the relationship with other holons. The self-transcendence brings the holon's ability to change. In contrary, the fourth dimension, self-dissolution focuses on the preservation of itself, of the current level, but also the potential to evolve (Gallifa, 2019).

2.2 Research Approaches – Research Strategy

Every research is a process of finding answers to one or more research questions. The way how researchers approach the process is based on the idea of research strategy. Research strategy is a description or distinction of different ways of how researchers construct the research. Quantitative and qualitative are two main identified research strategies.

Quantitative research strategy uses, as the name already suggests, measurements and quantitative methods for the analysis of data. The researched phenomena is fragmented into measurable or common categories, which are applicable to other subjects or similar situations (Winter, 2000). Quantitative research attributes are validity and reliability. "… The aggregated definition of 'validity' could be that of accuracy, and the definition of 'reliability' that of replicability" (Winter, 2000, p. 3). Often is quantitative research understood as the traditional scientific method because from epistemological orientation it has adapted natural science methods, particularly positivism. Quantitative research strategy is explanatory. This means that the research explains and tests propositions and hypotheses, which are drawn from precise aims and objectives by which it utilizes a deductive form of reasoning. Quantitative approach's ontological orientation is objectivism (Bryman, 2016).

Qualitative research strategy is exploratory, and usually draws attention to words than to quantifications. However, qualitative research needs to test and demonstrate its credibility, transferability, and trustworthiness (Golafshani, 2003). The exact definition of qualitative research is not possible as qualitative research is based on different theoretical perspectives, methodologies, and methods (Koro-Ljungberg & Douglas, 2008). Qualitative research refuses positivism, and is often based on interpretative epistemological orientation. The question of relationship between theory and research is approached from an inductive way of reasoning to assess individual interpretations and generate new theory (Bryman, 2016). Diverse techniques for collecting, analysing, interpreting, and reporting findings have been developed for qualitative research strategies to study people in their natural settings, or clarify phenomena in relation to people and their understanding (Denzin & Lincoln, 1994). Qualitative research comprises naturalistic, interpretive approach to the subject that is researched and prioritize the data contribution to existing knowledge (Higgins & Green, 2011). Constructivism represents the qualitative ontological orientation.

Quantitative and qualitative research strategy might be combined in mixed methods. Mixed methods are often used by researchers to comprehend different epistemological and ontological orientations. By designing a mixed method, the researcher often uses visual models with mixed methods notations (Creswell & Creswell, 2017; Morse, 1991). For the mixing of methods, there is no limit as it depends on the researcher what he/she chooses for supporting of the theory or developing of a new theory. "Quantitative methods might be used to embellish a primarily qualitative study" (Creswell et al., 2003, p. 167) or vice versa.

The type of the mixed method depends on theoretical perspective, priority of research strategy, sequence of data collection implementation, and the moment of data integration, as shown in Table 3. Theoretical perspective is drawn from the position of theory in the research. By explicit perspective the research is firmly based on a theory which is presented in beginning sections as a tread which will guide the study. By implicit perspective the research is only indirectly based on a theory (Creswell & Creswell, 2017). The next factors determining the type of the mixed method is which strategy plays the prior role to the research (quantitative, qualitative, or both strategies equally), and which data collection comes as first (quantitative, qualitative, or no sequence). Finally, the point at which data are integrated into the research has an influence on the type of the mixed method. Data might be integrated into the research at data collection, data analysis, data interpretation, or with some combination of these points (Creswell et al., 2003). Creswell uses the four criteria (implementation, priority, integration, and theoretical perspective) to specify six major mix research strategies:

- Sequential Explanatory Strategy
- Sequential Exploratory Strategy
- Sequential Transformative Strategy
- Concurrent Triangulation Strategy
- Concurrent Nested Strategy
- Concurrent Transformative Strategy

Table 3

Mixed-Methods Research Strategies

Mixed method	Theoretical perspective	Priority of strategy	Sequence of data collection implementation	The point at which the data are integrated
Sequential Explanatory Strategy	explicit	equal	quantitative first	during interpretation
Sequential Exploratory Strategy	implicit	equal (but can be given to either)	qualitative first	during interpretation
Sequential Transformative Strategy	The theoretical perspective guides the study.	to either or both	no sequence	during interpretation
Concurrent Triangulation Strategy	confirmation, corroboration or cross-validation	equal (but can be given to either)	two concurrent data collections	during interpretation or analysis
Concurrent Nested Strategy	A theoretical perspective may or may not guide the design.	to the primary data collection approach	two data collections, one embedded (i.e., nested) within the other	data are mixed during the analysis phase
Concurrent Transformative Strategy	The specific theoretical perspective guides the study.	equal (but can be given to either)	two concurrent data collections	during analysis or possibly during interpretation phase

Note. Adapted from Terrell (2012).

One of the mixed methods often used in construction is Triangulation with two concurrent data collections by which priority of strategy should be the same but might be given to either quantitative or qualitative methods (Fellows & Liu, 2015).

2.3 Influences on Research

Research is a cognitive process often influenced by ontological and epistemological beliefs, which might not always be recognized (Bryman, 2016). Research is done by a researcher who is not isolated from society and environment. Therefore, research is influenced to a greater or lesser extent by exterior and/or interior factors, by environmental and/or subject variables. The fact that the observer might influence the observation, especially by qualitative studies has been documented by Mayo (2014) and described by Jorgensen (2015). However, there are still questions remaining about how and to what extent this influence takes place. Quantum physics studies have brought an explanation to the phenomenon of “participating observer” on the quantum theory level (Stapp, 2011). Values and science influence each other reciprocally. Values are based on science, knowledge, and human beliefs. However, science is influenced by values which reveal themselves for example in choices of research area, strategy, methods, in the formulation of research question, or in the interpretation of data (Bryman, 2016). Scientific research intention is to be objective, however, contextual factors, such as environmental and subject variables, even by strict precautions have influence on research results (Fellows & Liu, 2015).

Environmental variables are very important to be considered. This study has been confronted with an influence of uncontrollable factors, such as outdoor RH and temperature, evaporation rate of the humidifier, and generally outside weather conditions. This fact was noticed to have an influence on results. However, as this research intended to imitate real house conditions where uncontrollable variables are always present, environmental variables have been welcomed as a part of real weather influence and an imitation of uncontrollable behaviours of occupants.

2.4 Research Design

Research design is the underlying structure of the generation of evidence that leads to answering research questions. The chosen framework for the collection and analysis of data has to follow certain quality criteria, such as validity, reliability, and replication. The chosen methods have to evaluate causal connections between variables (Bryman, 2016). Research methods are sometimes called research style or strategy, which is a technique for collecting and analysing data. The main research design styles are: survey, experiment, quasi-experiment, archival analysis, history, and case study (Yin, 2017). Runeson and Höst (2009) distinguish between theoretical and empirical studies, and compare survey, experiment inclusive quasi-experiment, and action research with case study. Unfortunately, definitions of research styles vary, therefore, it is not possible to set clear boundaries between the styles (Fellows & Liu, 2015). From growing computation of data and developing of computer software, a new entity arisen in the scientific world - simulation. Modelling and simulation reside in the intersection between theory and experiment (Morgan & Morrison, 1999).

2.4.1 Survey

Surveys are usually based on statistical sampling, as full population surveys are not possible from practical or economic reasons. Surveys are proceeded through questionnaires or interviews. By the survey it is crucial to choose a representative sample to assure the validity of data. Sample size, response rate, and the number of obtained responses should be considered regarding to the subject matter of the study (Fellows & Liu, 2015).

2.4.2 Experiment

Experiment is: "1. A scientific procedure undertaken to make a discovery, test a hypothesis, or demonstrate a known fact. 1.1. A course of action tentatively adopted without being sure of the outcome" (Lexico, n.d.). What all experiments have in common is that they vary something (cause) to discover what happens to something else (effect). Causal relations are very often not as simple as sometimes a combination of certain causes is required for an effect to happen. This means that many causal relations are context dependent and we rarely know all of the factors and how they interact (Shadish et al., 2002). Although cause and effect are a part of the everyday life, scientists and philosophers are still not in agreement about clear semantics for causal relationships. The Scottish philosopher David Hume (1711-1776) described causation in a counterfactual model (Hannart et al., 2016). "Counterfactual" expresses something contrary to fact. The logical structure of counterfactuals is the mathematical basis of causal theory. David Hume defined causality as "Y is caused by X if Y would not have occurred were it not for X" (Hannart et al., 2016, p. 101). The counterfactual reasoning is based on fundamentally qualitative causal reasoning, therefore, the counterfactual reasoning in experiments is fundamentally qualitative (Shadish et al., 2002).

Experiments in their classical form tend to hold a strong internal validity. To prove the external validity of the experiment there has to be a control group of data besides the experimental group of data. According to the place where experiments proceed, a distinction between laboratory and field experiments is made. As the term suggests, the laboratory experiment is carried out in laboratory controlled settings, and the field experiment in real-life settings (Bryman, 2016). Laboratory settings offer a possibility to test causal relationships between variables by changing only one independent variable and holding all the other independent variables constant. That way, influences from other independent variables are eliminated. However, the laboratory settings, although proving causalities between two variables, are often not reflecting the real-life situation where multiple variables might independently change and influence the dependent variable. Such experiments are called quasi-experiments. By quasi-experiments the possibility to control independent and environmental variables is constrained (Fellows & Liu, 2015).

The counterfactual framework, the econometric tradition, and the structural causal model (symbiosis between these two models) framework constitute current approaches to causal analysis (Pearl, 2009). The structural causal model framework enables a combination of data from different research designs, which is essential by analysis of big data. This way, data from multiple heterogeneous datasets, such as data from observational and experimental studies, dissimilar populations, and sampling selection bias can be used for one causal analysis (Bareinboim & Pearl, 2016).

Very often a correlation is used in studies to demonstrate the dependency of two variables. However, we have to keep in mind that correlation does not prove causation as correlation does not say which variable came first, and if there are other factors influencing the relation of these variables. Thus identification and understanding of different elements, which may have influence on the outcome of the experiment, constitutes a central task in experimental research (Shadish et al., 2002).

The experimental design has two basic forms: classical experiment and quasi-experiment. Quasi-experiments are similar to controlled experiments, as their primary objective is explanatory, primary data quantitative, and both have fixed design. The exception by quasi-experiment is that subjects are not randomly assigned to treatments. Quasi-experiments conducted in an industry setting are sometimes called case studies as they may have many characteristics in common with case studies' research strategy (Runeson & Höst, 2009).

Generally, the experimental design follows certain stages. In the first stage of the experimental design the aim of the research is determined. The aim of the experiment may be to test a theory, hypothesis, or claim. Before the actual experiment could be started, the researcher has to specify the objectives of the study to decree what is to be tested. By this stage limits of the test are specified. Based on theory and literature review, the researcher identifies variables and formulates the hypothesis. After the theoretical preparation the decision about the experiment procedure is made, inclusive practical thoughts about the length of the test, time, necessary equipment, and costs involved. By conducting the experiment, all possible effort has to be put into sustaining constant known conditions to assure the validity and consistency of results. The monitoring of conditions and accurate collecting of data is an essential precondition of data analysis which is the next stage of the experimental design. After testing the hypothesis with appropriate analytical and statistical tools, the results are discussed in relation to conditions of the experiment and to existing theory. On the base of results and the existing knowledge researcher decides whether to accept, reject, or suspend judgement on the hypothesis. In conclusions are incorporated restrictions and constraints on conclusions due to objectives and limits, used methodology and methods. During the last stage of experimental design researcher depicts recommendations for future research (Fellows & Liu, 2015).

2.4.3 Case Study

Case study is traditionally connected to the qualitative research style. However, there is no scientific consensus about case study definition. The reason for that is that case study as a research style may relate to more than one epistemological view (Mitchell, 1983). Easton (2010) defines a case study as:

> Case research can … be defined as a research method that involves investigating one or a small number of social entities or situations about which data are collected using multiple sources of data and developing a holistic description through an iterative research process (p. 119).

Yin (2017) describes a case study as the ethnographic, clinical, participant-observation, or otherwise “in the field” research which method is qualitative. George and Bennett (2005) state that the research of case study is characterized by process-tracing and define a case as an instance of a class of events what refers to a phenomenon of scientific interest. These definitions are seen by Gerring (2004) as certain kinds (subtypes) of case studies. Although agreeing with the definition of case study as an investigation of a phenomenon, instance, or example, Gerring (2004) proposes "… to define the case study as an intensive study of a single unit for the purpose of understanding a larger of (similar) units" (p. 342).

Runeson and Höst (2009) characterize case study as a flexible type of study, which is coping with complex and dynamic real-world phenomena, has its conclusions based on clear qualitative or quantitative chain of evidence, and is based on theory or develops new theory. Case study is distinguished by an in-depth investigation of a system in which boundaries may be determined in terms of time, space, or participants (Merriam, 2002). Case study may be rather seen as a frame providing boundaries for the study than certain research method. The case study gives direction to the research with many kinds of insights based on a different kind of information. The case study does not analyse causal relationships as the experiment offers, but it is possible to include an experiment into a case study. There are no strict rules, therefore, any method for the data gathering, such as interviews, observations, statistics etc. can be a part of a case study (Thomas, 2015).

George and Bennett (2005) identify four advantages of case studies which make them utilitarian especially in testing hypotheses and for developing new theory. Case studies have the potential to achieve high levels of conceptual validity, develop new hypotheses, exploring causal mechanism under certain conditions, and assess or model complex causal relations. On the other hand, case studies are weak at assessing how much the causal weight of variables is. An exception to this limitation represents the situation when a very well controlled comparison data about only one independent variable is available, alternatively, when very similar cases differ in only one variable. In such situation case study may be more persuasive about an estimation of causality. Other weakness of case studies may be seen in selection biases in the statistical sense. However, a case study with its assessing how and whether a variable mattered to the outcome is sometimes deliberately choosing cases on the dependent variable (George & Bennett, 2005).

2.4.4 Analysis of Knowledge

Critical analysis of literature, history, and archival documents depicts a crucial component of research in any discipline. To assess current knowledge, theory development, and areas where further research is needed, it is vital to establish a set of methodological principles which are relevant to the research. Literature review enables to understand the research topic, what and how it has been researched. The process of literature review is iterative and has two phases – a literature search and literature review. The literature search is a systematic search that includes justifiable vocabulary and is based on a robust scheme for the management of information. A literature review is a critical evaluation of synthetized and analysed existing knowledge, theories, and methods. Scholastic (traditional) review and interventionist (systematic) review are two main types of literature review (Hart, 2018).

The scholastic literature review is about an acquisition of knowledge and an enhancement of understanding through reading existing contemporary and previous research, history, and archives. Other objectives of the scholastic review might be examination and evaluation of theory to describe a phenomenon or inform research. The interventionist literature review is often but not exclusively used in medical and social sciences, or by different government departments. More commonly term used for interventionist review is "systematic review" or "evidence-based practice". Interventionist review is usually presented in an article or research report to guide decision making by providing evidence from primary research or evaluation. Literature review needs to be clear, consistent, and coherent (Hart, 2018). A combination of scholastic and interventionist review is called integrative research.

Meta-analysis is a kind of systematic review using usually statistical analysis. Meta-analysis is a method based on a statistical combination of results from separate studies. Alternative methods to Meta-analysis are: Mante-Haenszel method, the Peto method, and the Random effect inverse-variance model (Higgins & Green, 2011). These methods are mostly used in medicine studies; therefore, no further description of these methods is part of this thesis.

2.4.5 Simulation and Modelling

Computer simulations are techniques for studying complex systems which are translated into mathematical functions (Winsberg, 2003). Simulations are based on the existing knowledge, as computer software is an expression of the theory. Therefore, the epistemic value of the new knowledge produced by modelling is not better than the theory from which calculation originated. However, results retrieved from the simulation may have sources independent of the theory, as the computer program reflects theoretical assumptions used by its creation (Humphreys, 2004; Morgan, 2002; Winsberg, 2010). Model and its associated implementation in software are an expression of theory, theoretical ideas, analogies, encoding, ingenuity, and necessity (Roush, 2017).

In the last two decades, a philosophical discussion developed between scientists about the epistemic superiority of experiment over the computer simulation. The privileged status of experiments over simulations is usually based on the mistakenly generalized belief that experiments generate greater external validity, and that experiments are the only source of truly new insights (Parke, 2014).

Epistemically there is no difference in the value of simulation or experiment because simulation may be viewed as an experiment – virtual experiment. Roush (2017) argues that this is only truth for the use of simulation for explorative purposes, or as a tool to support classic experiments, or for pedagogical reasons. Roush (2017) implies that "The superiority thesis I will defend concerns simulations that aim to answer a specific, determinate question about the actual world, a question of the sort an experiment is often used to answer" (p. 2). In any case, modelling and simulation should never intend to replace actual experiments in the real-world. As research tools, modelling and simulation provide additional insights, serve to compliment experimental and theoretical scientific methods, and inform theory.

2.4.6 Evaluation of Theory

The consideration of the relationship between theory and research is based on reflection on what type of theory and what approach is used. Theory is a statement of ideas about how, why, and when constructs or variables relate to each other or more detailed, "…. a theory may be viewed as a system of constructs and variables in which the constructs are related to each other by propositions and the variables are related to each other by hypotheses" (Bacharach, 1989, p. 498). Variables mean units which are observable and measurable. Constructs are approximated units which are not possible to observe directly (Bacharach, 1989). Constructs have two types of meaning – systematic and observational (Kaplan, 2017). Systemic meaning reflects the theory in which the construct is embedded. Observational meaning refers to the notion that a construct, in order to have an explanatory power, has to be directly or indirectly operationalized (Torgerson, 1958). In other words, if a construct has no systemic meaning, it is just an observation, and if a construct has no observational meaning, it is solely a metaphysical term (Peter, 1981).

In empirical sciences, scientific statements are represented by hypotheses or systems of theories which scientists test against experience by observation and experiment. A hypothesis is "… a supposition or proposed explanation made on the basis of limited evidence as a starting point for further investigation" (Lexico, n.d.). From a new idea formulated as a hypothesis or theoretical system, conclusions are drawn in the process of logical deduction, which have to be critically tested. The testing of a theory may be done in four different ways. Firstly, the internal consistency of the system is tested by a logical comparison of conclusions among one another. In the second line, the logical form of the theory (for example: empirical, scientific, tautological) is explored. The third way consists of the question if the theory is of scientific advance in comparison to other theories. Fourthly, empirical applications of conclusions, which can be derived from the theory, are tested (Popper, 2005, p. 9).

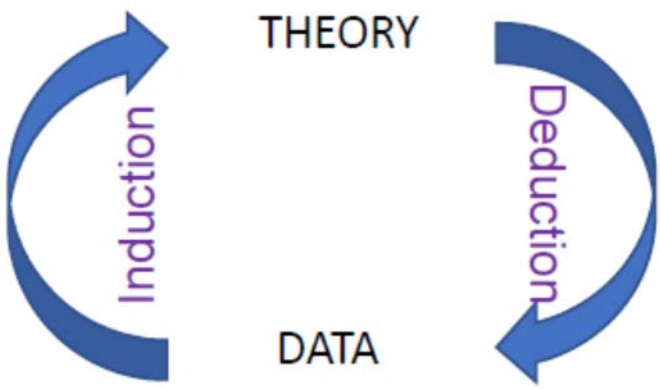
Deduction, induction, and abduction are forms of inference from the cognitive process or forms of reasoning. The deductive approach represents a research process by which theory guides the research. By the inductive approach, theory is the research outcome. The abductive approach is comparable to induction. However, it may be rather subjective and not based on statistical data (Fellows & Liu, 2015).

Deductive reasoning is used within the limits of existing theory. The process of deduction involves specific steps: theory, hypothesis, collection of data, findings, a hypothesis confirmed or rejected, revision of theory (Bryman, 2016). Deduction starts with existing knowledge. Based on theory and literature, researcher formulates a hypothesis which represents the focus for the research as it is the case in explanatory studies (Fellows & Liu, 2015). The hypothesis has to be critically examined by using various research approaches and scientific methods. The process of hypothesis's examination is based on the collection of data and their analysis. Findings of the research either confirm or reject the hypothesis (Popper, 2005).

The deduction process might be closed by revision of theory which is already a part of inductive inferences. Inductive reasoning starts with the formulation of a hypothesis and is based on data collection and analysis of real measurements which corroborate the hypothesis and lead to extended knowledge. The hypothesis should be tested before a new theory is formulated. As described, the deductive and inductive reasoning might be combined in a continuous process of extending the existing boundaries of knowledge as shown in Figure 1 which is based on iterative grounded theory (Orton, 1997). Grounded theory, first described by Glaser and Strauss (2017) in 1967, is an inductive approach to qualitative data analysis that aims to develop a theory based on empirical data (Chism et al., 2008).

Figure 1

Reasoning Forms and Their Influence on Knowledge



Some researchers question the validity of the induction process. The formulation of universal statements based on experience, like hypotheses and theories from singular ones, is not logically justified although, an inductive inference can attain some degree of "reliability" or "probability" (Popper, 2005). Popper developed a theory of deductive method of testing where he argues that a hypothesis can only be tested empirically whereby it has been advanced. The validity and reliability are two essential characteristics of any research project. However, the term "validity" has no scientifically agreed definition as validity can be exercised differently depending upon stages of the research process and the research strategy being used (Winter, 2000).

Abductive reasoning is a creative process of discovery which has been first defined in 1903 by Peirce (1997) in Harvard lectures on pragmatism with the title *"Pragmatism as a Principle and Method of Right Thinking"*. According to Peirce, abduction is the only way which creates new knowledge. Abductive reasoning is a logical operation based on causal hypothetical explanation of unexpected observations caused by unobserved causes (Dowson, 2017). Abduction has become a part of the grounded theory as "analytic induction" which is a research process using a comparative method with theory while combining deductive and inductive inferences (Suddaby, 2006). Abductive reasoning process has been the core for developing "systematic combining" where empirical fieldwork in the form of case study is simultaneously confronted with theory (Dubois & Gadde, 2002).

2.5 Methodology of the Research

Ontological position of this research is objectivism and epistemological perspective is based on integral theory. This research reasoning is fundamentally qualitative as it is based on causal reasoning, which is fundamentally qualitative (Shadish et al., 2002). The main theory is based on the following reasoning: when materials used in the building envelope have a significant influence on the hygrothermal performance of the building, then targeted specification of these materials during the design stage of construction has an influence on the as built hygrothermal performance. Therefore, the design of sustainable buildings cannot be done without hygrothermal modelling. A theoretical perspective, such as a conceptual framework for allowing interoperability through the BIM platform guides the study.

This research uses quantitative methods for testing the hypothesis. Prior to the decision about the research style, thoughts have been done about what design of the study would suit the research aim the best. This research utilizes a model of research strategy where experimental and simulation design are combined. A real-life setting was chosen for the generation of evidence that leads to answering research questions. The intention is to demonstrate the importance of using simulation during the construction design process because there are significant differences between materials regarding to their relation to water vapour. The in-field experiment delivers data not only for the testing of the hypothesis but for comparison to simulation data as well. Therefore, for the collection of data, a combination of experiment and simulation was chosen.

The data collection for this research is done in two sequences:

1. Step: the in-field/quasi-experiment with real-life experiment collecting data about the causal relationship between building materials and relative humidity.
2. Step: the simulation as a virtual experiment using the hygrothermal model for simulation of the quasi-experiment.

These steps rest upon inspecting the theoretical and practical understanding for the objective by analysing the reviewed papers and the background of building physics, building materials, moisture buffering, mould growth, BIM, and hygrothermal modelling.

The experiment is done in a real-life situation. Such experiments are called quasi-experiments or in-field experiments. To critically test the hypothesis the experiment style contains a combination of a virtual and in-field experiment. As the aim of the study is to demonstrate that expanding BIM in terms of the hygrothermal assessment of materials might prevent moisture related problems, the experimental method is applied in two ways. First, for real-life measurements, in-field experiment data are collected, second, for the satisfaction of the aim of the study, simulation data are drawn from a virtual experiment. For data analysis, this study chooses deductive reasoning methods, and statistical methods, such as analysis of variance and covariance. The used methods serve to the testing of empirical applications of conclusions which are derived from the theory, and to the evaluation of causal connections between variables.

The chosen framework for the collection and analysis of data follows quality criteria, such as validity and reliability. Particularly, in the initial stage of the research, which involves data gathering, the aim constitutes a high level of descriptive and interpretative validity with factual accuracy in the description and interpretation of what is observed and experienced.

2.5.1 Reasons for Choosing In-Field Experiment Combined With Simulation

Reasons for choosing in-field experiment and simulation in this research are:

- Testing the hypothesis in real-life situation.
- Testing the hypothesis in virtual-world situation – in simulation.
- Demonstrate that even minor changes to used building materials on the indoor side of the building have a measurable impact on hygrothermal performance of the building.
- Provide an example to New Zealand typical constructions.
- Compare hygrothermal performance of two construction types used in New Zealand.
- Generate new knowledge about different material scenarios.
- Use the experiment data for comparison with the hygrothermal model.
- Conduct induction reasoning about requirements for incorporation of hygrothermal modelling into BIM based on in-field study experience.
- Through creating high quality but imperfect source of counterfactual inference to generate a platform for understanding how this source differs from the treatment conditions.
- To identify the scope conditions of theory and assess arguments about causal relations in a particular case rather than generalize how much RH changes in different scenarios.
- To provide measurements for the demonstration of results from modelling.
- By quasi-experiment the ability to control environmental variables is limited. This corresponds to a real situation in real buildings.
- Testing the hypothesis in a real situation where the goal is to gain data for rather a tendency than absolute data for empirical/statistical generalization.
- The limitation of ability to control independent variables has been purposely chosen to demonstrate the influence of building materials on RH in as-built environment.

This research design is specifically chosen to demonstrate besides the hypothesis's testing the theory in both, sometimes controversially seen research styles, such as experiment and simulation. Not many researchers have an opportunity to face an other-things-equal comparison from practical reasons, such as feasibility, budgets, and boundaries (Roush, 2017). Through this combination of methods, new knowledge has been gained.

2.5.2 In-Field Experiment Design

Research design style generally represents the underlying structure of the generation of evidence that leads to answering research questions. This research uses experiment and simulation design style.

Aim

The aim of the experiment is to test the hypothesis.

Objectives

In the experiment, the relations between indoor RH and different building materials are tested. RH levels are measured by four different scenarios in two buildings. The scope of the experiment is limited by the technical equipment and by the influence of weather as the experiment proceeds over a time span of seven weeks. As only one humidifier is available, it is not possible to test the same scenario in two houses simultaneously.

Variables

RH represents the centre of the research interest. However, as the indoor RH is influenced by temperature and outside humidity, these variables depict another vital part of the monitoring. Diverse building materials epitomize other variables described by their physical characteristics, such as water vapour resistance factor, permeance, density, etc.

Hypothesis

"Materials used in the building envelope have a significant influence on the hygrothermal performance of the building."

Experiment Design

The research measures indoor RH, temperature, and due point by different room scenarios in two test houses while introducing water vapour into the room to simulate occupancy. The test houses are identical in size and cardinal direction but not identical in construction. Measurements for each scenario are done every hour for five consecutive days. The intervals are chosen with regards to data analysis and comparison requirements to data from the simulation. The length of each test is chosen with regards to practicability and the total time of the experiment. The experiment design is described in detail in Chapter 4 (p. 118).

Conduct of the Experiment

During the experiment, all possible effort is made to maintain constant and known conditions to achieve high validity and consistency of results. The mechanical ventilation is switched off and ventilation out- and in-lets are sealed with plastic foil. No unauthorized person has access to the testing room and test houses in general. The data are collected and after each testing period downloaded from the EasyLog USB to a computer.

Data Analysis

For data analysis, the research uses EasyLog, Excel, and IBM SPSS Statistics software. The combination of these analytics tools enables the researcher to conduct a multilevel analysis using statistics, visual methods (descriptive geometry), and deductive reasoning.

Discussion

Discussion part of the experiment consists of a comparison of RH levels by different scenarios in the context of existing knowledge. Some thoughts are given to the presumable influence of experimental conditions on results.

Conclusion

Based on the results of the experiment, the analysis of data, and the discussion conclusions are drawn.

Limitations of the Experiment

The major limitation of the experiment is that the maximum reached RH is not applicable in any generalizations or as a ground for any decisions about the materials. The reason for this limitation is that many factors, some of them uncontrollable, such as weather, initial temperature, initial RH etc. have an influence on the maximal level of RH.

Further Research

Based on experiences from this experiment, further testing with more sophisticated humidifiers running in both buildings simultaneously is advisable.

2.5.3 Simulation Design

Modelling and simulation, although based on existing theory, provide additional insights, serve to compliment experimental and theoretical scientific methods, and inform theory.

Aim

The aim of the simulation is to test the hypothesis and provide data for comparison with experiment data.

Objectives

In the simulation, the relation between indoor RH and different building materials is tested. RH levels are simulated for four different scenarios in two types of construction.

Variables

Variables for simulation are set the same as in the experiment (see p. 38).

Hypothesis

“Materials used in the building envelope have a significant influence on the hygrothermal performance of the building.”

Simulation Design of This Research

The research uses for the simulation WUFI Plus, which is a software developed by the Department of Hygrothermics at Fraunhofer IBP for hygrothermal modelling (Fraunhofer Institute for Building Physics, n.d.-e). WUFI Plus is a holistic model based on the coupled heat and moisture transfer model developed by Künzel (1994). Prior to performing the dynamic simulation, specification of boundary conditions and construction data inclusive room geometry, cardinal direction, construction details, and material properties, such as water vapour resistance factor, the geographical location of the house, etc. are required.

Conduct of the Simulation

During the experiment, all possible effort is made to achieve high validity and consistency of results. The WUFI software has been validated worldwide (Antretter et al., 2011; Marincioni et al., 2014). WUFI Plus provides a realistic simulation of hygrothermal performance of buildings under realistic climate conditions in the specific location as described in Chapter 5 in detail.

Data Analysis

For data analysis, the research uses WUFI Plus software. The software models the coupled heat and moisture transfer in the building envelope. It calculates diffusion, vapour adsorption and desorption, thermal performance, and capillary action. The coupling of heat and mass transfer represents a strong feature of the model (Antretter et al., 2011).

Discussion

Discussion part of the simulation compares simulated RH levels by different scenarios among themselves and with measured results from quasi-experiment in the context of existing knowledge. Some thoughts are given to the reasons for differences between model and experiment results.

Conclusion

Based on the results of the simulation, analysis of data, and discussion conclusions are drawn.

Limitations of the Simulation

The simulation software works with weather data based on supplied measurements from Unitec. However, the data set is missing accurate measurements about diffuse and global solar radiation giving only “solar radiation” without any distinction between the diffuse and direct component. Therefore, the data is not fully comparable with the experiment. However, this limitation does not interfere with the validity of simulation data as the weather, although not identical every week, follows a specific pattern typical for the region.

Further Research

Based on the experience from this simulation, further modelling of different scenarios with different materials would be beneficial. The results of such simulation in the form of a table of material performance would provide a supporting tool for architectural designers and specifiers.

2.5.4 Integration of Data

Data from the experiment and the simulation are integrated into the research at two points: data analysis and data interpretation. Reasons for collecting both forms of data are firstly, the comparison of the data in regards to the testing of the hypothesis, and secondly, the demonstration for the usefulness of the hygrothermal simulation for an optimization of the hygrothermal performance of the building. This way, the combination of two data collections serve the aim of this research: to clearly demonstrate that broadening of BIM in terms of hygrothermal assessment of materials applied during the early stage of design might prevent moisture related problems and improve durability and quality of construction.

2.6 Methodology of the Literature Review

The topic of this research is an improvement to BIM with a system extension based on the implementation of hygrothermal aspects to the decision process about building projects. The question on how to use BIM to achieve goals, such as healthy indoor environment, reduction of internal moisture fluctuations to minimize the negative impact of high RH on buildings, improve comfort, and sustainability are addressed. The subsequent step is a specification of requirements for integration of hygrothermal simulation, systems and databanks involving a sustainability assessment in relation to moisture into BIM.

The project started with a literature review on building physics, indoor environment, hygrothermal modelling, mould, condensation, moisture buffering, and BIM with a focus on the implementation of BIM into the construction process. Simultaneously, an analysis was carried out of the most advanced experiences with BIM by institutions and companies already working with this modelling tool. For this purpose, industry related documentation and personal discussions with experts in the field of design, construction and facility management have been conducted.

Further, information has been collected about the properties of construction materials related to hygrothermal modelling, and about the impact of different materials on moisture levels in buildings, ecology, health, and long-term costs. An essential part of the research was a critical review of existing knowledge about complex sustainability assessment including energy and hygrothermal modelling, life cycle assessment and costing. The theoretical knowledge applied and further developed in the study led to the demonstration of significance and feasibility of purposeful choice and placement of building materials to design and build of healthier and sustainable houses.

2.6.1 Methodology of the Literature Review of Hygrothermal Relations in Buildings

To examine the consequences of underestimating or neglecting hygrothermal relations in buildings, a three-step approach has been adopted.

Step 1

The first stage inspected the theoretical and practical understanding for this objective by analysing the reviewed papers and the background of building physics. Several questions related to building performance were asked and answers were provided by the latest research findings and the reevaluation of some older cognizance. For example, this study analysed the consequences of high RH for building structure, energy demands, and humans. Finally, after conducting an in-depth review of the hygrothermal aspects of the built environment, the unintended consequences of climate change, decarbonization process, and airtightness were outlined.

Step 2

Next, this research inspected the potential of selected building materials for passive regulation of RH. Firstly, the current conditions of buildings related to indoor dampness or mould were outlined by reviewing the latest indoor environment reports in different countries, focusing on the cause-effect relationship between indoor parameters, health and wellbeing of occupants. From this review moisture sources and the possibilities for the reduction of indoor RH were compared in terms of mould prevention. The study illustrates the applications of hygroscopic materials respectively and introduces the moisture buffering value theme. Finally, by summarizing the limitations of these characteristics of materials, the study gives a future direction to overcome the existing issues.

Step 3

The final stage discusses a proposed holistic approach to the design process that takes cognizance of the benefits of climate specific design principles and early determination of building materials and their purposeful placement for minimization of condensation and permanent wetting of the walls. This study examines the values of the building performance analyses and building hygrothermal simulation tools. Simulations evaluate the proposed construction and building materials and support decision during the early stages of the design process when the costs for changes in the project are the lowest.

2.6.2 Methodology of the Literature Review of Building Information Modelling (BIM) and Hygrothermal Simulation

To analyse the status quo in Building Information Modelling (BIM) and hygrothermal simulation for building and its possible interoperability with BIM platform, two-step approach has been selected.

Step 1

The first stage evaluated the state of the art in BIM and in hygrothermal modelling internationally and in New Zealand by analysing the reviewed papers and relevant industry documentation. This study focuses on the current situation in praxis.

Step 2

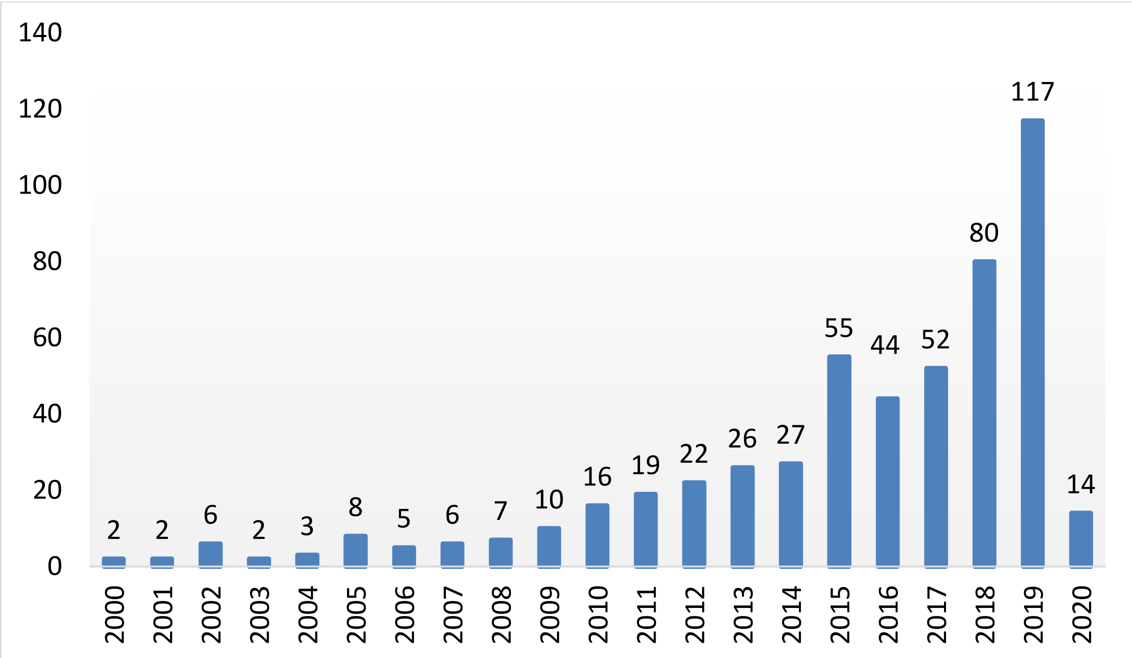
The second stage is based on a discussion on the research question of interoperability between BIM and hygrothermal relations in the proposed building.

2.6.3 Data Analysis

A comprehensive literature search based on the “title/abstract/keyword” search method was carried out. The keywords used in the literature search included, for example, “indoor environment“, “indoor air”, “hygrothermal modelling”, “building energy efficiency”, “mould”, “condensation”, “sick building syndrome”, “building information modelling”, and “moisture buffering”. A range of highly regarded journals appeared in the search including but not limited to: Building and Environment, Construction and Building Materials, Energy and Buildings, Indoor Air, Journal of Building Physics, International Journal of Heat and Mass Transfer, Journal of Building Performance Simulation, Journal of Allergy and Clinical Immunology, and Environment International. After delimitation, a total of 523 papers published from 2000 to 2020 and 31 papers published before 2000 were identified as the most relevant research. Most of the reviewed papers (85%) were published between 2010 and 2020 (see Figure 2). Additionally, 38 actual standards, 138 books, 100 book sections, and 128 other sources, such as conference proceedings, database or reports, dictionaries, a total of 958 (inclusive papers) have been chosen to support this research.

Figure 2

Frequency of Reviewed Publications Between 2000 and 2020 per Year of Publication



2.7 Ethics in Research

This research does not involve the use, collection, or disclosure of Health Information or Human Tissue, nor does it need any approval by an ethics committee because it does not use any tissue bank or database which would require it, nor HRC funding has been applied. Therefore, this research does not need any ethical approval.

Confidentiality of this research is highly respected. All used data about materials and construction are available to the public on the manufacturers' website or have been sourced from existing literature.

2.8 Summary

Research is a cognitive process often influenced by ontological and epistemological beliefs. In other words, the way how the researcher perceives and understands the material and non-material world and life in general. Consideration of philosophical position and methodology constitutes to crucial segments of this research because it is searching a new way to address an existing problem. This chapter focuses on the research perspective and explains how it fits in the general picture. This research perspective is based on integral theory and objectivism. This is conforming with the well approved position of the research in engineering.

This chapter concentrates on providing an overview of the general approach to research and on describing the primary research methods. After the description of research styles and methods, the chosen design of the study, which seemed to suit the research aim the best, is depicted. Realizing that each model should be simplified, this research resorts to experimental design which is combined with simulation design. A real-life setting was chosen for the generation of evidence that is expected to lead to answering research questions. Reasoning about the choice of approach builds a vital part of this chapter, but the researcher also finds that this case is somewhat undescribed in the formal research classifications.

Chapter 3 Theoretical Framework – Literature Review

This chapter addresses the theoretical framework of the study subject. Therefore, a comprehensive review of the existing literature is divided into four major topics. The methodology of the literature review forms a part of Chapter 2 (section 2.6). The literature review starts with an examination of the built environment nature. The investigations are especially related to resources, building materials, and the impact of the building industry on the environment. After the broader description of the sustainability issues, the research narrows to the New Zealand (NZ) construction industry and building physics. The first topic is followed by the review of existing knowledge in hygrothermal relations in the built environment, particularly the consequences of high relative humidity (RH) levels, condensation, and mould growth. Consequently, other moisture related phenomena, such as moisture buffering and sorption active thickness, are reviewed.

The literature review in hygrothermal analysis and modelling forms the third topic of the theoretical framework. The study examines the history and the status quo of indoor airflow models; heat, air, and moisture (HAM) models, and the coupling of these tools. After a description of the models, praxis-oriented themes, such as the influence of hygrothermal interactions and reasons for the limited use of hygrothermal models, are explored. The building information modelling (BIM) and software interoperability constitute the fourth topic of the literature review. After the short description of BIM, history and praxis worldwide and in NZ, the chapter focuses on the interoperability, particularly between BIM and hygrothermal modelling. The conclusions drawn from the literature review delineate the existing gaps in the current knowledge. In the summary the major points of this chapter are outlined.

3.1 The Nature of the Built Environment

Physical, economic, ecological and environmental factors stimulate the improvement of the construction process (Bomberg et al., 2016). Looking back at the beginning of the building industry, the original focus of interest was to enhance the stability and durability of the structure (Bomberg & Onysko, 2002). However, the same economic laws, as in any other branch of commercial activity, determine business-wise the building industry (Kurth et al., 2019). Higher investment efficiency, building cheaper houses in a shorter time, minimizing costs and time by maximizing the gain are the main interests of the stakeholders (Kristensen, 2011; Nuñez-Cacho et al., 2018). In spite of the fact that these attributes are still valid, humanity is facing new challenges. The natural resources are limited and the ecological system of the Earth is heavily threatened (Berthelsen et al., 2020; Rehman et al., 2020). The question, how to create indoor comfort and damage free construction without a negative impact on the ecology and the environment, is motivating research and encouraging changes in the whole building industry (Hart et al., 2019).

One of the suggested ways to reduce the impact of the built environment on nature is the circular economy (CE) concept (van Stijn & Gruis, 2019), first introduced in the 1960s in the United States as a part of the environmental protection movement (Shen & Qi, 2012). The CE approach promotes the transformation of the production model from traditional linear development to responsible and cyclical use of resources (Moraga et al., 2019). Although various definitions of CE have been developed, the applied principles remain the same. The CE principles aim to keep the materials in circulation, remove waste from the cycle for maximum possible time, and minimize the exploitation of primary resources (Kiser, 2016). Additionally, the CE principles might be extended to reduce the embodied carbon in building materials (Densley Tingley et al., 2018). However, the CE principles in the construction industry are used very sparingly, decreasing the applications to waste management only (Adams et al., 2017).

Designing an optimized building in terms of energy efficiency, sustainability, and comfort need comprehension of the building as a part of a complex and interchanging ecosystem (Brauner et al., 2016). Since the 70’s oil crisis, followed by the global warming process, the main interest of governments and research are energy savings and low carbon buildings. Therefore, official bodies in many countries evaluate and supervise the energy efficiency of buildings during the design stage of the construction process (Carlton et al., 2019; Dawood et al., 2013; Thomson et al., 2013; Tonn et al., 2018). However, simplifying the issues to insulation and airtightness only is not the solution (Gasiorowski-Denis, 2015; Hall et al., 2013; Vereecken, Van Gelder, et al., 2015). The praxis has shown that the as-built reality might be different from the designed performance of the building (Bauwens & Roels, 2014; Fokaides et al., 2011;

Hörner & Lichtmeß, 2019). Therefore, Mitterer et al. (2012) argue that "Whether the targeted savings potentials can be achieved in practice depends not only on the used technology but also on degree to which the design process is integrated and on the quality of craftsmanship" (p. 230).

Energy efficiency of residential and commercial buildings is influenced by outdoor climate as well as by the intended use of the building. The climate, which is undergoing significant changes, represents an essential factor in the energy demand of buildings (Fisk, 2015; Levesque et al., 2018; Samuel et al., 2013). The necessary terms, definitions and symbols for the assessment of the building energy performance are provided in ISO/TR 16344:2012 (British Standards, 2012a). However, the scope of building performance objectives became a multidisciplinary task that necessitates an interdisciplinary approach and optimization of all the components and stages in the life cycle of the building (Mendes & Mendes, 2019; Tweed & Zapata-Lancaster, 2018). Not only that, the acceleration of the building performance optimization process requires a holistic and systematic approach (Brauner et al., 2016; Gasiorowski-Denis, 2017; ISO, 2017). A relatively new way of how to enhance building performance depicts the integrated design process. In the integrated design process, several architectural concepts, such as a passive house, solar engineering, and integration of mechanical services, are combined (Romanska-Zapala et al., 2018). It leads to the following research question: What are the steps to design warmer, drier, and healthier houses for NZ context?

The role of the built environment and its influence on ecology are largely determined by resources and materials used during the whole building life cycle (IEA EBC, n.d.). Therefore, the following literature review investigates resources, building materials and their impact on the environment.

3.1.1 Resources and Building Materials

Prior to the twentieth century, most of the building materials were sourced from the surrounding nature (Jester, 2014). However, the development of the chemical industry brought synthetic building materials that replaced and are still replacing a significant part of the natural matter (Zimmer & Ha, 2017). Although plastic and other petrochemical products have many advantages, they purvey a cocktail of irritant, non-biodegradable, and toxic emissions into the environment (Ding, 2019) at every life cycle stage of the synthetic building products (Hess-Kosa, 2017).

Building materials, their sourcing, transport, and waste have an immense impact on the ecological ramifications caused by the construction industry (Heeren & Hellweg, 2019). However, although the building stock represents a significant consumer of resources, the existing buildings incorporate a potential for the future resource supply (Kleemann et al., 2017). Therefore, diverse building stock models are developed, such as bottom-up three-dimensional models and geographical information systems (GIS) data (Heeren & Hellweg, 2019). The purpose of these databases is to determine volumetric and spatial information of the material stocks to enable future use of certain materials. Ostermeyer et al. (2018) developed a component-based building inventory database to reduce both the embodied impact of the building stock and the consumption of resources. The organization of the database distinguishes and clusters the building stock according to building typology, year of construction, and the main building components. For each building component, the database allows for listing the material input and output in the form of waste for diverse refurbishment options. Therefore, the extendable data set enables flexible refurbishment alternatives and their holistic optimization to minimize the environmental or economic impact (Ostermeyer et al., 2018).

However, despite any attempt to manage the building stock, the adopted materials in the building components determine the factual reusability (Akanbi et al., 2019). Consequently, the end of building life decisions about reusability might lead to selective deconstruction and the incorporation of some building parts into the new construction rather than complete demolition. Therefore, a complex analysis using the life cycle assessment tool supports the repurposing decisions to minimize the environmental impact (Assefa & Ambler, 2017). The end-of-life assessment of the building helps to determine the life span of the building materials and the quality of the recoverable materials while the building is still in use (Akanbi et al., 2019). Alternatively, the coupling of radio frequency identification technology with BIM may enable tracking and importing of materials to support the process of reuse and therefore improve their efficiency (Ness et al., 2015).

The building performance evaluation has developed from separated characteristics, such as thermal performance to a system approach where building materials contribute to this system (Bomberg et al., 2017). Therefore, the quality and physical characteristics of building materials represent another field of interest. Researchers and building practitioners are looking for new materials to improve the thermal and hygrothermal performance of the built environment. Most of the targeted and newly developed materials are based on the demand principle. This means that these materials absorb/store surplus of heat energy or moisture and discharge it when the temperature or RH drops. With other words, when needed (Medjelekh et al., 2016; Nore et al., 2017). Such promising materials are many traditional materials (e.g. stone, solid bricks, concrete, timber, and fabrics) and new materials, e.g. phase change materials (Jeon et al., 2019; Salloum et al., 2015; Wu et al., 2018; H. Zhang et al., 2017). Consequently, researchers develop diverse thermal energy storage systems and moisture buffering systems. These systems usually include sensible heat, latent heat, and ventilation systems to optimize the energy use in buildings (Zeinelabdein et al., 2018). However, despite any optimization processes used in the built environment, the construction and buildings have an immense impact on the environment and people.

3.1.2 Impact on the Environment and People

Nowadays, it is no longer sufficient to build a robust and durable construction but simultaneously to eliminate the negative impact on the environment (Adams et al., 2017). Therefore, a sustainable building design focuses on three bioclimatic perspectives, such as ecology, humans, and energy. The bioclimatic aspects allow evaluating thermal comfort of building inhabitants and regulating the temperature by diverse features, such as urban heat islands, roof ponds, and strategic trees and vegetation (Nag, 2019). Generally, the success in the construction of optimized buildings depends on the comprehension of multiple factors inclusive the climate-responsive and climate-adequate design principles (Rempel et al., 2016). Already in 2008, Stopp and Strangfeld emphasized the complexity of the thermal improvements:

> In this context it is not enough to improve the thermal insulation of outside walls, roofs and so on. We have to consider the envelope parts as an element of a reactive surface. It is necessary to prefer a climate-adequate building as opposed to building an adequate air condition. (p. 244)

The motivational research problem behind this statement is the recognition of the fact that many of the modern dwellings do not perform as anticipated during the design stage of the projects. Although written more than ten years ago, the industry is still facing the same problems. The real energy demand of the building is often significantly higher than calculated, indoor air quality (IAQ) is poor, and the running costs of climate-inadequate buildings are high (Hörner & Lichtmeß, 2019; Wingfield et al., 2011; Shui Yu et al., 2012). It leads to the following research question: How can building sustainability be improved based on effective hygrothermal simulation?

Hence buildings are responsible for approximately one third to 40% of the world total energy consumption and about 25% of the greenhouse gas emissions (Levesque et al., 2018; Y. L. Li et al., 2019; Robati et al., 2019). Therefore, energy savings, low and net-zero energy houses are the main focus of architects, designers and engineers (Ajayi et al., 2019). The need for energy efficiency is also recognized and supported by governments and standards, such as ISO/TR 16344:2012 (British Standards, 2012a), ISO 52000-1:2017 (ISO, 2017), and EN 16798-1:2019 (European Standard, 2019). Consequently, with increased energy efficiency, the selection of building materials will gain on importance (Belussi et al., 2019; Bennai et al., 2018). In spite of the fact that the operational energy will be minimized in the future and the environmental impact of the operational face relatively small, the buildings will still have a significant impact on the environment (Ezema, 2019). The embodied energy and durability of materials will more significantly impact the final sustainability measure of the built environment (Crawford et al., 2018; Davies & Trabucco, 2018; Hammad et al., 2018). However, the current life cycle analysis (LCA) confirms that the operational phase still represents the major energy consumer in the life cycle of buildings (Abd Rashid & Yusoff, 2015).

Diverse building materials consist of different amount of embodied energy (Crawford et al., 2018). Nevertheless, the decisions based on this measure might not be correct (Densley Tingley et al., 2018). Therefore, it is crucial to use LCA for the complete assessment of the environmental impact, as the embodied energy index might be misleading (Kovacic & Zoller, 2015). The final environmental impact depends on many factors and is not limited to the climate specific situation, the durability of materials, and the construction methods (in situ or prefabricated) (Abd Rashid & Yusoff, 2015; Utama & Gheewala, 2008). For example, Longo et al. (2020) introduce a user-friendly tool ELISA to improve the estimation of the life-cycle impact of the solar air-conditioning technologies. The ELISA depicts a design tool which might assist the early design phase of heating and cooling systems. Therefore, it enables an energy design optimization process (Mugnier, 2019).

The building envelope plays a crucial role in the energy performance of the house. Therefore, minimizing the energy losses, caused by infiltration, uncontrolled vapour transfer, and condensation are desirable (Bhandari et al., 2018; Domínguez-Amarillo et al., 2019). To solve this problem, air, wind and vapour barriers, retarders and control layers are used. Nevertheless, these membranes are influencing or some of them even blocking the interaction of the building with the environment (Cho et al., 2016). Therefore, the correct ventilation, customized on every building reveals to be vital to enhance building performance and minimize the impact on the environment (Crawley et al., 2019; McNeil, 2018; McNeil et al., 2015). Additionally, sustainable energy system design enables optimization of energy supply and management. Therefore, credible and innovative strategies, and technology, such as solar walls or passive cooling systems might replace traditional forms of heating and cooling in buildings (Maas et al., 2013; Saadatian et al., 2013).

In addition to the environmental pollution and energy demand of buildings (Levesque et al., 2018; Y. L. Li et al., 2019; Lichtfouse et al., 2015), the built environment causes fragmentation and diminution of natural habitat, and therefore, the loss of biodiversity (Zari, 2014). However, on the other hand, the built environment might support biodiversity and serve the human needs for connection with nature in the form of green urban spaces (Lepczyk et al., 2017; Nilon et al., 2017). As the biodiversity offers social, economic and environmental advantages beyond the protection of habitat, its embodiment into the urban environment is essential to the sustainability of the built environment and health of occupants (Hoisington et al., 2019; Opoku, 2019).

Despite the evident impact of the building sector on the environment, society, and the economy, the industry, to make a change, requires instant measures (Mahmoud et al., 2019; Nuñez-Cacho et al., 2018). However, there is an uncertainty about what to be measured because the used indicators may have an influence on the conclusions (Moraga et al., 2019). Nuñez-Cacho et al. (2018) suggest eight dimensions of indicators in the construction industry: negative externalities, emissions, waste generated, energy management, water management, materials management, the 3R principles (reduce, recycle, and reuse), and general indicators of transition to the CE. Mahmoud and Zayed (2017) distinguish and specify seven criteria for determination of buildings impact on the environment. Site, transportation, energy efficiency, water use, material and waste, indoor environmental quality, and building management.

To control and manage the undesirable impacts of buildings on the environment, many sustainability rating and certification systems have been developed. The Building Research Establishment's Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) represent two examples of internationally known sustainability rating systems (Yosun et al., 2018). Green building councils (GBCs) have been formed in the USA, Canada, Japan, Australia, New Zealand, and many other countries (Ade & Rehm, 2019). However, the GBCs are non-governmental organizations, financially dependent on the private sector. They generate income through providing of training, membership, and certification fees. Therefore, the GBCs are not independent research institutions (Ade & Rehm, 2019; Sedlacek & Maier, 2012). In New Zealand Green Star is considered one of the most utilized sustainability assessment tools (GhaffarianHoseini, Doan, et al., 2017). However, the Green Star certification uptake is facing several challenges leading to lack of its attraction to clients and building developers (Doan et al., 2019). For the residential sector, the Homestar rating tool was developed by New Zealand Green Building Council (NZGBC), Building Research Association of New Zealand (BRANZ), and Beacon Pathway (Ade & Rehm, 2019).

Generally, most of the attributes of the assessment tools are based on their local context (Mahmoud & Zayed, 2017). Therefore, the green building industry, similarly to other industries, might benefit from the implementation of a macro-environmental assessment as an integral part of systematic strategic planning. For the improvement of the decision-making process, Ulubeyli and Kazanci (2018) and Mahmoud et al. (2019) recommend fuzzy models of the macro-environmental assessment.

Environmental health represents another aspect of the environmental assessment. "A holistic definition of environmental health would include physical, chemical, biological, social, and behavioural factors that influence the environment" (Schaffer et al., 2018, p. 97). The broad definition of environmental health indicates that buildings have a significant impact on environmental health. Therefore, indoor environmental quality represents one of the most critical characteristics of buildings. Indoor environmental quality (IEQ) is determined by IAQ, thermal conditions, illumination, and acoustics (Lawrence et al., 2018). However, this view is limited to the physical and chemical properties of the indoor environment. The researcher suggests that there are many more aspects of indoor environmental quality. Aesthetics, use of colours, and a functionality of spaces, inclusive intentional zoning should be assessed, in order to achieve a healthy environment for human beings. Some issues connected to public health are addressed by Gibberd (2015), who proposes two measurements of sustainability. Beside the assessment of the environmental footprint, the impact of buildings on sustainability is evaluated by the measure of the quality of life, using the Human Development Index. The capability of buildings to support sustainability is conducted by proposing a Built Environment Sustainability Tool, which combines human development with the ecological carrying capacity. This view of environmental health is broadened by Hoisington et al. (2019) who raises questions about the influence of the built environment on public and particularly mental health.

After the examination of the building sector's impact on the environment, the researcher reviews the nature of the construction industry and buildings in New Zealand.

3.1.3 The Construction Industry in New Zealand

This research is concerned with methods leading to improving the NZ housing quality. The current NZ housing condition might be described as substandard (Chisholm et al., 2019; Leardini et al., 2012). Dwelling and household estimates for the June 2019 quarter show there were 1.9 million private dwellings (homes) in New Zealand (Stats NZ, n.d.-a). A large portion of the NZ housing stock is energy-inefficient, unhealthy, cold, mouldy, and damp (Bennett et al., 2016; Gillespie-Bennett, 2013; X. Li et al., 2019). About 50% of NZ residential houses are affected by mould (Plagmann, 2018). Approximately 10% of total dwellings, constructed between 1992 and 2008 by the use of monolithic cladding contributed significantly to the building failure, known as "leaky building syndrome" (Shi et al., 2017).

The latest BRANZ 2015 House Condition Survey reveals that in 49% of surveyed houses was visible mould and 51% of houses did not heat children's bedrooms (White et al., 2017). The survey emphasizes the fact that mould is a key indicator of poor indoor environmental quality (IEQ), and is correlated to the lack of effective heating, ventilation, and insulation. Therefore, BRANZ research provided evidence to support the Residential Tenancies Act (RTA) changes that are expected by 2019. Consequently, approximately 180,000 residential rentals require upgrades to the ceiling and/or underfloor insulation (BRANZ, 2018). Although the improvements of thermal insulation and heating to existing homes have positive impacts on the health of occupants (Howden-Chapman & Chapman, 2012; Howden-Chapman et al., 2008), there might be diverse "psychosocial factors" linked to affordability and household functioning effects too (Howden-Chapman, 2015). Not deniable, but very often are ignored issues with indoor chemical pollution and radon concentration in well-sealed and insulated buildings (Walls et al., 2014). The solution of this issue offers a holistic approach consisting of coupling airtightness design, high efficiency, and ventilation strategy (British Standards, 2019a; Crawley et al., 2019; Quaglia & McNeil, 2012).

However, the situation of newly built NZ residential buildings is not much better (Cox-Smith, 2015). The number of defects and poor quality, especially weathertightness problems, demand attentiveness (Rotimi et al., 2015). According to the BRANZ New House Owner's Satisfaction Survey, call-backs by new owners reached 88% in 2014. Alarming is the rising up of this percentage compared to 73% in the previous year (Page, 2015). Additionally, to the quality issue of housing NZ experiences a shortage of affordable homes. Therefore, "… the government has proposed a 10-year strategy to build 100,000 affordable homes with the aim of providing assurances that the policy will not contribute to a weakening of construction activity" (Political Risk Services, 2017, p. U2). However, prices of real estate in NZ are continuously rising and pushing the inflation rate up (Susan, 2017). NZ "… average property values rose by 2.4% in the year to September 2019" (CoreLogic, 2019, p. 18).

All homes in NZ, without regard to affordability, have to be built to the minimum legal standards. However, the NZ Building Code is behind the international standards for comparable climate (International Energy Agency, 2017; OECD, 2017). Therefore, the costs over the whole life cycle of the houses built to the minimum legal standards are much higher than by houses built to a higher standard (Ade & Rehm, 2019). The economic consultancy Sense Partners assessed the New Zealand Government's KiwiBuild programme costs over the next 30 years. The estimated financial and social losses from constructing the 100,000 homes to the minimum legal standards compared to the adoption of 6-Homestar independent standard reach more than $680 million (Eaqub & de Raad, 2018). Of concern is the existing resistance of homeowners and building practitioners to improvements and complex solutions (Chisholm et al., 2019).

The other problem with NZ housing is resulting from demographic changes in the population. The resident population of NZ rose since June 2012 from an estimated 4.41 million to 4.79 million in June 2017 (Stats NZ, 2017) and 4.93 million in December 2018 (Stats NZ, n.d.-b). Simultaneously, like many other countries, the NZ population is ageing and NZ is experiencing a significant change in the structure of its population (Statistics New Zealand, 2013). From these population changes unfold increasing demands on housing and communal dwellings. To suit these demands, Yavari et al. (2018) suggest alternative design options inclusive a conversion of existing dwellings based on a life cycle energy analysis.

The environmental impact of the building sector in NZ is gaining importance. A significant number of commercial dwellings demand high energy to operate (Ghose, McLaren, et al., 2017). However, before deciding about office buildings refurbishment, different potential policies concerning not only operational energy but resource management are recommended (Ghose, Pizzol, et al., 2017). Therefore, increasing renewable energy supply, better construction practices, and building-specific properties (location, size, construction material, etc.) are important to reduce the environmental impact of existing buildings in NZ (Ghose et al., 2019).

As briefly described above, the building system legislative in NZ requires a reform (Leardini et al., 2012). NZ government finally released a discussion paper on proposed changes to the building regulatory system inclusive an improvement to the Building Act. The proposal addresses building products information and certification, environmental impacts of the products, and building performance (New Zealand Government, 2019d). However, the adoption of innovation in the construction industry worldwide is knowingly very slow. The NZ construction industry, with its complexities, seems to be resistant again advancements (Hunt & Gonzalez, 2018). The building construction industry has difficulty in managing costs arising from uncertainties and is resisting to new technology for buffer management (Poshdar et al., 2018). Approval process delays for new and "not used before" products or systems, and building compliance requirements cost time and money. The fact is that "The building industry is based around selling and installing products not solutions with measurable performance benefits" (New Zealand Business Council for Sustainable Development, 2003, p. 6). Therefore, in this highly competitive environment, it is often easier to build the "usual" way rather than aim improvements and innovations.

The researcher finds that the building consent process in NZ significantly influences the innovations. In spite of the fact that Duncan (2005) critiqued the performance-based building code (adopted in NZ 1992) more than one and a half decade ago, the lessons are still valid. The researcher's personal experience is that local authorities still largely demand the "Acceptable Solutions" to be followed. This practice hinders innovations. The NZ government is aware of this problem for a long time: "We're focused on meeting improved minimum standards rather than enabling people to get ahead of them" (New Zealand Business Council for Sustainable Development, 2003, p. 7). Many of the descriptors of the performance requirements of the NZ Building Code are provided in a non-quantifiable manner, in words or terms, such as "reasonable", "adequate", or "acceptable" (New Zealand Legislation, 2017). Additionally, the non-existence of mandatory means of demonstrating compliance and incomplete building performance measures (Meacham, 2016) might lead to unintended consequences. Structural failures due to moisture-related issues of enclosed structural systems (Mumford, 2011; Shi et al., 2017), mould growth due to weather-tight buildings (Mudarri, 2010), or health and fire hazards due to thermal insulating materials (Babrauskas et al., 2012) represent some examples of these unintentional consequences.

Sustainability continues to gain interest in NZ (New Zealand Government, 2019d). For more than 15 years, the NZ government has continued effort towards sustainability in the form of waste management (New Zealand Government, 2007, n.d.). To reduce plastic waste and improve resource efficiency, the government has recently proposed a program for the transition to a circular economy (New Zealand Government, 2019a). This includes initiatives, such as the NZ Plastic Packaging Declaration signed in June 2018. Here, committed business groups who declared to use 100 per cent reusable, recyclable, or compostable packaging by 2025 (New Zealand Government, n.d.).

To improve housing quality, Stats NZ released a document defining four elements of housing quality, such as housing habitability, environmental sustainability, housing functionality, and social and cultural sustainability (Stats NZ, 2019). Housing habitability relates to physical qualities of housing design, materials, construction, and services. Environmental sustainability addresses housing interaction with an impact on the natural environment, and it focuses on the resource efficiency, durability, and resilience of housing. Housing functionality describes the degree to which housing supports the specific physical, mental, emotional, cultural, and social needs of individuals, families, and whānau in their kāinga and communities (Stats NZ, 2019). However, NZ has no guidelines or recommended maximum levels of VOCs for IAQ (Berry et al., 2017). Although the high levels of indoor pollutants have been recognized (Taptiklis & Phipps, 2017), the only regulations are the National Environmental Standards for Air Quality (NESAQ). The NESAQ are made under the Resource Management Act 1991, which set a maximum level for some outdoor air pollutants (New Zealand Government, 2017). The only existing guidelines in NZ for ambient air (Ministry for the Environment, 2002) are more than 17 years old. The researcher notes that these guidelines ignore IAQ and indoor sources of pollution. Generally, information on indoor air quality in New Zealand is limited, which is alarming because people spend typically about 80 to 90% of the time inside (Ministry for the Environment & Stats NZ, 2018).

To examine the scientific background leading to possible improvements in NZ housing quality, the following section reviews the knowledge of building physics/building science.

3.1.4 Building Physics

Building physics is concerned with diverse phenomena, such as sick buildings, the energy crisis and sustainability, and considers the performance of buildings in terms of climatic loads and indoor thermal and hygrothermal conditions (Bomberg, Kisilewicz, et al., 2015). Hens (2017) defines building physics:

> As an applied science, building physics studies the hygrothermal, acoustic and visual performance of materials, building assemblies, spaces, whole buildings and, be it under the name urban physics, the built environment. The constraints faced are the user demands related to overall comfort, health and safety, together with architectural facts and figures, durability issues, economic restrictions and sustainability-related requirements. (p. 1)

Building physics/science developed as a branch of building engineering in Russia, Germany, and Sweden during the twentieth century (Bomberg, 2012). "Building physics surged at the crossroads of several disciplines: applied physics, comfort and health, building services, building design and construction" (Hens, 2017, p. 5). The engineering knowledge merged with architectural science from the UK and Australia and formed an academic discipline in Central and Northern Europe in the 1970s. However, in North America, very little or no building physics have been included in universities' curriculum (Bomberg, 2012). A similar situation has occurred in New Zealand (Rosemeier, 2010). Generally, the discipline of building physics in the English-speaking countries is poorly taught to architectural students or more often it is not taught at all (Bomberg, Kisilewicz, et al., 2015). The Victoria University of Wellington has recently renewed the building science subjects, such as Project Management and Sustainable Engineering Systems (Victoria University of Wellington, n.d.). However, to the opinion of the researcher, it is questionable what the discipline of project management has in common with building physics/science? Project managers are usually appointed during the construction phase of the building process. Therefore, they have little or no influence on the design and specification of the buildings. Additionally, the separate subjects do not guarantee the level of knowledge taught to the architectural designers. Therefore, until the building science/physics will be taught to each and every architectural designer in NZ we still will face serious problems in NZ house performance.

Building physics is developing sustainability solutions, as the pressure on saving energy and raw materials is growing (Padfield et al., 2018; Romanska-Zapala et al., 2019). The praxis of the past 30 years has shown that the intense improvements in thermal insulation, air- and vapour-tightness of buildings might bring dramatic consequences (Winkler et al., 2018). For example, mould and microbiological growth on the surfaces or inside of walls and air conditioning systems (Bomberg, Gibson, et al., 2015; Boudreaux et al., 2018; Cho et al., 2016; Crawley et al., 2019; Straube, 2002). Building physics, architectural studies, and practical experience advocate that an improvement to the built environment is not possible by a one-sided solution, such as increasing the thermal insulation only (Smith, 2017; Tweed & Zapata-Lancaster, 2018; Vereecken, Van Gelder, et al., 2015). Consequently, without simultaneous consideration of energy efficiency, quality of the indoor environment, and moisture management, the achievement of sustainability is hardly feasible (Yarbrough et al., 2019). Therefore, a new approach to building envelope design, called the Environmental Quality Management is proposed by Yarbrough et al. (2019). The described factors in achieving sustainability lead to another research question: Considering building physics, what are the major differences in the design process, including hygrothermal simulation compared to the traditional design process?

Energy savings are crucial for reducing or slowing down the process of global warming of the Earth (Zakula et al., 2019). One of the current tasks of the construction industry is to build houses which do not have a negative impact on the health of their inhabitants and the environment (ASHRAE, 2017b). In the area of building physics, hygrothermal models are widely used to simulate and prevent building pathologies originated by moisture (Delgado et al., 2013). The design and construction process of energy-efficient and comfortable houses should respect building physics (Hens, 2016; Mitterer et al., 2012), and sustainability factors (Gervásio et al., 2014; Suzer, 2015). However, despite new technology and simulation software, a significant uncertainty factor in the prevention of moisture-related problems remains (Hens, 2015; Künzel, 2014). Therefore, a new holistic approach to the construction process is needed (Bomberg et al., 2016). This approach is based on the conceptual design of the whole system as a set of design principles, rather than a description of a specific construction technology (Romanska-Zapala et al., 2019). In this context, Bomberg et al. (2017) write:

> Yet, the building physics is changing. It merges with building science in the quest of predicting building performance, it merges concepts of passive houses with solar engineering and integrates building shell with mechanical services, but is still missing an overall vision. Physics does not tell us how to integrate people with their environment. (p. 193)

Therefore, the contribution of building physics to the sustainable built environment should be based on harmony between diverse aspects of the environment, society, and economy. Consequently, the building design should be re-directed towards people. The indoor environment, its quality, thermal and hygrothermal relations depict the crucial characteristics of people-oriented, sustainable design (Yarbrough et al., 2019).

3.2 Hygrothermal Relations in Built Environment

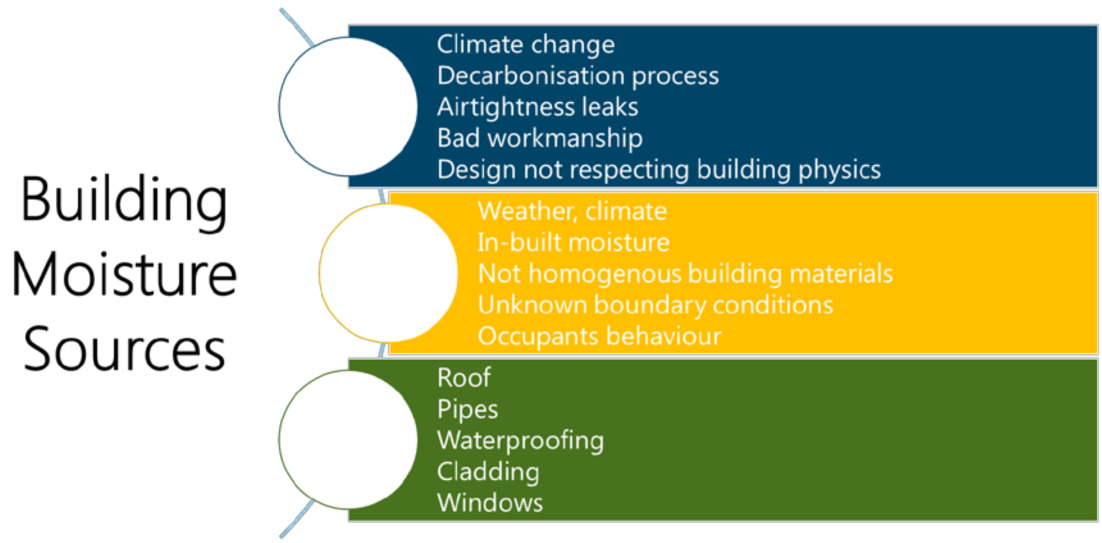
Research has shown that heat movement correlates to moisture (Bomberg & Onysko, 2002; Hens, 2017). The heat and moisture transport for porous materials was first described by Philip and De Vries (1957) and Luikov (1964). Subsequently, Künzel (1994) applied this physical phenomenon to building components using one- and two-dimensional calculations (Künzel, 1995). However, water as the most important substance in existence has a vast variation of properties. Therefore, "… a continuous description of the thermodynamic properties of water over the entire thermodynamic surface can only be achieved with a suitable equation of state that is able to represent all the data considered to be reliable to within their experimental uncertainty" (Wagner & Pruß, 2002, p. 395). The IAPWS-95 formulation explicit in Helmholtz free energy, developed by Wagner and Pruß (2002), is the best equation of state of fluid water proposed until now (Mao et al., 2011). The International Association for the Properties of Water and Steam (IAPWS) is responsible for the international standards for several thermophysical properties. From the IAPWS-95 formulation, all thermodynamic properties, inclusive the saturated properties of water can be derived for general and scientific use (Mao et al., 2011).

The term "hygrothermal" is used as of, or pertaining to both humidity and temperature in the field of transmission of mass (especially moisture or air) by various mechanisms (British Standards, 2007b). Moisture has become a leading cause of building damage (ASHRAE, 2016a; Othman et al., 2015). WHO estimated that moisture caused 75-80% of building envelopes defects (Heseltine & Rosen, 2009). BRANZ identified in 49% of NZ surveyed homes visible mould (White et al., 2017). The moisture defects also have serious economic and sociological effects (Heseltine & Rosen, 2009; Shi et al., 2017). On these examples and in numerous contemporary scientific literature (Bomberg et al., 2017; Leivo et al., 2018; Park et al., 2019; Romanska-Zapala et al., 2019) it is evident that hygrothermal relations in built environment need attention. It leads to the following research question: What levels of RH are reached in occupied NZ houses by different internal envelope materials?

Every building has moisture sources, such as in-built moisture, the moisture released by occupants, wind-driven rain, or water leakages (Figure 3).

Figure 3

Building Moisture Sources



Unintended moisture sources occur as a by-product of other decisions in the construction process and often arise from disregarding the hygrothermal relations in buildings (Mundt-Petersen & Harderup, 2015). Additionally, recent studies are warning from unintended consequences of climate change (Zhang et al., 2019), decarbonization process (Davies & Oreszczyn, 2012; Richard A. Sharpe et al., 2015b), and increased air-tightness of buildings (Domhagen & Wahlgren, 2017; Gupta & Barnfield, 2014), or bad workmanship (Jones, 2018; Milion et al., 2017; Othman et al., 2015). Several studies demonstrated in the last 30 years that the thermal resistance of building envelope is significantly reduced by defective or partial installation of insulation products (Antretter, Pazold, et al., 2013; Brown et al., 1993; Cho et al., 2016; Silberstein & Hens, 1996). The fact that approximately one third of the energy used for residential heating and cooling is lost due to the unintentional air leakage (Spengler, 2012) is not only the energy performance issue (Belleudy et al., 2015). Air leakages influence the ventilation performance and the quality of the indoor air (Guyot et al., 2019). Consequently, air movement through the building envelope brings moisture into the construction (Hens, 2017). This phenomenon is unintended and often ignored or unknown (Bomberg & Onysko, 2002; Hens, 2015). Therefore, a consensus about the definition of the best practice for different construction types would allow using hygrothermal simulation for building forensics. Such practice may help to determine whether the designer or the builder is responsible for failures (Künzel, 2014).

Unavoidable moisture sources exist due to external factors, such as weather, non-homogenous building materials, unknown or variable contact and boundary settings. The geometry of building envelopes, inclusive gaps, cracks, voids etc. remains unidentified (Hens, 2012). “Although the theory looks well established and the computer software, actually available, quite complete, still it does not always help explaining and curing the damage cases, encountered in practice” (Hens, 2015, p. 138). In-built moisture as a result of the construction processes, such as concrete or plastering, is unavoidable. However, wetting of timber members during construction should be avoided and moisture-trapping details already prevented in the design (Schmidt & Riggio, 2019). Outdoor climatic conditions and uncontrolled occupant behaviours count to the unavoidable and hardly predictable moisture sources (Bagge et al., 2014; Labat et al., 2015). However, the occupant behaviours might be changed or adjusted by relevant information and users’ education (Optis et al., 2012). Nevertheless, the determination of occupant behaviours is essential to achieve accurate energy building simulation results (De Simone et al., 2018).

The humidity levels in the indoor air affect occupant comfort, health, indoor environmental quality (Derby et al., 2017), and durability of the building construction (Bomberg, Gibson, et al., 2015). Thermal comfort is a condition of mind resulting from satisfaction with the thermal environment (Bano & Tahseen, 2017; Rahmillah et al., 2017). Comfort depends on multiple factors that are based on the subjective perception of the thermal environment, clothing insulation, humidity, air movement (ASHRAE, 2017b), outdoor climatic conditions, and buildings orientation (Asif et al., 2018). The BS 5250:2011+A1:2016 standard sets the human comfort conditions in the range from 45% RH to 60% RH at 18 °C to 24 °C (British Standards, 2016). The EN 16798-1:2019 standard sets the levels for medium indoor environmental quality at 25% RH for humidification and 60% RH for dehumidification. The temperature limits for heating between 20 °C and 25 °C and for cooling between 23 °C and 26 °C (European Standard, 2019).

However, the maintaining of thermal comfort for building occupants with HVAC is energy consuming (Schiavon et al., 2014). Therefore, the adaptive thermal comfort theory proposes to set the indoor temperature in relation to the outside temperature. Consequently, the neutral temperatures proposed by the hybrid or mixed mode model might be lower than by the ASHRAE 55 model (ASHRAE, 2017b) and the EN 16798-1 (European Standard, 2019) for the natural ventilation buildings (Barbadilla-Martín et al., 2017). Therefore, from the indoor temperatures adjusted to the outdoor climate and humidity levels derives the potential for energy savings by natural ventilation mode (S. Kumar et al., 2016; Rupp et al., 2018). Another opportunity for energy savings represents the correct dimensioning of HVAC installations. An in-situ determination of the room hygric inertia as proposed by Vereecken et al. (2011) allows for evaluation of ventilation rate by using the effective moisture penetration depth and effective capacitance models. These models are further addressed in section 3.3.

Statistics and research show that the energy performance based on in-situ measurements, such as coheating test (Alzetto et al., 2018; Bauwens & Roels, 2014; Johnston et al., 2013), of newly erected dwellings may differ from the predicted energy efficiency (Latif, Lawrence, et al., 2016). This phenomenon, known as the energy performance gap, reveals that the real savings of energy demand of buildings are often not achieving the aimed values (Farmer et al., 2016; Roels, 2017). Building energy performance gap, according to recent studies, might reach twice to five times higher energy consumption than predicted during the design stage (Zou et al., 2019). However, the achieving of targeted thermal performance depends not only on the used materials and technology but also on the design process integration and the quality of craftsmanship (Mitterer et al., 2012). Unless taking into account the problematics of moisture-related issues, improvements in the real energy performance of new or refurbished buildings might be accompanied by serious unintended problems in the future (Romanska-Zapala et al., 2019). This fact was already emphasized by McLeod and Hopfe (2013) with the suggestion for widespread building physics training schemes for building professionals in the UK. Consequently, the researcher suggests that this extension of knowledge would be beneficial for architectural designers in any and every country without exception.

Hygrothermal relations in the built environment, as described above, play an important role in building performance. Therefore, the next section deals with the high RH and its consequences.

3.2.1 High Relative Humidity and its Consequences

The interconnectedness of heat and mass explains why every change in the building envelope influences simultaneously both — energy and moisture. Therefore, improving the thermal performance of the building envelope and airtightness of the building has changed the moisture movement as well (Bomberg, Kisilewicz, et al., 2015). To manage moisture in buildings BS 5250:2011+A1:2016 informs: “Excess moisture in a building can lead to condensation and mould growth which represent risks to the structural integrity of the building and the health of its occupants” (British Standards, 2016, p. 13).

Based on studies from the 1960s and 1970s, Bomberg and Onysko (2002) show that indoor RH is influenced by changes in the efficiency of natural ventilation and the position of the neutral pressure plane. Additionally, moisture from the construction phase (inbuilt moisture) and the rate at which occupants generate humidity have a major influence on the indoor RH level (Winkler et al., 2018). Missing airtightness membrane or air leakages impact indoor comfort, energy consumption (Domínguez-Amarillo et al., 2019), and humidity levels inside the construction (Hurel et al., 2016). However, as shown in Finish study, airtightness levels do not influence the average values of moisture excess in the indoor environment (Vinha et al., 2018). Nevertheless, even relative minor air leakages through construction elements have a substantial impact on humidity levels within the building envelope (Belleudy et al., 2015; Kölsch et al., 2016). Consequently, when moisture levels exceed the tolerance of structure for extended time period biodeterioration in the form of mould, fungi, decay, or insect damage may occur (Plagmann, 2018; H. Viitanen et al., 2010; Hannu Viitanen et al., 2010). It leads to the following research question: How do RH levels differ in NZ houses based on the presence/absence of airtightness membranes?

Morris and Langari (2016) define RH as follows:

> Relative humidity is the ratio of the actual water vapor density in air to the saturation vapor density, usually expressed as a percentage. The saturation vapor density varies with temperature, and so the relative humidity also varies with temperature for any given measured value of actual vapor density. (p. 659)

RH inside of buildings has occupant, structural, and energy aspects. Before addressing those aspects, it is important to mention that the absolute water content per volume air by constant RH and barometric pressure is dependent on the given temperature (Parish & Putnam, 1977). The absolute mass of water vapour (m_w) in the air could be calculated as shown in formula (1) based on Dengler (1997).

$$m_w = \frac{M \cdot p_p}{R \cdot T} \tag{1}$$

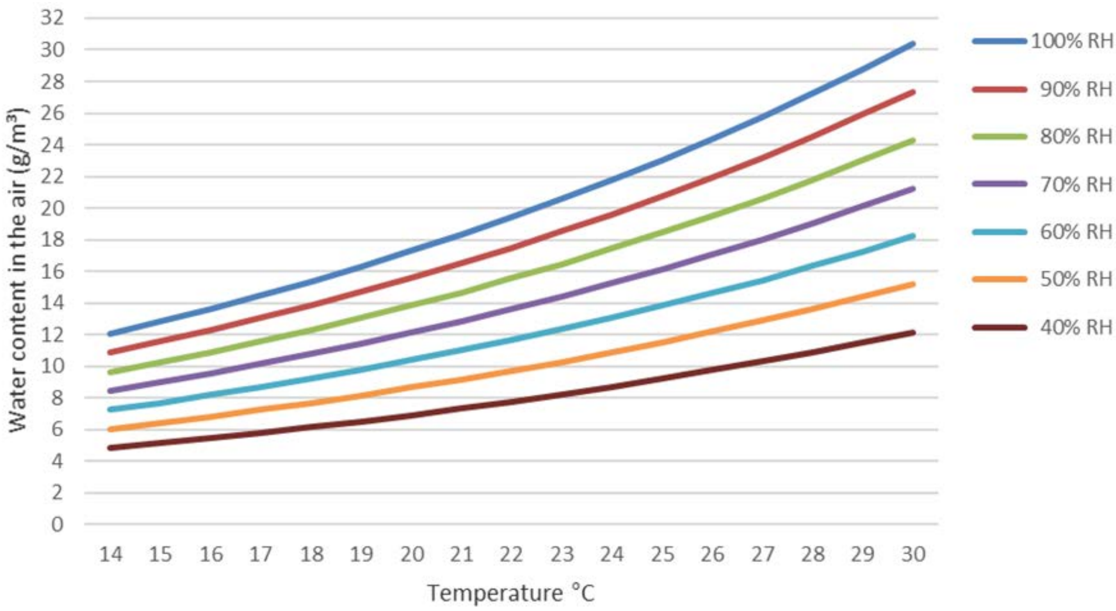
Where p_p represents the actual partial vapour pressure (Pa) and *T* - thermodynamic temperature (K). *M* - molecular weight of water (H_2O) has been calculated from the sum of the atomic masses of its constituent atoms and has a value of 18.015 g mol^{-1} (Haynes, 2015). *R* represents the molar gas constant (8.3144598 J mol^{-1} K^{-1}) (The National Institute of Standards and Technology, 2019). Therefore, the absolute mass of water vapour calculation formula might be written as follows:

$$m_w = \frac{18.015 \cdot p_p}{8.3144598 \cdot T} \tag{2}$$

Results of the calculation demonstrate that with higher temperature by the same RH more water is contained in the air (Figure 4). The actual water content in the air is dependent on the moisture release, ventilation, dehumidification, and moisture storage/release in/from building materials (TenWolde & Walker, 2001).

Figure 4

Absolute Water Content in the Air by Different Temperature and RH



Occupant Aspect

As mentioned earlier, RH inside of buildings has occupant, structural, and energy aspects. The occupant aspect of IAQ is highly subjective and individual (Bluyssen, 2009; Bluyssen et al., 2016; Stats NZ, 2019). Therefore, the determination of the optimum RH is complicated as the fluctuations of RH have an influence on chemical interactions and growth of biological pathogens (Derby et al., 2017; Sterling et al., 1985). Fungi, mould, and dust mites flourish in damp habitat. The microbial volatile organic compounds (MVOCs) produced by these organisms are associated with allergies and asthma (Heseltine & Rosen, 2009; Richard A Sharpe et al., 2015). Therefore, many researchers over the last few decades recommended reducing/controlling the indoor RH. Sterling et al. (1985), for example, recommends RH between 40% and 60% and Arlian et al. (2001) even less than 50% RH to reduce the amount of house dust mites.

The ASHRAE Standard 55-2017 describes the temperature and humidity levels that are comfortable for 80% of people engaged in largely sedentary activities. The recommended indoor temperature is between approximately 67 °F (ca. 19 °C) and 82 °F (ca. 28 °C). A more specific range of temperature depends on RH, season, clothing worn, activity levels, and other factors (ASHRAE, 2017b). The standard suggests maintaining a humidity ratio by HVAC of at or below 0.012. This means that systems designed to control humidity must be able to maintain a dew point temperature of 16.8 °C (62.24 °F). The humidity ratio or moisture ratio determines the mass of water vapour per unit mass of the dry air (Hens, 2017). Therefore, the humidity ratio 0.012 corresponds to the maximal humidity level about 83% RH by recommended 19.44 °C and about 52% RH by 27.78 °C. Although the standard does not specify a minimal humidity limit, it provides information about the possible impact of low humidity on the inhabitants. Very low humidity environments might cause factors, such as skin drying, irritation of mucus membranes, dry eyes, and static electricity (Derby & Pasch, 2017; Wolkoff, 2018b).

However, low RH usually does not have a negative impact on the building rather than directly affects IAQ (Angelon-Gaetz et al., 2015; Wolkoff & Kjærgaard, 2007). Nevertheless, by extremely low RH (under 30%) timber, paper, and textiles might shrink and crack (Hens, 2016). Temperature and humidity have an influence on the perception of IAQ and the chemical and volatile organic compounds (VOCs) emissions of building materials (Sarigiannis et al., 2011; Simonson et al., 2002; Sterling et al., 1985; Wolkoff, 2018a). Consequently, airtightness and therefore, the level of infiltration influence temperature, humidity, and VOCs levels (Berry et al., 2017; Poppendieck et al., 2015). Additionally, some evidence suggests that the perceived air quality decreases with higher temperature and humidity, regardless of the actual air quality (Fang et al., 1998; J. Liu et al., 2019; Wolkoff & Kjærgaard, 2007). High RH and dampness are often associated with health problems and sick building syndrome (Hahm et al., 2014; Molina et al., 1989; Sahlberg et al., 2013; Saijo et al., 2011), especially with recent energy efficiency improvements (Howden-Chapman, 2015; Richard A. Sharpe et al., 2015b; Sutcliffe et al., 2015; Švajlenka et al., 2017). Howden-Chapman, Benett, Chisholm, and others describe the users' experiences of the indoor environment in New Zealand (Bennett et al., 2016; Chapman et al., 2016; Chisholm et al., 2019; Howden-Chapman, 2004; Howden-Chapman et al., 2008).

Structural Aspect

Especially during the last two decades, researchers and official bodies gained interest in the structural aspect of high RH (Champiré et al., 2016; Mijakowski & Sowa, 2017; Strangfeld & Kruschwitz, 2018). High RH and dampness cause moisture-related issues, such as mould growth, condensation, deterioration of building materials, and frost damage (Feng et al., 2019; Harriman, 2012). Dampness is associated with the risk of rot in timber and other organic matter, therefore, causing decomposition of materials (Riggio et al., 2015). ASHRAE standards 62.1 and 62.2 recommend maintaining average RH for mechanical systems with dehumidification capability in occupied spaces below 65% to reduce the likelihood of microbial growth (ASHRAE, 2019a, 2019b).

However, for simple mechanical system types or spaces without any mechanical systems, ASHRAE standard 62.1 has no humidity limitations. The mould growth criteria are set in the ASHRAE standard 160. The new standard 160 (ASHRAE, 2016a) incorporates several changes focused on simplifying the conditions necessary to minimize mould growth. A new feature of the standard is the mould index (MI) that predicts the risk of mould growth. The mould index accounts for the type of material, the surface temperature, and the surface RH (Glass et al., 2017). The standard recommends limiting indoor RH to 70% or less in the design analysis and revising the residential design moisture generation rates. Additionally, the calculation procedure for wind-driven rain is simplified without significantly impacting the accuracy of results (ASHRAE, 2016a).

Energy Aspect

The energy aspect of high RH represents the energy needed for dehumidification, heating, cooling, and ventilation (Logue et al., 2016). Until now, there are only a few studies of coupling HVAC to RH level (Krus et al., 2011; Winkler et al., 2018). Apart from the ventilation adjustments, the energy needed for the regulation of air humidity could be reduced by using moisture buffering property of building materials (Winkler et al., 2014). This potential direct energy savings combined with well-controlled ventilation systems are relevant for reducing the total building energy demand (Osanyintola & Simonson, 2006; Romanska-Zapala et al., 2018). However, this positive effect of demand-controlled ventilation, combining a RH sensitive ventilation system with indoor hygroscopic materials, may bring some disadvantages. For example, indoor pollutants, such as CO_2 levels may exceed recommended limits (Woloszyn et al., 2009). Lower fluctuations of indoor RH would allow for indirect energy savings, such as reducing outdoor ventilation, reducing the indoor temperature in winter, and increasing the indoor temperature in summer (Asif et al., 2018; P. Kumar et al., 2016). The adjustment of temperature to outdoor conditions and indoor RH is in accordance with the theory of heat index, where the perception of dry bulb temperature is dependent on the level of RH (ASHRAE, 2017b; Steadman, 1979). However, recent improvements in energy efficiency and thermal comfort seem to overlook the IAQ issues (Fisk, 2015; Markopoulos et al., 2013). The issues reviewed in this section lead to the following research question: What are the most significant impacts of high humidity on NZ housing?

Ways of Controlling Indoor Relative Humidity

Unfavourable indoor climate conditions with high RH have a negative impact on human health, may lead to degradation of building parts, mould growth, or damage to artefacts (Davies & Oreszczyn, 2012; Plagmann, 2018; Todorović et al., 2015). It is important to mention that the indoor moisture level should not exceed for longer time periods the critical limit for risk of damage (ASHRAE, 2016a). Thus, for the protection against failures caused by high moisture, maintaining the correct relations between moistening and drying are essential (Delgado, 2014; Zirkelbach, 2013). Especially for timber constructions and bio-based building materials, as long as the construction can dry out, the risk of damage is minimized (Colinart & Glouannec, 2014; Delgado, 2014; Verbist et al., 2019). However, extreme wetting of the construction influences the structural timber stiffness and dissipation capacity (Poletti et al., 2019).

In the context of controlling moisture, the suggestion for decreasing of the ventilation rate is in contrast to other researchers who promote the opposite. The increasing of ventilation rate is beneficial to RH reduction, supports moisture buffering, and improves air quality (Fisk et al., 2011; Mendell et al., 2008). However, too high ratio of exchanged air might have some unintended effects, such as draft and energy loss (Schiavon et al., 2016). The researcher agrees with the suggestion that the discussion about the ventilation rate would be beneficial to shift from the amount of fresh air into a more purposeful approach to a higher quality of indoor air. This means to approach the ventilation and IAQ problematic from a holistic point of view (Bomberg, Gibson, et al., 2015; Brauner et al., 2016; Yarbrough et al., 2019). The ventilation rate should be rather demand controlled by measured indoor humidity and CO_2 levels than pre-set just by volume (Osanyintola & Simonson, 2006; Persily, 2015). The HVAC setpoints should be optimized to the local climate conditions without compromising energy consumption and thermal comfort (Papadopoulos et al., 2019). European standard EN

16798-1:2019 sets limit values of substance concentration of CO_2 and RH, which might be used as set up points for demand-based ventilation (European Standard, 2019). However, the minimum outdoor air exchange, particularly with the increasing air-tightness of the building envelope, must be guaranteed to provide a healthy indoor environment (Wolkoff, 2018a).

With the emphasis on energy savings, research and praxis are coming with new ventilation alternatives. For example, studies based on BIM, such as wind-driven natural ventilation at top floors of residential high-rise buildings in suitable climates (Weerasuriya et al., 2019), or using natural ventilation during certain seasons when the thermal comfort could be maintained (Gan et al., 2019). On a similar idea is based a hybrid ventilation system with an overpressure of the supply air proposed for houses with environmental quality management (Romanska-Zapala et al., 2019). Another alternative to HVAC systems could be natural ventilation with parallel-action opening windows regulated by an automatic control mechanism as proposed by Pazold et al. (2014).

Another option represents IEQ management by decisive use of heat storage systems operating on thermal energy, sensible heat, and/or latent heat. To this category belong direct ventilation and evaporating cooling (Johnston et al., 2016). These systems use climate variables, like temperature and humidity, as the cooling potential for a passive cooling system (Campaniço et al., 2019). The latent heat storage systems follow a similar concept in offering free cooling based on phase change materials (Zeinelabdein et al., 2018). Today’s technology enables an automatic ventilation control system based on an algorithm considering the IEQ factors and occupant ventilation behaviour (H. Kim et al., 2019). Therefore, the demand-controlled ventilation would improve the building operations’ adaptability to variable occupancy and save operational energy (Ouf et al., 2019).

The different ways of controlling the RH fluctuation and their impact on the total energy consumption are shown in Table 4.

Table 4

Ways of Controlling RH Fluctuation and Their Impact on the Energy Consumption

	Passive control	Active control	Energy consumption	References
Mechanical ventilation		√	+	(Barbosa & Mendes, 2008; Crawley et al., 2019; Fisk et al., 2011; H. Kim et al., 2019; Leardini et al., 2012; McNeil et al., 2015; Mendell et al., 2008; Romanska-Zapala et al., 2019)
Dehumidifier, air conditioning		√	+	(Asif et al., 2018; Galvin, 2010; Krus et al., 2011; Winkler et al., 2018)
Moisture buffering materials	√		-	(Osanyintola & Simonson, 2006; Ramos & de Freitas, 2009; Shi et al., 2018; Soudani et al., 2016; Wan et al., 2019; Winkler et al., 2014; Wu et al., 2018; H. Zhang et al., 2017)
Moisture release reduction		√	-	(Lawrence et al., 2018; Nazaroff, 2013; Nevalainen et al., 2015)

The review of possible ways how to control indoor environment reveals the need for a holistic and sustainable approach to building performance (Brauner et al., 2016; Lan et al., 2019; Weerasuriya et al., 2019). However, building performance analysis is a complex activity for which does not exist a generally accepted evaluation framework (de Wilde, 2019). Building performance is described by de Wilde (2019) as a concept allowing to quantify the degree to which a building fulfils its functions and can be studied from an engineering, process, and aesthetic point of view. Complex assessment of building performance is crucial for the design of sustainable houses (Ahmad et al., 2019). Therefore, improved hygrothermal models should be connected with energy modelling (Romanska-Zapala et al., 2019) because moisture buffering beside influencing the indoor RH also reduces peak energy loads (Fadejev et al., 2017).

High RH might lead by certain circumstances to condensation. Therefore, the following section reviews the existing research concerning physical processes in condensation and dew point.

3.2.2 Dew Point and Condensation

Condensation represents a physical process of conversion of water vapour (WV) to liquid water (Camuffo, 2014). Development of condensation depends on the complex interrelationships between heat, moisture, air movement, building layout, and the physical properties of building materials (British Standards, 2016). Condensation develops where the vapour pressure exceeds the vapour saturation pressure (Simões et al., 2002), with other words, where the temperature reaches or falls below the dew point at initial pressure and water content (Jensen et al., 2014). This means that the condensation is dependent on indoor temperature, indoor RH, outdoor temperature, air movement (air leakages), and thermal resistance of the weakest element in the building envelope (Belleudy et al., 2015). Condensation might occur on surfaces or within layers of a construction (interstitial condensation) (British Standards, 2016).

Nevertheless, damage caused by condensation can occur to the building body and contents (Karagiannis et al., 2018). Condensation also affects to different degree the thermal conductivity of insulation. The water sensitivity of thermal insulation depends on the material hygroscopic capability (the degree of wettability) and the impact of the water content on the reduction of thermal resistance (Gullbrekken et al., 2019; Jerman et al., 2019; Kosiński et al., 2018). Additionally, the dampness and associated mould growth can be distressing to occupants and causing respiratory and other health issues (Carlton et al., 2019; Fisk et al., 2010). The control of condensation is an essential factor in building design and construction. Consequently, the design process needs to implement a hygrothermal performance assessment into calculations of energy efficiency and/or conservation measures (Oladokun et al., 2017).

The amount of WV content in the air is in correlation with temperature and follows an exponential curve (Hens, 2017). By sufficient water availability, the evaporation continues until the vapour pressure reaches the saturation point. To provide the temperature dependence of the saturated vapour pressure (p_s) most scientific textbooks use the Clausius-Clapeyron equation (Rittner & Bailey, 2016; Velasco et al., 2009; Zhang et al., 2019). The most accurate approximation of saturated vapour pressure based on Dengler (1997) and Hens (2017) is:

(3)

$$p_s = C_1 \cdot e^{\frac{C_2 \cdot t}{C_3 + t}}$$

Where p_s the saturated vapour pressure (Pa) is solely related to t the temperature (°C) but not to the air pressure. The saturated vapour pressure by 100 °C is 101,325 Pa. The constants used in (3) are different for each evaporating medium status, as shown in Table 5.

Table 5

Constants for Clausius-Clapeyron Equation

	Water **t= 0.0 to 100.9 °C**	**Ice** **t= -50.9 to 0.0 °C**	**Super cooled water** **t= -50.9 to 0.0 °C**
C_1	610.780	610.714	610.780
C_2	17.08085	22.44297	17.84362
C_3	234.175	272.440	245.425

Note. Adapted from Sonntag (1990).

However, the absolute WV content in the air is usually lower than the maximal possible. The ratio between p_p the actual partial vapour pressure and p_s the saturated vapour pressure at the same temperature represents RH in per cent %:

(4)

$$RH = \frac{p_p}{p_s} \cdot 100$$

Dew point is defined as the temperature at which air becomes saturated with WV (British Standards, 2016). Therefore, by a decrease of temperature and the same absolute water vapour content, the saturated water vapour pressure sinks, and the RH rises. This physical phenomenon is the cause of condensation. As the temperature drops on or below the dew point temperature water starts to condensate. Therefore, the dew point temperature is the temperature by which the actual partial vapour pressure is equal to the saturated vapour pressure. Dew point (T_{dp}) by initial RH and temperature could be calculated as follows (Dengler, 1997):

$$T_{dp} = C_3 \cdot ln\frac{p_p}{C_1}/(C_2 - ln\frac{p_p}{C_1}) \quad (5)$$

Dew point temperatures for selected initial temperatures and RH are shown in Table 6.

Table 6

Dew Point Temperatures (°C) by Initial RH und Temperature

Initial Temperature °C	Initial RH				
	75%	80%	85%	90%	95%
14	9.8	10.8	11.6	12.5	13.3
15	10.8	11.7	12.6	13.5	14.3
16	11.8	12.7	13.6	14.5	15.2
17	12.8	13.7	14.6	15.5	16.2
18	13.8	14.7	15.6	16.4	17.2
19	14.7	15.7	16.6	17.4	18.2
20	15.7	16.7	17.6	18.4	19.2
21	16.7	17.7	18.6	19.4	20.2
22	17.7	18.7	19.6	20.4	21.2
23	18.7	19.6	20.6	21.4	22.2
24	19.7	20.6	21.5	22.4	23.2
25	20.6	21.6	22.5	23.4	24.2
26	21.6	22.6	23.5	24.4	25.2

The initial RH above 75% represent the critical moisture levels in buildings because the air is already saturated with WV from three quarters or more. Therefore, in such a case, a fall of temperature just about 4.5 to 1 degree Celsius (depending on the initial RH) would reach saturation point, and the WV would condensate. Consequently, for the description of moist air is dew point not sufficient because a second parameter, such as the initial temperature or initial RH is needed (Hens, 2017).

With the recognition of the moisture impact on buildings during the last century, diverse methods for the moisture performance in building physics have been developed. The most significant and known method is the Glaser method (Glaser, 1959). However, the Glaser method has several limitations which often lead to false predictions (Schwaller et al., 2016). These limitations are based on the assumption that moisture transfer is exclusively affected by diffusion, whereas thermal conductivity and thermal resistance of materials stay constant (Künzel & Sedlbauer, 2015). Therefore, this method ignores the effects of phase changes, the specific heat capacity of materials, diurnal temperature changes (British Standards, 2016), the effects of solar radiation, and air movement (Schwaller et al., 2016). On the contrary, many hygrothermal simulations allow for detailed moisture analysis with simultaneous consideration of the most relevant and concomitant factors (Zirkelbach, 2013). The moisture analysis might be used for mould growth prediction, as described in the following section.

3.2.3 Mould Growth

Mould is a type of fungus which thrives in warm and humid conditions (Pizzorno, 2016). Mould is, therefore associated with temperature, substrate conditions, and humidity (Glass et al., 2017; Johansson et al., 2012; Vinha et al., 2018). "Mould growth remains a highly complex microbiological process consisting of hyphal tip extension, hyphal branching, conidiophore formation, sporulation and so on. Small differences in water activity, temperature, nutrient availability, stress conditions and so on can induce totally different microbiological processes" (Vereecken, Vanoirbeek, et al., 2015b, p. 119). Indoor dampness or mould are estimated to be present in the order of 10-50% of indoor environments depending on climate among the most countries (Heseltine & Rosen, 2009; Mudarri & Fisk, 2007; Plagmann, 2018).

As already mentioned in section 3.1.2, IEQ plays a vital role in human health. Fungi spores constitute biological components which are ubiquitous in the indoor air. Even though mould growth as a biological process has an inhibition effect on formaldehyde emission (Liang et al., 2019), it negatively impacts human health. Fungi and fungi spores pollute the indoor environment and cause severe damage to the building interior and building envelope (Khan & Karuppayil, 2012; Nevalainen et al., 2015; Viitanen et al., 2011). Indoor fungi might cause biodeterioration of structural integrity in building materials, such as gypsum boards, wood, polyvinyl chloride (PVC), natural fibres, etc. (Kazemian et al., 2019).

Therefore, several recent studies are warning from unintended consequences of climate change and decarbonization process, especially by vulnerable population impacted by fuel poverty (Domínguez-Amarillo et al., 2019; Eisenberg, 2016; Fisk, 2015; Richard A. Sharpe et al., 2015a; Yavari et al., 2018). In spite of the fact that mould growth often occurs in poorly insulated houses (Künzel, 1999; Plagmann, 2018), mould damages could also occur in low or zero-energy houses when very high RH persists over longer time periods (Sedlbauer & Krus, 2003; Smith, 2017). Therefore, the improvements in thermal properties, especially by applying interior insulation (Jerman et al., 2019; Krus & Sedlbauer, 2011) might cause cold hygrothermal bridges, condensation, mould growth, and decay (Antretter, Pazold, et al., 2013; Davies & Oreszczyn, 2012; dos Santos & Mendes, 2014; Hildebrandt et al., 2019). Especially highly insulated wood-frame walls are sensitive to moisture and moisture changes (Ameri & Rüther, 2019). The thick insulation minimizes the heat flow in assembly, and therefore, in the case of moisture entrance into the envelope, the drying-out process is very slow (Lacasse et al., 2016). However, the design based on a good understanding of building physics will preclude most of the unintended consequences of thermal improvements (Smith, 2017).

Human beings and their relationships with the environment are complex and still not completely known or understood (Mendell & Heath, 2005; Zhang et al., 2015). Nevertheless, the evidence for the significant association of high indoor RH with negative health effects is present (Bornehag et al., 2001; Sahlberg et al., 2013; Shrestha et al., 2019; J. Wang et al., 2019; Zhang et al., 2012). Although the clinical effects of mycotoxins have been widely researched in the respiratory region (Pizzorno, 2016), the research of non-respiratory effects of mycotoxins is limited (Pizzorno & Shippy, 2016). However, the mould toxicity-related symptoms, such as headache, fatigue, weakness, lack of concentration, difficulty focusing, red eyes, blurred vision, multiple chemical sensitivities, allergies, and nosebleeds to name just a few, are well-known (Lane, 2019). Meta-analyses have been used to show that building dampness and mould are associated with respiratory tract infections and bronchitis (Carlton et al., 2019; Fisk et al., 2010), rhinitis (Jaakkola et al., 2013), and increases of 30-50% of asthma-related health effects (Al-Ahmad et al., 2019; Fisk et al., 2007).

However, the science is still not able to successfully assess the cause-effect relationships between factors, such as chemical, biological, or physical indoor parameters, and health and well-being of occupants (Pizzorno & Shippy, 2016). "Dampness is the driving factor and yet health effects are mostly considered to be associated with microbial exposure, even though the specific causative agent is still unknown" (Sauni et al., 2015, p. 3). A possible reason for this unsatisfactory situation might be the synergistic effect of many stressors which act in unison or add together (Bluyssen et al., 2011; Piggott et al., 2015; Saijo et al., 2011; Wolkoff, 2018a). Additionally, the state of immune system may be different for each person (Tuuminen et al., 2019). One other reason might be that fungi are just a part of a complex community of biological agents. Fungal components and products relevant for indoor air sciences are fragments of fungal origin, mycotoxins, MVOCs, glucans, ergosterol, extracellular polysaccharides (EPS), fungal allergens, and fungal nucleic acids. The fungal nucleic acids contain the genetic information of a fungal DNA or act in converting of the genetic information carried in RNA (Nevalainen et al., 2015).

Generally, the ability of fungi to affect human health is still not fully apprehended. However, recently published research is warning about the worldwide unprecedented emergence rate of pathogenic fungi (Rhodes, 2019). Therefore, more multidisciplinary research by adopting toxicological and immuno-toxicological methods is needed (Janbon et al., 2019; Nevalainen et al., 2015). The fact that the mechanisms behind the association between dampness, mould, and health are not proven to be causal (Crook & Burton, 2010; Sauni et al., 2015) may not be the validation of their nihility. A recent NZ study proved a dose-response relationship between dampness/mould and acute respiratory infection hospitalization rates of young children (Ingham et al., 2019). Therefore, it seems to be more effective to focus on source control and avoid dampness and high RH in buildings (Nevalainen et al., 2015; Yarbrough et al., 2019). Dampness sources are not only water damage or poor maintenance of buildings but more prevalent and always present is moisture generated by humans (Huang et al., 2011). A household with two children, for example, generates and releases into the indoor air between 6 and 14 kg of water each day (ASHRAE, 2016a; British Standards, 2016).

Ventilation, dehumidification, and moisture buffering are the most effective means of controlling IAQ and reducing moisture content. However, these means are inadequate when indoor emission rates of pollutants and WV are superfluous (Nazaroff, 2013). Therefore, ventilation (HVAC systems) as prevention of high RH and condensation should be accurately commissioned to each project (Barbosa & Mendes, 2008; British Standards, 2019a) and regularly maintained (Angelon-Gaetz et al., 2015; Fisk & Seppanen, 2007). The maintenance and cleaning of the ventilation systems prevent additional contamination of indoor air (Mendell et al., 2008; Totaro et al., 2019). Consequently, the problem of condensation and mould growth could not solve without reduction of RH under a critical level of 70% or less (ASHRAE, 2016a). Decrease of indoor RH is a crucial factor in avoiding mould growth, particularly in buildings with inadequate thermal insulation (Künzel, 2006; Richard A. Sharpe et al., 2015a). The fastest way how to decrease indoor RH recommended by Galvin (2010) is dehumidification. However, although a dehumidifier is practical and easy to use, it might cause high energy consumption and low IAQ due to insufficient air exchange (Bomberg et al., 2017; Osanyintola & Simonson, 2006; Shehadi, 2018).

Mould or fungi growth may occur not only on interior surfaces but inside of the wall construction (due to the interstitial condensation or long-term wetting) or on the outside of the building (Knudsen et al., 2017). Another widespread potential for mould growth is found in insulated and uninsulated suspended timber ground floors (Pelsmakers et al., 2019), or cold attics (Hagentoft & Kalagasidis, 2013). Thermally insulated building envelopes reduce the heat movement through walls (Krus et al., 2013; Krus et al., 2009). This means, from a building physics point of view, that the walls are not drying out. In some cases, as an effect of transient wetting, RH, temperature, and material properties, the high moisture content will support microbiologic growth, such as mould or algae and discolouration on the exterior side of the building (Krus et al., 2013). This might happen on wooden claddings (Lie et al., 2019) or by external thermal insulation composite systems (Barreira & de Freitas, 2013). Some indoor fungi cause biodeterioration upon building material substrates, such as gypsum board, wood, polyvinyl chloride (PVC), etc. (Kazemian et al., 2019). In the case of infestation with wood-destroying fungi, buildings are severely damaged and potentially not safe (Haas et al., 2019). Although the biodegradation of wooden structures might be prevented with biocidal chemical preservatives, the toxicity of this treatment affects the environment and is hazardous for human health (Ringman et al., 2019). Therefore, the assessment of the mould growth prediction depicts an essential part of the building physics and design decision process (Hensen & Lamberts, 2019).

Despite diverse available mould growth models, their results are not always reliable as they are widely varying (Vereecken, Vanoirbeek, et al., 2015b). Several mould prediction models are based on material-specific mould growth curves so-called isopleths. Isopleth diagrams describe critical conditions for germination or growth rates of mould in relation to temperature and RH (Sedlbauer et al., 2011). With isopleths, it is possible to predict critical conditions regarding temperature and RH, or assess different building materials for propensity to mould growth (Johansson et al., 2013).

Biohygrothermal IBP modelling, as another mould growth prediction tool, allows for a dynamic hygrothermal description of mould or fungi spore behaviour depending on surface temperature, RH, and substrate material (Sedlbauer & Krus, 2003; Viitanen et al., 2011). The current WUFI Bio 3.5 is a biohygrothermal model for assessing indoor mould growth under transient hygrothermal boundary conditions (Fraunhofer Institute for Building Physics, 2017a). The WUFI Bio models the growth of a mould hyphen as a function of the transient ambient conditions (Viitanen et al., 2015).

The next most used mould growth model is the VTT model. The VTT model was originally developed by Finnish research institute VTT for wood but might be used for some other materials as well (Vereecken, Vanoirbeek, et al., 2015a). The VTT model is an experimentally validated empirical model based on visually assessed mould growth (Ojanen & Viitanen, 2016). The new ASHRAE Standard 160 adapted the Hannu Viitanen Mould Index (MI) as improved moisture performance criteria (ASHRAE, 2016a). Therefore, Fraunhofer IBP developed in collaboration with the Finish research institute VTT the WUFI Mould Index VTT postprocessor (add-in) which contains the mould growth criteria according to the ASHRAE standard 160 (Fraunhofer Institute for Building Physics, 2017b).

Natural or “green” building materials are suspected to be more prone to the microbial growth than conventional materials. Therefore, the selection of building materials that can withstand expected higher moisture level in specific situations might be used as a way of minimizing the mould growth risk (Johansson et al., 2014; Kukletova & Chromkova, 2019). However, the propensity to mould growth tests, material-specific isopleth curves, and settings of critical moisture levels for building materials are usually based on laboratory conditions (Vereecken, Vanoirbeek, et al., 2015a). These conditions are without house dust and mostly over a limited time span. However, house dust is a source of biological nutrients which promote mould growth on nearly every material when conditions for such are ideal (Mensah-Attipoe et al., 2015). Even materials that are non-biodegradable may support mould growth over time when they are covered by organic matter contained in the dust (Hoang et al., 2010), paint, or wallpaper (Giosuè et al., 2017). Therefore, natural building materials are neither more inclined nor more resistant to fungal growth than conventional materials. The susceptibility of mould growth on any material is correlated to the presence of organic matter and the equilibrium moisture content (Hoang et al., 2010). Based on this knowledge, logically, the selection of mould resistant or treated materials is not a “cure it all” solution. Therefore, the researcher suggests that we need to address the mould growth conditions and not to try to stop or modify the effects of the unfavourable situation.

In contrary, the advantages of natural or “green” building materials have been proven. Qualities, such as low toxicity, carbon neutrality (Labat et al., 2016), minimal VOC emissions (Maskell et al., 2015), and high moisture buffering capacity (Barclay, Holcroft, Patten, et al., 2014; Jerman et al., 2019; McGregor et al., 2014) have been recognized. Some of these materials, such as hemp-lime plasters have hygric and thermal qualities which can be used to reduce energy consumption (Barclay, Holcroft, & Shea, 2014; Mazhoud et al., 2016). However, all cellulose-containing, organic-based materials, such as wall paper and plasterboard top layer, are more susceptible to microbiological growth than inorganic materials (Hoang et al., 2010). Therefore, some research recommends antifungal additives as prevention to mould growth (Latif et al., 2015). However, the antifungal treatment seems not to be an environmentally friendly solution to the mould growth problem. Fungicides have very limited effectiveness

(Krueger et al., 2013), the addition of poisonous chemicals to the building fabric may pollute the indoor air (Horn et al., 2003; Taptiklis & Phipps, 2017), and the environment (Krus et al., 2009).

Taptiklis and Phipps (2017) argue:

> The need to control moisture is consistently made throughout much of the literature. This is obviously a challenge in New Zealand's maritime climate. More studies investigating the incidence of mould and other biological agents is required as a means to reduce moisture, dampness and mould. Greater understanding of the health effects of dampness and biological agents is also recommended (p. 80).

The moisture-related issues and the need for more NZ studies lead to the research objective: Examine the hygrothermal performance of NZ housing construction, focusing on internal envelope materials. Consequently, the topic of the following section leads to the research question: What is the impact of different building materials used on the indoor side of walls on the hygrothermal performance of a building? As mould and fungi thrive in the moist environment, it is desirable to regulate the RH in buildings. One of the suggested methods for moisture management is to use hygroscopic building materials and moisture buffering. Therefore, the following section reviews the existing knowledge in the moisture buffering.

3.2.4 Building Materials and Moisture Buffering

Temperature and RH levels in buildings are often regulated by large, costly, and energy-consuming HVAC (Van Belleghem et al., 2011). The literature review and praxis reveal that moisture buffering might assist the humidity control in buildings. Consequently, a significant decrease in indoor RH might be achieved with a targeted selection of construction materials and finishes (Brauner et al., 2019). Steady indoor humidity environment in an optimal range of 40-70% RH can be achieved with some existing materials or new developed composite hygroscopic materials (De Rossi et al., 2018; Xie et al., 2018). These materials are capable to absorb moisture and quickly dry out when the RH drops (Winkler et al., 2018). However, other factors have to support the moisture buffering to enhance the building hygrothermal performance (Romanska-Zapala et al., 2019). Thus, the consideration of complex processes and factors, such as thermal and moisture loads, materials, ventilation, airtightness, insulation, and drying possibility are necessary (Bomberg, Gibson, et al., 2015). Consequently, the design process has to take into account the evaluation of moisture buffering capacity (MBC), sufficient thickness and surface area of hygroscopic materials together with diffusion open surface protection (Maskell et al., 2018; Woods & Winkler, 2018). This leads to the research objective concerning development of a framework for designers to provide warmer, drier, and healthier houses for the NZ context. A research gap exists in the knowledge of an optimal design for hygrothermal performance, as stated by Wan et al. (2019):

> However, there is little study about the optimal design when hygroscopic materials are taken into application. It is better to know what type of hygroscopic material is suitable, how much area of the material is sufficient, and what thickness is best for moisture buffering at the design stage (p. 2).

Consequently, from this arises the following research question: What factors have the most influence on hygrothermal performance of houses in NZ?

Despite ISO 24353:2008 and JIS A 1470-1 standards, and various protocols to characterize moisture buffering potential (MBP) of single matter (Delgado et al., 2006; ISO, 2008; JIS, 2014; Rode et al., 2005), there is still not reliable moisture buffering characterization reflecting different moisture production regimes (Janssen & Roels, 2009; Roels & Janssen, 2006). The standard ISO 24353:2008 specifies a test method used for determination of moisture adsorption/desorption properties of building materials in response to humidity variation. This standard was last reviewed and confirmed in 2018. Therefore, this version remains current, although, it is more than 10 years old (ISO, 2018a). However, the current methods reveal to be unsuitable for the representation of the actual hygroscopic material performance in real buildings (Cascione et al., 2019). Therefore, M. Zhang et al. (2017) proposed basic moisture buffering value (MBV_{basic}) which is a new mathematical expression for moisture buffering value (MBV).

MBV was originally defined in the NORDTEST protocol with the assumption that the thickness of the material is greater or equal to the moisture penetration depth of the material (Rode et al., 2005). In the case when the thickness of the used building material is smaller, the retrieved MBV is lower. Therefore, MBV should be a product property provided by the manufacturer and not a material property (Roels & Janssen, 2005). The NORDTEST distinguishes between the standardized MBV and the practical MBV:

> The standardized Moisture Buffer Value (MBV) indicates the amount of water that is transported in or out of a material per open surface area, during a prescribed period of time, when it is subjected to specific variations in relative humidity of the surrounding air with a specified velocity. When the moisture exchange during the period is reported per open surface area and per % RH variation, the result is the MBV. Standardized exposure is 8 h of 75% RH, and 16 h of 33% RH. The unit for MBV is kg/(m^2·% RH) (Rode & Grau, 2008, p. 339).

> The practical Moisture Buffer Value ($MBV_{practical}$) indicates the amount of water that is transported in or out of a material per open surface area, during a certain period of time, when it is subjected to variations in relative humidity of the surrounding air. When the moisture exchange during the period is reported per open surface area and per % RH variation, the result is the $MBV_{practical}$. The unit for $MBV_{practical}$ is kg/(m^2·% RH) (Rode et al., 2005, p. 18).

The experimental determination of the $MBV_{practical}$ is based on an exposure of the material sample to cyclic step-changes in RH for 8 hours at 75% RH and 16 hours at 33% RH (Rode et al., 2005). As the phase change of water from liquid to vapour in the form of adsorption and desorption requires energy (Collet, 2017), the moisture buffering of hygroscopic materials influence the energy efficiency and potential energy savings (Osanyintola & Simonson, 2006; Rempel & Rempel, 2016). By using appropriate hygroscopic materials, the potential energy-saving rate might reach 25–30% (Kreiger & Srubar, 2019; M. Zhang et al., 2017). Recently published studies about the cooling potential of moisture buffering depict another field of interest (Campaniço et al., 2019; Rempel & Rempel, 2016; Xie et al., 2018). However, the complex building-scale benefits are still unknown and require further research (Kreiger & Srubar, 2019). As MBV is related to the hygroscopicity of the material, protective coatings might have an influence on the actual moisture buffering (Ramos et al., 2010). Therefore, coatings depending on their diffusion qualities have an impact on the MBV and the hygroscopic inertia of the room (Colinart et al., 2016). The hygroscopic inertia classes theory, introduced by Ramos in 2007 originally in Portuguese, shows that the RH peaks could be reduced by the use of hygroscopic materials (Ramos & de Freitas, 2009).

For some extreme subtropical conditions during the summer and winter period, Wu et al. (2015) suggested for hygroscopic characterization of composite materials ultimate moisture buffering value (UMBV). The UMBV is a testing method to different RH and temperature in three stages in the 24-hour cycle. The first stage is set at 50% RH at 23 °C for 12 hours, the second stage at 98% RH at 40 °C for 8 hours, and the third stage at 3% RH at 18 °C for 4 hours (Wu et al., 2015). This method demonstrates the strong relation of moisture buffering ability of materials to RH, temperature, and time the materials are exposed to certain humidity. However, the researcher notes that the only difference between MBV and UMBV is due to the different water region of the sorption isotherm. The sorption isotherm covers the hygroscopic and capillary water region where the moisture transport is conducted by a different physical phenomenon. Up to 95% RH, the adsorption is governed by vapour diffusion, and over 95% RH by capillary water transport (Lakatos, 2014; Tariku et al., 2010). Therefore, by the liquid water transport, the pores of the material are filled with water which promotes mould growth (Kazemian et al., 2019).

The exposed surface area of the indoor hygroscopic material determinates the effect of hygroscopic inertia (Ramos & de Freitas, 2012), and has an inevitable impact on the IAQ and thermal/hygrothermal performance of the whole building (Shehadi, 2018; Soudani et al., 2016). Accordingly, moisture buffering materials as a passive factor in the regulation of RH are preferably used as a finishing layer (De Rossi et al., 2018; H. Zhang et al., 2017) or separate features (Brauner et al., 2016). An example of a separate feature is a solar-regenerated rotating hygroscopic curtain system proposed by Salloum et al. (2015). Another is a desiccant coated air-to-air energy wheel in the HVAC system (Fauchoux et al., 2014). The finishing layer stands for an exposed indoor layer of walls and ceilings, but not an in-wall material. However, the vapour permeability of hygroscopic materials is significantly influenced by coatings and/or primers which can reduce their moisture absorbance (Brauner et al., 2019; Ramos et al., 2010; Santos et al., 2019). Consequently, the hygric properties of coating layers affect the inner layers by changing their MBV (Giosuè et al., 2017; Kaczorek, 2019).

During the last decades, new materials and admixtures are developed which support moisture buffering, such as a composite based on Typha Australis reeds and clay soil (Niang et al., 2018). Or a combination of insulation materials based on technical hemp, cultivated flux, or jute with plant facades (Korjenic et al., 2016). To maintain MBV but decrease the undesirable liquid water intake into materials, Jiang et al. (2018) tested a surface application of silica nanoparticles to hemp shiv. Consequently, the appropriate surface treatment might reduce water adsorption and the hysteresis between adsorption and desorption isotherms (Jiang et al., 2018). Another example of mechanical and physical properties' improvement of hygroscopic materials is the stabilization of hypercompacted earth by alkaline activation and silicon-based admixture (Bruno et al., 2017).

As already mentioned, the moisture buffering effect is based on continuous adsorption and desorption physical processes. Therefore, the drying time of the buffering material and the desorption phase are the key factors to moisture buffering (Aït Oumeziane et al., 2014). To evaluate the relationship between the moisture adsorption effect (MBE_a) and moisture desorption effect (MBE_d) of the hygroscopic materials H. Zhang et al. (2017) proposed a new index of MBE_a/ MBE_d.

For example, hygric properties of different natural fibre insulation could influence the hygrothermal performance of building thermal envelope (Latif et al., 2014; Latif, Tucker, et al., 2016). However, the use of insulation as a moisture buffering material is not desirable because the absorbed moisture might be locked inside of the wall construction and eventually cause its permanent wetting (Latif et al., 2015). As the drying phase is so important, especially biomaterials due to their thermal and hygric properties are potentially applicable for insulation on the indoor side of historical building envelopes (Jerman et al., 2019). Alternatively, using the hygroscopic natural insulation, such as sheep wool as an excellent acoustic insulating material (Zach et al., 2012) for internal walls (Brauner et al., 2016). High water content in porous material not only increases the density of the material, but it might influence the thermal conductivity and vapour diffusion resistance factor too (Collet, 2017). Therefore, the thermic characteristics of insulation are dependent on water content (Palumbo et al., 2018; Stazi et al., 2014). However, rather the cycle of wetting and drying than the actual water content of the insulation influences the energy performance of the building (Abdou & Budaiwi, 2013).

The idea to use hygroscopic qualities of insulation thus is controversial to the energy efficiency of the envelope. Besides that, considering a moisture buffering by insulation conflicts with the definition of moisture buffering capacity (MBC) (Padfield, 1999).

Insulation in the conventional building is usually encapsulated in a cavity and screened from the indoor by painted plasterboard and vapour barrier without any contact with surrounding air (Bomberg & Onysko, 2002; McNeil, 2018). Therefore, the drying potential of such construction is unknown. Due to the physical processes of phase-change, the mass transfer in hygroscopic materials has a significant impact on heat transfer (Collet, 2017; Lakatos, 2014). Therefore, the use of MBC of in-wall insulation is a risky attitude, which might cause several unintended problems, such as wetting and decay of the construction, and/or decreasing the thermal resistance of the building envelope (Latif et al., 2015). A different situation, as already mentioned, exists by retrofits of existing and historic buildings. Insulating materials with unique properties, such as capillary active thermal insulation calcium silicate boards, are applicable for the insulation of buildings with a high degree of wetting (Břenek et al., 2015). However, to avoid possible failures by energy retrofits, hygrothermal analysis and risk assessment shall constitute vital parts of the design decision process (Vereecken, Van Gelder, et al., 2015). Therefore, the next section deals with the depth of water penetration into building materials.

3.2.5 Sorption Active Thickness

Sorption consists of two physical processes — adsorption and desorption. The sorption isotherm is a function between RH and absolute moisture content (Hens, 2017). Therefore, the sorption isotherm depicts the relation of the equilibrium moisture content to the ambient relative humidity by constant temperature (Mazhoud et al., 2016). The determination of hygroscopic sorption properties of porous building materials, as specified in ISO 12571:2013, consists of two alternative methods, such as desiccator and a climatic chamber. Both methods measure the steady-state water content after establishing the equilibrium at each RH by constant temperature of (23 ± 0,5) °C or (27 ± 0,5) °C in tropical countries (ISO, 2013). However, the built environment is rarely in steady-state. Thus, to simulate the real situation in building Růžička and Diviš (2019) developed a full-scale test of dynamic sorption for building structures. Unfortunately, for most building materials, the exact sorption isotherm is unknown (Strangfeld & Kruschwitz, 2018). Alternatively, by some materials, such as cement-based products, sorption isotherms are influenced by the test method used (Krejcirikova et al., 2018). Therefore, the experimental results for the description of water transport might differ depending on the used assumptions and concepts (Korecký et al., 2015), or the material tested (Hansen et al., 1999). Consequently, the exactness of laboratory-measured material characteristics is often insufficient for use in advanced hygrothermal models (Bomberg & Pazera, 2010).

Adsorption at low moisture contents, called mono-molecular adsorption, is based on water physically bound to the pore surfaces in the porous material. The water molecules form a monolayer to which adhere further water molecules when RH increases. The second stage calls the poly-molecular adsorption. When the water content in the pores reaches the critical moisture saturation degree, the water forms a liquid bridge and the adsorption is based on capillary condensation on the menisci in the pores (Collet, 2017). S. Yu et al. (2012) describe the critical moisture content in this stage as: "Moisture content at which capillary liquid flow carries more moisture than the WV diffusion (so called transition point). Typically, it happens between 80% and 95% RH but generally is unknown" (p. 209). This process is graphically plotted as the sorption isotherm, which describes the moisture storage capacity for porous materials at equilibrium with the ambient air (Eriksson et al., 2019). However, the actual hygroscopicity of a material depends on the pore size. As the smaller the pore size, the higher the specific pore surface and the sooner the capillary condensation (Hens, 2017). Therefore, by larger pore diameters higher ambient RH is needed before the capillary condensation starts. This phenomenon explains the strong increase in moisture content by most building materials above 90% RH (Hens, 2017).

The desorption process usually progresses differently from the adsorption process. Therefore, a difference between water content by the same ambient RH might appear between adsorption and desorption. This difference is called hysteresis (Alioua, Agoudjil, Chennouf, et al., 2019). The hysteresis has many causes. According to Strangfeld and Kruschwitz (2018), the hysteresis is due to trapped water in the pore system. However, the water uptake and release represent very slow processes which are often not respected while testing. These processes depend largely on the pore size, the contact angle of the meniscus, the salts content, and temperature (Hens, 2017).

However, the water penetrates during the sorption process in the normal circumstances only to a certain depth of the material (Maskell et al., 2018). The aspiration to reflect the influence of the cyclic variations in indoor humidity on mass-based moisture content led to the development of the effective penetration depth concept (Cunningham, 1992; Kerestecioglu et al., 1990). The penetration depth is a material property determining the thickness of hygroscopic material, which is subjected to RH variations at its surface in a periodic way (Rode et al., 2005). Therefore, beyond the thickness of material determined as the effective penetration depth, the MBC does not increase (Maskell et al., 2018). On the contrary, if the thickness of the outer layer in a wall assembly is less than the penetration depth, the WV reaches the next layer in the assembly. The whole MBC of the assemblies are therefore determined by MBV and thickness of the outer layers (Kaczorek, 2019). However, as the models due to approximations tend to overestimate the moisture penetration depth, Maskell et al. (2018) recommends direct measurement of the penetration depth. Therefore, the researcher suggests using for the penetration depth measurements a device based on the non-destructive method of gamma rays attenuation, introduced by Guimarães et al. (2018).

Similar to the effective penetration depth concept, the sorption-active thickness introduced by Hens (2017) depicts an attribute of each hygroscopic surface. The sorption-active thickness is defined as "the distance between the inside surface and the interface where the vapour pressure amplitude due to a 1 Pa periodic oscillation at the inside surface dampens to 0.368 Pa" (Hens, 2017, p. 283). Therefore, the moisture buffering/hygric inertia has only an impact when the vapour pressure indoors and/or outdoors change (Růžička & Diviš, 2019). In the context of sorption, the capillary absorption coefficient and the capillary moisture content represent two important hygric material properties. However, until now, any full agreement regarding the data processing and the experimental protocol of the capillary absorption has been reached between researchers (Feng & Janssen, 2018).

The moisture penetration depth concept was further developed in the effective moisture penetration depth (EMPD) model (Cunningham, 1992; Kerestecioglu et al., 1990). The EMPD model calculates the moisture buffering by accounting for the diffusion resistance of the material, and the resistance between the air and the surface (Cascione et al., 2019). Therefore, the EMPD model is a compromise between the simple, effective capacitance model and the complex finite-difference approach

(Woods et al., 2013). The original EMPD model calculates for one buffering layer only and constitutes a part of EnergyPlus v7.2 as a fixed model (EnergyPlus, n.d.). However, the improved EMPD model accounts for the moisture transfer between the air and two layers with uniform moisture content. The first layer is the surface, short-term moisture buffering layer and the second is the deep, long-term buffering layer (Woods & Winkler, 2018). Generally, the advantages of EMPD models are especially a reasonable accuracy and short computing time (Wan, Xu, & Li, 2017). The EPDM models are widely used among the HAM models addressed in the following section.

However, if the hygroscopic material is thinner than its moisture penetration depth, the simulation results of the original EMPD model might be inaccurate. Therefore, Wan, Xu and Li (2017) proposed a theoretical moisture penetration depth (TMPD) model. The TMPD model evaluates the conditions of the moisture permeation through the building wall materials. For example, the gypsum board daily TMPD is 0.064 m but its real thickness is usually 0.01 m. Therefore, already during the first 24 hours, the WV penetrates the material (Wan, Xu, & Li, 2017, p. 6), and the amount of absorbed WV drops (Wan et al., 2019). To determine the optimal thickness for the maximum possible MBC Wan et al. (2019) proposed a method for the optimal moisture buffering thickness of hygroscopic material. Another improvement of EMPD models, to make them suitable for thin and limited moisture buffering materials, represents a double effective moisture penetration depth (DEMPD) model developed by Wan, Xu, Gao, et al. (2017).

Based on moisture buffering, effective moisture penetration depth, and other physical properties of materials, hygrothermal analyses and modelling deal with moisture transport in buildings (Wan, Xu, & Li, 2017). This leads to the research question: What are the requirements for undertaking an effective hygrothermal assessment of houses during the early design stage? Before going more into the depth of hygrothermal modelling, a brief history and an overview of the methods for hygrothermal analyses are addressed in the following section.

3.3 Hygrothermal Analyses and Modelling

In the 21st century, saving energy and reducing CO_2 emissions became the priorities of politics and the economy. Researchers are therefore focusing on the reduction of the negative impact of buildings on the environment, and developing diverse analytical and simulation tools to improve the thermal and hygrothermal performance of buildings.

3.3.1 Looking Back

Hygrothermal analyses and modelling emerged as a result of expanding moisture problems in buildings (Bomberg & Onysko, 2002). Since Philip and De Vries (1957), Krischer and Kröll (1963), and Luikov (1964) published their work, several researchers developed mathematical models based on numerical methods for calculation of distributions and fluxes of heat and moisture transfer in buildings. The first models were utterly based on water vapour diffusion (ASHRAE, 1977; Glaser, 1959; Kieper et al., 1974). Vos (1969) added to the diffusion capillary suction and explained the process of condensate deposits in assemblies and their influence on water adsorption. Bomberg (1974) united capillary suction and diffusion in a generalized suction concept. However, the moisture and heat transfer, as a very complex phenomenon (TenWolde, 1989), is affected by variable material properties and different time scale for each physical process (Gasparin et al., 2018a). In spite of the fact that the role of air movement in the hygrothermal condition of buildings was already mentioned by Rowley et al. (1941), air convection and ventilation were not modelled until the 1980s (Cunningham, 1988; Haghighat et al., 1989; Kronvall, 1980; TenWolde, 1985).

Several improvements to the traditional diffusive models enable researchers and building practitioners for the evaluation and analysis of the hygrothermal performance of buildings (Busser et al., 2019). Based on De Vries, Krischer, and Luikov, Kießl (1983) introduced moisture potential of materials and modelled heat and mass transfer in building components. Neiß (1982), although dealing with soil, successfully integrated complex frost phenomenon of capillary media into existing models. The mathematical formulas of heat transfer dependent on water content and temperature above and under freezing point represent an important improvement to the hygrothermal models (Neiß & Winter, 1982). Pedersen (1990) modelled some consequences of unfit moisture tolerance in building constructions. Wang et al. (1991) studied influences of air infiltration on the airflow and contaminant distribution in a ventilated isothermal two-zone enclosure.

Based on moisture buffering, Kerestecioglu et al. (1990) and Cunningham (1992) developed an effective moisture penetration depth (EMPD) model. Another improvement to the modelling of moisture transport was a single moisture transport coefficient formulated by Garrecht (1992). The united coefficient reflects the fact that the water phases – fluid and vapour are not possible to measure separately but only as moisture transport. The moisture transport coefficient is determined by experimental measures. Garrecht also investigated the influence of different salts on sorption isotherms by diverse building materials and simulated complex 2D building structures (Grunewald, 1997). Häupl et al. (1993) described coupled moisture, air, and heat transport in capillary building materials. The development of whole building heat, air, and moisture (HAM) analysis started with the introduction of inter-zonal airflow patterns within a building (Allard et al., 1990). Baker et al. (1994) applied Computational Fluid Dynamics (CFD) models to predict indoor room air motion. However, the CFD models as a vital part of HAM modelling exist already since the 1980s (Maas, 1992).

Another significant milestone in the hygrothermal simulation represents the work of Künzel (Künzel, 1995; Künzel, 2014; Künzel et al., 2012). Künzel (1994) implemented air moisture gradient and water vapour pressure gradient into hygrothermal models and developed hygrothermal simulation software (Fraunhofer Institute for Building Physics, n.d.-b). Grunewald (1997) added to the diffusion in porous materials convective flows as heat and moisture transport phenomenon. Janssens (1998) originated a 2D model for HAM calculation in lightweight roofs. Janssen investigated thermal diffusion as a complementary force to vapour pressure gradients in WV transport in porous materials. His investigation confirmed that the thermal diffusion, due to its low magnitude in WV transport, could be neglected. Therefore, vapour pressure represents the sole significant transport driver of WV in porous materials (Janssen, 2011).

The improved convection/diffusion method takes the air in- and exfiltration, and related bulk heat and vapour flow into account (Busser et al., 2019). Therefore, at the beginning of the 21st century, the convection/diffusion method was, besides the Glaser method, the most used simplified HAM simulation (Hens, 2002). However, more sophisticated models have been developed. For example, models dealing with mould growth (Ojanen et al., 1994; Ojanen & Viitanen, 2016; Sedlbauer & Krus, 2003; Viitanen & Ojanen, 2007), or simulating wind-driven rain loads on envelopes (Blocken et al., 2003; Janssen et al., 2007; Kalagasidis, 2004; Künzel & Zirkelbach, 2013).

Consequently, the aim for more energy efficiency of built environment led to the coupling of hygrothermal models to Building Energy Simulation (BES) models, or Computational Fluid Dynamics (CFD) models (Van Belleghem et al., 2011). Van Belleghem et al. (2014) introduced a coupled heat, vapour and liquid moisture transport model for porous materials implemented in CFD. The presented differential formulation in the air domain coupled with moisture transfer allows for a simultaneous modelling of convective and diffusive HAM transport in porous materials (Ayres de Mello et al., 2019). Another example of an improved model is the hygro-thermo-mechanical multiphase model which accounts for long-term water absorption into air pores (Eriksson et al., 2019).

The most common use of HAM models in building physics is to investigate the physical phenomena (Mendes et al., 2019). However, some researchers use numerical methods for solving inverse problems in building physics. Thus, it is possible to estimate, for example, the material properties from experimental data (J. Berger et al., 2018). Generally, the numerical methods used by hygrothermal simulation models are well described in *Numerical methods for diffusion phenomena in building physics: A practical introduction* (Mendes et al., 2016). The new edition of this book intends to encourage new ways of hygrothermal simulation in building physics (Mendes et al., 2019). Mendes et al. (2019) introduce innovative approaches, such as reduced order models, boundary integral approaches, and spectral methods into the field of building energy simulation tools.

3.3.2 HAM Models

HAM models allow to simultaneously quantify heat, air, and mass transfer in buildings. Therefore, HAM models are suitable for simulation of the thermal and hygrothermal interactions in building elements or whole buildings (Van Belleghem et al., 2011). Some HAM models additionally deal with consequences of moisture related issues, such as mould, corrosion, frost damage, and salt transport (Kalagasidis et al., 2008).

Examples of HAM models are MATCH, WUFI, Latenite, Delphin, UMIDUS, HAM-Tools, EMPD, MOIST, and HygIRC (Boudreaux et al., 2017; Gasparin et al., 2018b; Woloszyn & Rode, 2008). Annex 41 named seventeen HAM tools capable of whole building hygrothermal simulation. One of the named simulations has been HAM-Tools (Woloszyn & Rode, 2008). HAM-Tools might be rather described as a modular system, using the graphical programming language Matlab/Simulink, and being more suitable for research and education than for commercial use (Kalagasidis et al., 2008). However, HAM-Tools is not a whole building simulation tool but a one-dimensional HAM transfer simulation model (Delgado et al., 2013). The software, originally developed by Kalagasidis (2004) is since 2012 no more available (International Building Physics Toolbox, 2012).

However, the number of available HAM tools is continually changing. Although proceeding a comprehensive search, the researcher was not able to determine the exact count of current HAM tools. In 2008 there have been seventeen tools used for IEA-Annex 41 analysis (Rode et al., 2008). According to López et al. (2017), fourteen programs have been publicly available in 2017. However, these programs vary in mathematical complexity (Karagiannis et al., 2018). The sophistication of each software depends on various parameters, such as input material properties (López et al., 2017), moisture transfer dimension, and type of flow (steady-state, quasi-static or dynamic) (Delgado et al., 2013).

Most of the HAM simulation tools are based on mass and energy conservative modelling using standard discretization techniques (Berger, Mendes, et al., 2017). The discretization process concerns time and space. The implicit time discretization scheme solves the mathematical problem through matrix inversion. By non-linear problems, which is the case by hygrothermal processes, the solution is calculated in sequential steps (Janssen et al., 2007; Mendes & Philippi, 2005; Rieth et al., 2018). The explicit time discretization scheme solves the mathematical problem through diagonal matrix inversion, which includes inversion of the terms on the diagonal only (Kalagasidis et al., 2007; Kovács & Ván, 2015). The majority of the HAM programs use the Euler and Crank-Nicolson (Crank & Nicolson, 1947) implicit scheme with finite-element, finite-difference, or control-volume spatial discretization methods (Janssen et al., 2007; Mendes & Philippi, 2005; Steeman et al., 2009). Nevertheless, transient models of moisture transfer through porous materials, based on the diffusion process, struggle with the simulation of the moisture advection transfer (Colinart et al., 2016; Labat et al., 2015; McClung et al., 2014). To overcome the discrepancies between the simulation and experimental results, Berger, Gasparin, et al. (2017) proposed the Scharfetter and Gummel (1969) numerical scheme. However, this scheme is not unconditionally stable as the Crank–Nicolson scheme. Therefore, the calculation with the Scharfetter-Gummel method is possible with the Courant-Friedrichs-Lewy condition (Gosse, 2018). The inclusion of an advective term in the diffusive model may improve the results (Berger, Gasparin, et al., 2017).

However, the implicit methods require sub-iterations by treatment of nonlinear problems, which increase the total central processing unit (CPU) time - computational run time (Gasparin et al., 2018b). Therefore, Berger et al. (2016) investigated the use of model reduction techniques, so-called Proper Generalised Decomposition (PGD), for building physics applications. PGD represents an option to reduce computational costs at different levels (Berger, Mendes, et al., 2017).

Despite all the developmental process, the complex heat, air, and moisture phenomena requires the solution of large algebraic systems for the whole building modelling (Berger, Mendes, et al., 2017). To further minimize CPU time, Gasparin et al. (2018c) proposed the use of improved DuFort-Frankel explicit scheme. The DuFort-Frankel scheme proved to be unconditionally stable and twice faster than the Crank-Nicolson approach (Gasparin et al., 2018c). The driving force behind this and other model reduction techniques represents the intention of producing efficient methods for moisture diffusive transfer through porous materials with a reduced CPU time (Gasparin et al., 2018a).

Gasparin et al. (2018a) argue:

> It is important to mention that *the computational resources available in a computer are not increasing any more* [emphasis added] (Waldrop 2016). Thus, it is worth investigations to develop numerical models based on an optimal usage of the available computational resources. (p. 967)

However, this argument is not correct. The in the quote cited author, Waldrop (2016) describes the limitations of semiconductors while they get too hot by smaller and smaller silicon circuits. But he does not write that the computer's resources are stagnating:

> For the past five decades, the number of transistors per microprocessor chip — a rough measure of processing power — has doubled about every two years, in step with Moore's law... Chips also increased their 'clock speed', or rate of executing instructions, until 2004, when speeds were capped to limit heat. (Waldrop, 2016, p. 146)

The researcher agrees that the classical computer chips are down for Moore's law because of the heat problem. However, scientific and industrial communities are working on the increasing semiconductor device integration density using new technologies and new materials (Oh et al., 2019). For example, Mizsei and Lappalainen (2019) introduced new phonsistor (phonon transistor) based thermal-electronic logic system or thermal-electronic logic circuit. Nanoelectronics (Ahopelto et al., 2019), carbon nanotube and nanowire (Chaudhury & Sinha, 2019), ultrathin wafer (Dong & Lin, 2020), or hybrid spintronic materials (W. Liu et al., 2019) to name a few, are new technologies in computing. Simultaneously, new ways of digital communication are accompanying the technical development of the chip production. Fibre-optic communication with the application of high-speed digital signal processing (DSP) enables to maximize system performance (Hui, 2020).

Therefore, the argument that the computational resources in a computer are not increasing any more is unfounded. Nevertheless, the reduction of CPU time for hygrothermal simulations is crucial to the implementation of these techniques into the construction design process based on optimal usage of the available hardware (Gasparin et al., 2018a). Therefore, the calculation method has to be chosen with the consideration of the computational cost (CPU time) and required solution accuracy (Berger et al., 2019).

Building Energy Simulation Tools and Hygrothermal Analysis

To evaluate and test the thermal performance of buildings, several building energy simulation tools have been developed (Campana & Morini, 2019). The International Building Performance Simulation Association (IBPSA) lists in the Building Energy Software Tools (BEST) directory currently 68 whole building energy simulation tools (International Building Performance Simulation Association, n.d.). However, although the web page offers search under diverse capabilities of the listed software, hygrothermal simulation or HAM is not an option. In the BEST directory, amongst others are tools, such as TRNSYS, ESP-r, Autodesk Green Building Studio, IES VE, and EnergyPlus. However, not all the programs in the BEST directory are coupled HAM transfer models and some are not listed at all, such as WUFI Plus or Delphin. Schmidt et al. (2012) compared TRNSYS with WUFI Plus and found out that the simulation results are similar with quite small distinctions. Another software in the BEST list is IES Virtual Environment (IES VE). IES VE is a suite of building performance analysis tools, such as Apache, Apache HVAC, and MacroFlo (Integrated Environmental Solutions, n.d.). Apache is a module for heat transfer by conduction, convection, and radiation; Apache HVAC is a module for heating, ventilation and air conditioning, and MacroFlo deals with moisture balance (Corrado & Fabrizio, 2019).

EnergyPlus is often used to evaluate the energy performance of buildings (Krone et al., 2015). Additionally, EnergyPlus offers a heat, air, and moisture transfer (HAMT) model of a building component in the form of a one-dimensional model (EnergyPlus, n.d.). However, the EnergyPlus HAMT model with assumptions and simplifications neglects some physical phenomenon, such as sensible and latent heat effects or multiple condensation planes (Antretter & Pallin, 2019). Therefore, EnergyPlus as "The user defined model relies completely on a good user input for the resulting air flow and it applies one static number over the whole simulation period" (Antretter & Pallin, 2019, p. 6).

However, the building energy modelling (BEM), to be reasonably accurate, require a large computer memory and CPU time (Gao et al., 2019). Therefore, researchers investigate the employment of artificial intelligence in the form of intelligent co-simulation to dramatically reduce the building performance simulation CPU time (Julien Berger et al., 2018). Nevertheless, most energy simulation tools do not adequately model the hygrothermal performance of buildings (Ferroukhi et al., 2016). The BEM are still not able to systematically deal with temperature, heat, and RH nor to adopt an integrated modelling approach (Harish & Kumar, 2016). Although several times have proven that the coupled HAM transfer influences the cooling and heating energy consumption (Jerman et al., 2019; Khoukhi, 2018), the current conventional BEM ignore the hygrothermal interactions in building envelopes (Yu et al., 2019).

Additionally, the BEM require accurate data; otherwise, their results might not be reliable (Prada et al., 2018). The researcher notes that the accuracy of data is equally important for the hygrothermal models.

3.3.3 Influence of Hygrothermal Interactions

Based on the existing literature and praxis, it is evident that the coupled HAM transfer influences the indoor environment, the energy demand, and the durability of buildings. The investigation of hygrothermal risk analysis gains importance especially under the ongoing climate changes (Gaur et al., 2019). Therefore, the assessment of the critical hygrothermal parameters should constitute a part of the construction design process (Ameri & Rüther, 2019).

Consequently, to make buildings more resilient, architectural design has to be informed by the investigation of the hygrothermal interactions (Tariku et al., 2011). Factors, such as wind-driven rain exposure, plaster capillarity, or presence of a vapour barrier affect the hygrothermal performance (Bastien & Winther-Gaasvig, 2018; Carbonez et al., 2015). Therefore, HAM models enable the simulation of leaks at specified locations (Carbonez et al., 2015) or the moisture control and energy efficiency potential of construction components (Antretter et al., 2019). As the coupled HAM transfer leads to the change of latent heat in the building envelope, the hygrothermal processes influence the total energy balance of the building (Liu et al., 2017; Yu et al., 2019). Therefore, Steeman et al. (2009), Woloszyn et al. (2009), and Rempel and Rempel (2016) investigated moisture buffering capacity of building materials for evaporative cooling while using hygrothermal simulations. Leroux et al. (2019) studied a low-energy evaporative cooling system based on the porous evaporator wall. The moisture buffering impacts the indoor environment by reducing or delaying peaks in the indoor humidity (Winkler et al., 2018). Therefore, using different building materials leads to notable differences in hygrothermal performance (Radon et al., 2018). It leads to the research question: Which physical qualities of building materials influence hygrothermal performance most significantly?

As the hygrothermal interactions influence the building performance (Ferroukhi et al., 2016), many researchers scrutinize existing and new materials on their hygrothermal properties. Alioua, Agoudjil, et al. (2019a) used a combination of experiment and numerical modelling to test the hygrothermal properties of innovative concrete based on date palm fibres. Hygrothermal models proved to be sustainable for studies of hygrothermal behaviours of bio-based building materials and walls (Alioua, Agoudjil, et al., 2019b). The hygrothermal material properties are considerably influenced by water content and temperature of the material (Ferroukhi et al., 2019). Therefore, the knowledge of hygrothermal material properties enables informed design decisions by using hygrothermal simulation (López et al., 2017). The hygrothermal parameters and hygrothermal simulation provide a comprehensive reference for sustainability assessment of building materials. For example, a substitution of timber by bamboo reveals to be feasible in lightweight construction in hot and temperate regions where the bamboo grows (Huang et al., 2017). Another area of interest represents the improvement of thermal insulation by existing buildings. Especially interior insulation requires a careful approach to potential moisture risks and benefits from an analysis by hygrothermal simulation (Jerman et al., 2019; Knarud & Geving, 2017).

The airflow through air leakages transports water vapour into the building envelope (Künzel et al., 2012). Particularly in lightweight wall assemblies, the airflow through leakages influenced by pressure difference might cause convective moisture entry and interstitial condensation (Kölsch et al., 2016). Consequently, cracks in construction timber, such as engineered wood, glulam beams, or CLT panels considerably impact their water vapour resistance properties (Fortino et al., 2019; Kukk et al., 2017). However, not only engineered timber products but generally all laminated composites are influenced by temperature and intruding water. As a result of these processes, laminated composites are affected by hygrothermal ageing (Rocha et al., 2017). Therefore, the influence of cracks on the hygrothermal performance of lightweight construction needs further analysis, particularly in high RH environment (Ameri & Rüther, 2019; Schmidt & Riggio, 2019).

The correlation of temperature and high humidity by timber products was already emphasized by Baker et al. (2009). The permeability of timber-based materials, notably at RH above 70%, is influenced by temperature (Chiniforush, Valipour, et al., 2019). However, the moisture transfer in the most porous building materials is mainly driven by the vapour pressure gradient and not significantly temperature dependent (Baker et al., 2009). Therefore, particularly by timber-based products sorption/desorption tests and the comprehensive numerical multi-scale and micro-scale experimental studies need to support the hygro-thermo-mechanical and long-term analysis of engineered timber (Chiniforush, Akbarnezhad, et al., 2019). The data from such studies would be similarly vital for hygrothermal modelling as the numerical simulations in the classic diffusive model tend to underestimate the adsorption process (Busser et al., 2019).

3.3.4 Reasons for Limited Use of Hygrothermal Modelling

Although numerous HAM models, such as WUFI, EnergyPlus or ESP-r, are available the applying of hygrothermal simulation in the design process is not common (Jaques et al., 2016). Possible reasons for the limited use of hygrothermal modelling in architectural practice are various. The primary barrier to the more widespread use of hygrothermal simulation by architectural designers is the missing knowledge of building science (Romanska-Zapala et al., 2019). The hygrothermal models require regional weather data, prediction of indoor conditions, and correct material properties. Additionally, some models require a high level of user input (Antretter & Pallin, 2019). Therefore, user errors remain a significant cause of unreliable (Zakula et al., 2019) and sometimes legally actionable building performance simulation results (Melton & Yost, 2014). Consequently, the careful use of HAM models needs correct boundary conditions and hygric material properties (Desta et al., 2011; Feng et al., 2015).

The shortage of complete sets of hygroscopic material property data represents another barrier to the use of HAM models in design praxis (Barclay, Holcroft, & Shea, 2014). Additionally, current material data is sometimes incorrect (Prada et al., 2018), not reproducible (Feng et al., 2015), or varies in its detail (Melton & Yost, 2014). Therefore, to enhance the reliability of HAM analysis determination of accurate material properties depending on temperature is necessary (Feng & Janssen, 2016). However, full consensus about the capillary absorption test and the processing of experimental data does not exist (Feng & Janssen, 2018). Consequently, some published data are presented with deficient hygric material properties. For example, the presentation of incorrect vapour permeability of wood-fibre insulation in Vololonirina et al. (2014) led to misinterpretation of air-gap-corrected vapour permeabilities by several authors. Janssen (2018) writes in this matter: "… the measurement, the calculation and the presentation of this vapour permeability has suffered from various errors, invalidating the obtained intrinsic vapour permeabilities of wood-fibre insulation" (p. 39). Another issue exists with the adsorption process measuring in most of the over-hygroscopic range. Therefore, to solve the unsatisfactory experimental protocols for the measuring of moisture storage curves, Feng and Janssen (2019) proposed the semi-permeable membrane method and the psychrometer method.

Early integration of building performance simulation tools in the design process could support the aim to reduce the energy consumption of buildings (Yigit & Ozorhon, 2018). However, architectural designers find most of the tools inadequate in supporting the design decision process (Attia et al., 2012). Thus, the research question developed: How can integral principles be applied to determine potential building performance weakness during the design stage?

After the description of the state-of-the-art in hygrothermal modelling, the literature review addresses changes in the building process from traditional to interdisciplinary and collaborative practices. Therefore, the following section examines Building Information Modelling (BIM) and interoperability.

3.4 BIM and Interoperability

The tools and techniques brought by Building Information Modelling (BIM) are reforming how the modern construction industry operates (Ghaffarianhoseini, Tookey, et al., 2017). Therefore, BIM represents a paradigm shift in construction (Khosrowshahi, 2017). The traditional building process in separate stages is transforming into a dynamic operation with shifting important decisions ahead towards design stage (Borrmann, König, et al., 2018; Sacks et al., 2018). BIM constitutes a vital part of digital transformation in the built environment and supplying manufacturers (The British Standards Institution, 2018). Consequently, BIM is described in the relevant standards, such as the ISO 19650 series as a process (British Standards, 2019c; NBS, 2019). The whole procedure of building is becoming more complex from concept, through design, construction, maintenance and operation to decommissioning (Doumbouya et al., 2017; Kent & Becerik-Gerber, 2010). Therefore, interdisciplinary and collaborative practices within the built environment are pivotal to the efficiency in delivery and operation of assets (British Standards, 2019b). Consequently, interoperability between diverse BIM tools enables the comprehension of diverse factors in the process (Dixit et al., 2019; Yan et al., 2013).

3.4.1 BIM

BIM is a term that represents simultaneously a business process, the digital representation of physical and functional characteristics of a facility, and the organization and control of the business process over the entire life cycle of a building (National Institute of Building Sciences, 2015). From the BIM original goal of achieving more efficiency and economic gain of an investment, is BIM increasingly considered as a method for optimization of economic aspects as well as ecological and environmental issues (Chong et al., 2017). The processes and technologies behind BIM are based on parametric design, using computers, calculations and modelling, deriving 2D and 3D drawings from a model and a single integrated database for visual and quantitative analyses (Howden, 2015). The BIM models can also incorporate time and scheduling resulting in 4D data, cost elements (5D), and asset management (6D) during the whole life cycle of a building (Georgiadou, 2019). Each D indicates the data dimension affiliated to the BIM model, such as 7D for sustainability measures (Mayouf et al., 2019).

BIM creates and uses standardized information about the building during the whole life span of the asset (Dastbaz et al., 2017). The standardization includes design, calculations, economic and ecological considerations, construction process, scheduling and materials ordering, operation, rebuild to demolition, and recycling of materials (Jensen et al., 2013). BIM exploits the potential to manage data about the life cycle of an asset, inclusive the potential for sustainable building refurbishment (Kim, 2019). Consequently, the synchronization of BIM data with the real-life construction process constitutes a vital part of the BIM process (Chen et al., 2015). Additionally, the emergence of spatial information by integrated BIM-GIS data improves the potential for energy efficiency and sustainable energy management (H. Wang et al., 2019). BIM can also be used in diverse fields of the design decision process, such as path planning in fire safety (Lin et al., 2013) or for fire emergency management (Ma & Wu, 2020).

During the design process of sustainable assets, it is important to evaluate the project from different points of view, for example, by using the integrated design process approach (Romanska-Zapala et al., 2019). Focusing on building design and assembly, including operation costs, sustainability issues, and preventing premature failures have an impact on the building life cycle costs and the environment (Bryde et al., 2013). Continuous life cycle costing and LCA through the life of assets, on the other hand, contribute to BIM by maintaining data of financial and environmental impacts (Tam & Le, 2019). Therefore, building sustainability assessment methods might benefit from BIM (Carvalho et al., 2019).

"BIM … contains all the data needed for supporting sustainable design of projects throughout its whole life cycle, particularly when coupled with relevant performance analyses tools" (Khosrowshahi, 2017, p. 54). However, the researcher notes that this statement is true in theory only as a potential of BIM. In reality, there are many known interoperability issues and factual lack of data for sustainability assessment (Akanbi et al., 2019; Carvalho et al., 2019). Nevertheless, modelling allows the variation of parameters in calculations for better decisions on the concrete design at the stage when the costs for changes are the lowest (Azhar et al., 2015). Every dollar spent properly at the design stage could save 20 dollars in construction and 60 dollars during the operation of the building (Lopez & Love, 2012).

The traditional method to construct a building is logical and linear. In essence, the sequence is to fully design the building, tender the project, select a contractor, construct the building, and finally hand over the project to the occupant (Sacks et al., 2018). However, as timelines have contracted and expectations have risen, the building industry has reached a turning point (Carvalho et al., 2019). The traditional linear way of the design and construction process is increasingly incompatible with the technology used for those activities and the growing demand for sustainability and efficiency (Alwan et al., 2017). The use of 2D and 3D modelling and large amounts of data have traditionally served architectural designers well (Sacks et al., 2018). However, the traditional way is lacking cooperation during the building process itself (Azhar, 2011). Between the architectural designer and the contractor, there is a risk gap based on the lack of cooperation or willingness to share information, and non-existence of an agreement or contract (Lopez & Love, 2012). Additionally, the often poor architectural designer – client relationship, described as a “wicked problem” has multiple causes (Frimpong & Dansoh, 2018). As a result of this situation, today’s building costs are too high, they do not work as well as they could, and they do not last long enough - in other words, they are not sustainable enough (Georgiadou, 2019).

BIM implementation process requires besides the firm technical knowledge of the highly complex building model human intervention (Dimyadi et al., 2016). The successful data exchange between project stakeholders form a vital part in the ultimate success of BIM (Nawari, 2012). However, the architecture, engineering, and construction (AEC) industry with its fragmented nature delays the widespread use of BIM (Borrmann, König, et al., 2018). Therefore, the social proactive and reactive opportunities for enhancing BIM benefits include collaboration, transparency, and clear communication (Blay et al., 2019). The most reported BIM benefits relate to the cost control and reduction, and to time savings (Bryde et al., 2013). However, the unavailability of data limits the numerical cost-benefit analysis of BIM implementation (Lu et al., 2014).

Apart from the energy modelling (Shoubi et al., 2015; Stegnar & Cerovšek, 2019), sustainability assessment has a minimal presence in the used BIM tools (Carvalho et al., 2019). To be able to take the responsibility for our future there is a significant requirement for accountability and the ability to quantify the ecological, social and economic value of the projects (Chong et al., 2017). For example, quantification of the impact of reducing volatile organic compounds (VOCs), maximizing day light use and fresh air, reducing noise or humidity in buildings on health issues, such as asthma, chronic headaches, burnout syndrome and their macroeconomic costs (Hoisington et al., 2019; Lane, 2019). Consequently, how can these building components have their environmental impact factored into the BIM process (Jin et al., 2019)?

Green BIM faces several challenges, such as weak interoperability of green building tools and lack of holistic industry standards (Lu et al., 2017). However, some researchers use BIM for modelling of the social housing requirements (Baldauf et al., 2013), natural ventilation, and thermal comfort (Gallardo et al., 2017; Gan et al., 2019). Others investigate the daylight analysis by using BIM (Welle et al., 2012; Yan et al., 2013). Rahmani Asl et al. (2015) and Natephra et al. (2018) introduced BIM-based optimization of energy performance into the energy-efficient building design.

In response to the changing construction process sequence, BIM is increasingly being implemented around the world. In particular, BIM is used widely in the USA, UK, Scandinavian countries and Singapore (Ghaffarianhoseini, Tookey, et al., 2017). Due to the significant UK government decision in 2011, about BIM level two becoming mandatory for all public construction projects by 2016, the UK became a global leader in the employment of BIM (Georgiadou, 2019). Other countries are following these pioneers and have the opportunity to learn from their experiences. New Zealand and Australia are considered "fast followers" of these BIM adopting countries (Bernstein, 2014). However, this information was published in a commercially-driven industry report. Generally, research-based analysis of macro BIM adoption allowing for evaluation or comparison of BIM policies worldwide are not available (Succar & Kassem, 2015). Therefore, Kassem and Succar (2017) assessed macro BIM adoption across markets using five conceptual models validated through capturing data from 21 countries.

3.4.2 BIM in New Zealand

New Zealand (NZ) needs a new approach to waste minimization (New Zealand Government, 2019a) and to improve urban development and housing affordability (New Zealand Government, n.d.). The increase in productivity and affordability of construction sector is partly dependent from the level of BIM integration (Jowett, 2015). Therefore, NZ is accelerating the adoption of BIM since the first BIM handbook was published in 2014 (BIM Acceleration Committee, 2019). However, according to BIM macro maturity components, NZ ratings are equal or below 25% with a gap in learning and education (Kassem & Succar, 2017, p. 291, Table 8). To improve the level of BIM adoption, NZ established the National Technical Standards Committee in 2012 and the National BIM Education Working Group in 2014 (Puolitaival et al., 2016).

Recently some NZ companies use accurate BIM model of the building for off-site manufacturing resulting in dramatically shortened building times and more housing (Barton, 2019). However, the level of BIM implementation in NZ is still low (Doan et al., 2019). This comes down to education around what BIM is, what are the uses and benefits for stakeholders, and how the BIM knowledge is transferred (Rotimi et al., 2019). Simultaneously to support BIM implementation for NZ towns and cities, the development of data infrastructures inclusive geospatial information are necessary (Ivory et al., 2019). Another issues represent the prevailing lack of BIM-based building life cycle considerations in NZ (Tran et al., 2012) and the lack of client demand for either BIM or Green Star projects (Doan et al., 2018). Nevertheless, "BIM is expected to aid designers to shift the construction industry towards more environmentally and economically sustainable construction practice" (GhaffarianHoseini, Doan, et al., 2017, p. 696).

3.4.3 Obstacles to BIM Adoption

Although the BIM advantages are well-known (Ghaffarianhoseini, Tookey, et al., 2017; Olawumi & Chan, 2019), the rate of BIM worldwide adoption is still slow (Charef et al., 2019). Chien et al. (2014) identify thirteen risk factors in diverse dimensions, such as technical, management, environmental, financial, and legal risk. Similarly, Sun et al. (2017) allocate BIM limitations into five categories, such as technology, cost, management, personnel, and legal. Remaining challenges lie in the requirements for technical expertise and in the high implementation and training costs (Charef et al., 2019; Dixit et al., 2019; Schlueter & Thesseling, 2009). Another hindrance seems to be the reluctancy to the radical change of a project approach from linear to collaborative, interdisciplinary, and long-term (Migilinskas et al., 2013).

The BIM requirement of sharing information might clash with the intellectual property, copyrights, and cybersecurity (Ghaffarianhoseini, Tookey, et al., 2017). Considering cybersecurity in the AEC industry, Halmetoja (2019) suggests compliance with the PAS 1192-5:2015 specification for security-minded building information modelling, digital built environments and smart asset management (British Standards, 2015). Software updates and new versions of software often invoke restrictions in multi-user access to the model (Azhar et al., 2015). For example, a model created in a recent version of software will not open in the older version of the program (Dixit et al., 2019).

The BIM tools are being used across a range of different construction projects inclusive of infrastructure, commercial and residential sectors of the industry (Dave et al., 2013). The significant barrier in achieving the higher efficiency and advantages offered by BIM is due to a widespread lack of knowledge in new processes, possibilities and their potential (Dave et al., 2013). This corresponds with the findings of Oesterreich and Teuteberg (2019) who determined the lack of expertise, lack of training, and shortage of skilled personnel as the major barriers affecting the BIM socio-technical system. Another barrier to broader implementation of BIM represents the persistent fragmentation of the industry as the relationship between stakeholders is still lacking communication and trust (Piroozfar et al., 2019). Therefore, "The promise of BIM use during the whole life cycle of the building is a dream far from being realized" (Miettinen & Paavola, 2014, p. 86). Additionally, BIM transparency might have a negative influence on contractors' interests and further on BIM adoption as contractors are reluctant to share information with owners (Guo et al., 2019).

From the technical dimension, broader BIM implementation requires an automatic information exchange based on interoperability of diverse BIM tools. Therefore, the following section analyses the status-quo in interoperability.

3.4.4 Interoperability

Interoperability represents the ability of computer-based tools to exchange information and use it for further processing (Chituc, 2017). However, the term "interoperability" is defined in the ISO/IEC/IEEE 24765:2017 international standard by using the definitions from four other standards, such as ISO/IEC 25010:2011, ISO/IEC 19500-2:2012, ISO/IEC 2382:2015, and ISO/IEC 10746-2:2009. Thereby, exchange and use of information, ability to cooperate, the capability to communicate, execute programs, transfer data, and collaboration of objects are the main attributes of interoperability. In order to prevent an interpretation of compatibility as replaceability, the ISO/IEC/IEEE 24765:2017 international standard uses interoperability instead of compatibility (ISO/IEC/IEEE International Standard, 2017).

BIM enables the digital transfer of building data. Therefore, all BIM data exchange operations are based on the consistent utilization of a comprehensive building model (Borrmann, König, et al., 2018). However, in the building industry, most software applications are becoming more complex but not fully interoperable (Smith & Tardif, 2009; Tchouanguem Djuedja et al., 2019). The ways of achieving software interoperability in the construction and facility management industry sector are numerous. The most known are using standard data formats, such as Industry Foundation Classes (IFC), and eXtensible Markup Language (XML) (Adamus, 2013).

The IFC format is a common data schema and together with four other open standards of the buildingSMART portfolio enables holding and exchanging relevant data between different software applications (buildingSMART International, n.d.-a). The IFC is translated into the open international standard IFC ISO 16739-1:2018 specifying BIM data schema and an exchange file format structure among software applications (ISO, 2018b). IFC includes definitions of data required for buildings and infrastructure assets over their life cycle (buildingSMART International, n.d.-a). IFC describes the data schema in EXPRESS data specification language, defined in ISO 10303-11:2004 (ISO, 2004).

XML is standardized by The World Wide Web Consortium (W3C), an international community that develops open Web standards (The World Wide Web Consortium, n.d.). ISO 10303-28:2007 specifies the XML schema definition and the way in which XML representation can be used in the exchange of data (ISO, 2007). Consequently, XML can be used as a data model in the form of XML schema file, and in the form of XML data file to hold the actual data (Koch & König, 2018). Therefore, for the exchanging and sharing data from one computer system to another can be used XML exchange format or clear text encoding of the exchange structure, defined in ISO 10303-21:2016 (ISO, 2016). Alternatively, other exchange file formats conforming to the IFC data schemas might be used (Borrmann, Beetz, et al., 2018).

Other ways to achieve interoperability represent Application Programming Interfaces (APIs) or proprietary data exchange formats (Jeong et al., 2016; Smith & Tardif, 2009). These ways are proprietary methods for information exchange between diverse software. Therefore, software vendors need agreements in order to develop and use the proprietary interoperability formats (Borrmann, Beetz, et al., 2018).

Although the importance of interoperability in BIM process has often been mentioned (Grilo & Jardim-Goncalves, 2010; Kadadi et al., 2014), there is a general shortage of studies on interoperability (Chen et al., 2015). Recently, da Silva Serapião Leal et al. (2019) presented a detailed systematic literature review of interoperability assessment related articles. Out of 22 compared interoperability assessment approaches, only seven are suggesting improvements to interoperability based on the assessment results (da Silva Serapião Leal et al., 2019). Contemporaneously, the researcher notes that data about the actual costs of inadequate interoperability are not available. Only in 2004, NIST published the results of a survey estimating $15.8 billion as the annual cost of inadequate interoperability in the U.S. capital facilities (Gallaher et al., 2004). In the U.S. aerospace and automotive industry, the total estimated organizational cost of inadequate interoperability in one company, on average, ranged in 2012 from $1,7 to $2 billion (Sigo, 2012). In the U.S. health care, the medical device interoperability and the adoption of commonly accepted standards for interoperability might annually save $30 billion (West Health Institute, 2013). Generally, interoperability plays a crucial role in the internet-based enterprises, such as cloud architecture (Panetto et al., 2016).

Although the current AEC industry aims in many countries for energy efficiency, the actual information exchange between the building and energy modelling encounters numerous challenges (Guzmán Garcia & Zhu, 2015). The issues range from object parametric information deficiencies, geometric misrepresentations to the need to re-input data. Often, the interoperability issues are semantic, causing diverse technical problems (Davies et al., 2020; Steel et al., 2012). Therefore, multiple research areas in the application of information technology are emerging in the AEC industry. The architectural designers would appreciate a BIM-based BEM method for early design stage (Gao et al., 2019) and BIM enabled building performance simulation (BPS) within the context of life-cycle (Jin et al., 2019). However, due to the missing knowledge of materials and processes in the early design stage, the evaluation of the environmental performance is uncertain. Therefore, the LCA in the early stages could guide the design optimization process in order to select more sustainable materials and lower the environmental impact of the building (Rezaei et al., 2019).

BEM based on BIM is often a time-consuming task involving several tools. Therefore, Reynders et al. (2017) propose a novel tool chain for the direct coupling between BIM and BEM implemented in Modelica model. For window thermal performance simulation C. Kim et al. (2019) propose a method to automatically extract and convert BIM data to improve the productivity of the simulation process. Nonetheless, BIM, BPS and building environmental assessment methods (BEAM) are currently not fully interoperable. In other words, there is still not possible to fill the BEAM forms directly from BIM or to use any intuitive interface to do this (Calquin, 2017).

3.4.5 BIM and Hygrothermal Modelling

The energy performance of a building depends on the specific outdoor environment and is essentially determined by the hygrothermal characteristics of the building elements, installed services, and building usage (ASHRAE, 2016a; Hensen & Lamberts, 2019). As the building usage is not easy to predict nor control, the building elements and installed services are decisive in achieving the envisaged building energy performance (European Standard, 2019). Therefore, the interactions of the external and internal building surfaces with the outdoor and indoor climate components are determining the as-built performance (Romanska-Zapala et al., 2019).

However, there is limited research on the practical incorporation of hygrothermal modelling into BIM although the knowledge about the early design impact on the final building energy performance is available (Gao et al., 2019). From this reason, BIM should be extended in the direction of energy assessment of the buildings, with dynamic correlative methods analysing hygrothermal performance in real climate and orientation of the building in the early stage of design (Fedorik et al., 2017). This existing gap in the knowledge led to the research question: What are the requirements for integration of hygrothermal modelling into BIM? Consequently, the BIM extension will allow for adjustments or changes to the design in the phase of the project when the costs to do so are the lowest (Gao et al., 2019). Therefore, the right usage of the hygrothermal modelling will close or narrow the existing gap between the calculated and the real as-built energy performance, and will help to create a permissible indoor climate in winter and summer periods (Kubilay et al., 2019).

Climate adequate buildings have low maintenance costs and minimal need for air-conditioning (Mitterer et al., 2012). Therefore, the combined assessment of HAMT allows to decrease the risks associated with moisture and increase the energy savings potential (Antretter & Pallin, 2019). For this purpose, the building performance and hygrothermal modelling has to be strictly dynamic, regularly revised and improved according to the in-field testing and measurements of realized projects (Clarke & Hensen, 2015; Hensen & Lamberts, 2019). Therefore, the automatic and effortless exchange of relevant building information between BIM and analytical applications, such as hygrothermal modelling and simulation, are vital to minimize the impact of buildings on the environment (Hensen & Lamberts, 2019). This awoke another research question: How can a BIM-integrated hygrothermal simulation tool improve the building performance? However, current BIM lacks sufficient information to enable automatic building performance analysis (Gao et al., 2019). Building performance is a complex issue where the whole building performance cannot be based on the performance of the individual components (Augenbroe, 2019). Consequently, full scale dynamic hygrothermal testing and analyses methods under real outdoor and indoor conditions can improve the real building performance. Reciprocally, the full scale dynamic testing can help to validate the calculation tools, such as building energy simulation models (Roels, 2017).

The common praxis in determination and evaluation of energy efficiency in buildings is to use heat transfer coefficient (U-Value) or its reciprocal, thermal resistance coefficient (R-Value) measures. However, these values are not always representing the real as-built performance of the building components because they are set as constant values under uniform conditions, such as temperature gradient of 24 °C (75 °F) and RH 50% with no wind (constant air pressure) (Dastbaz et al., 2017). Nevertheless, in the real life these conditions vary and the thermic properties are dependent on humidity, temperature amplitude, air pressure, orientation, and hygroscopic characteristics of the material (Flood et al., 2017). For this reason, to realistically evaluate the energy performance it is crucial to determine and assess the hygrothermal behaviour of materials and whole buildings based on dynamic total energy consumption and climatic data (Hopfe & McLeod, 2015). Therefore, in the field of real building energy performance assessment exists a potential for bridging the performance gap and use the assessment of different designs for energy efficiency enhancement (Roels, 2017). This led to the next research question: How can a BIM-integrated hygrothermal simulation tool reduce errors affecting the hygrothermal performance of buildings?

Energy efficient buildings feature a high level of thermal insulation and airtightness. Thus, the temperatures and RH levels between indoor and outdoor often differ. Praxis and research have shown that high and uncontrolled RH has negative consequences for the buildings and indoor air quality (see section 3.2). However, there exists a gap in the current knowledge as formulated by Fedorik et al. (2017): "Implementing the hygro-thermal control together with the mold growth risk analysis provides additional tool to be developed into future BIM systems to promote and balance the health control and energy efficiency requirements" (p. 138). Therefore, using critical hygrothermal material characteristics, and merging energy and hygrothermal models are necessary for the building performance assessment (Romanska-Zapala et al., 2019; S. Yu et al., 2012). Consequently, the following research question was formed: How can a BIM-integrated hygrothermal simulation tool increase hygrothermal efficiency?

3.5 Conclusions

This chapter discusses in detail diverse aspects of the AEC industry to examine possibilities of interoperation between BIM and sustainability tools, particularly hygrothermal modelling. The new challenges in the AEC industry are related to worldwide necessity to reduce the negative impact of buildings on the environment and improve energy efficiency. In order to control and manage the undesirable impacts of buildings on the environment, many sustainability ratings and certification systems have been developed. However, some non-governmental sustainability assessing organizations, such as Green building councils are not financially independent research institutions. Therefore, to enhance the overall quality of houses, the architectural designers would appreciate a BIM-based BEM method for the early design stage. However, most of the research and initiatives concentrate on the improvements of building thermal performance. In spite of the fact that research has shown that heat movement correlates with moisture, the majority of research ignores hygrothermal processes. The interconnectedness of heat and mass explains why every change in the building envelope has an influence on both - energy and moisture. Therefore, improving the thermal performance of the building envelope and airtightness of the building simultaneously change the moisture movement.

Moisture defects have become a leading cause of building damage and also have serious economic and sociological effects. For the protection against failures caused by high moisture, maintaining the correct relations between moistening and drying are essential. The researcher agrees with the suggestion that the discussion about the ventilation rate would be beneficial to shift from the amount of fresh air to higher quality of indoor air. This means to approach ventilation, building performance, and IAQ problematic from a holistic point of view. Therefore, a complex assessment of building performance is crucial for the design of sustainable houses. Based on the literature review, it is evident that hygrothermal relations in the built environment need attention. However, despite new technology and simulation software, a significant uncertainty factor in the prevention of moisture related problems still remains. Unless taking into account the problem of moisture related issues, improvements in the real energy performance of new or refurbished buildings might be accompanied by serious unintended problems in the future. Therefore, improved hygrothermal models should be connected with energy modelling.

A significant part of the NZ housing stock is energy-inefficient, unhealthy, cold, mouldy, and damp. Nevertheless, the new houses in NZ are built to the minimum legal standards, which are below the international standards for comparable climates. Therefore, the houses are not durable and the costs over the whole life cycle of the houses are much higher than by houses built to a higher standard. The researcher's personal experience is that local, territorial authorities still largely demand the "Acceptable Solutions" to be followed. This practice hinders innovations. In order to improve the housing quality Stats NZ released in 2019 a document defining four elements of housing quality, such as housing habitability, environmental sustainability, housing functionality, and social and cultural sustainability. However, practical tools on how to achieve these targets are missing. Similarly, as in most English-speaking countries, very little or no building physics have been taught to architectural students in NZ universities. Additionally, anecdotal evidence based on personal conversations with building professionals would appear that building physics education to architectural designers is lacking. Therefore, until the building physics/science will be taught to each and every architectural designer in NZ, we still might face serious problems in NZ house performance.

As mould and fungi thrive in the moist environment, it is desirable to regulate the RH in buildings. One of the suggested methods for moisture management is to use hygroscopic building materials and moisture buffering. The fact that the mechanisms behind the association between dampness, mould, and health are not proven to be causal may not be the validation of their non-existence. Therefore, it seems to be more effective to focus on moisture source control and avoid high RH levels in buildings. The susceptibility to mould growth on any material is correlated to the presence of organic matter and the equilibrium moisture content. Thus, the selection of mould resistant or treated materials is not a “cure it all” solution. Therefore, the researcher suggests that we need to address the mould growth conditions and not to try to stop or modify the effects of the unfavourable situation. The hygrothermal modelling might be used for mould growth prediction.

The heat, air, and moisture (HAM) models are suitable for investigation of the thermal and hygrothermal interactions in building elements or in whole buildings. Some HAM models additionally deal with consequences of moisture related issues, such as mould, fungi, corrosion, frost damage, and salt transport. Despite all the developmental process, the complex HAM phenomena require the solution of large algebraic systems for the whole building modelling. In this context, the researcher agrees with Gasparin et al. (2018a) that the classical computer chips are down for Moore’s law because of the heat problem but strongly disagrees that the computational resources are stagnating. Scientific and industrial communities are working on the increasing semiconductor device integration density using new technologies and new materials. Therefore, the argument that the computational resources in a computer are not increasing any more is unfounded. Nevertheless, the reduction of CPU time for hygrothermal simulations is crucial to the implementation of these techniques into the construction design process based on an optimal usage of the available hardware.

In order to evaluate and test the thermal performance of buildings, several building energy models (BEM) are available. However, the search for hygrothermal simulation or HAM in the BEST directory (International Building Performance Simulation Association, n.d.) are not available under the offered capabilities of the listed software. Although the literature review revealed that the coupled HAMT influences the indoor environment, energy consumption, and durability of buildings, the current conventional BEM ignore the hygrothermal interactions in building envelopes. The researcher agrees with Prada et al. (2018) that the BEM require accurate data otherwise, their results might not be reliable. However, the accuracy of data is equally important for both the HAM models and BEM.

In spite of the fact that the literature analysis confirms that the assessment of hygrothermal building performance should be a part of the design process, the application of hygrothermal simulation in the design process is not common. There are diverse reasons for limited use of hygrothermal modelling in architectural practice, such as the missing knowledge of building science, a high level of user input which connotes possible errors, unreliability, and sometimes legally actionable simulation results. Another barrier to the use of HAM models in the design process represents a shortage of data and sometimes incorrectness or incompleteness of hygroscopic material property data.

The literature review of BIM and interoperability confirms that interdisciplinary and collaborative practices within the built environment are pivotal to the efficiency in delivery and operation of assets. Consequently, interoperability between diverse BIM tools enables the digital transfer of building data and the comprehension of diverse factors in the construction process. However, the statement that BIM contains all supporting data to sustainable design throughout the asset's life cycle (Khosrowshahi, 2017) is correct in theory as a possibility only. Contemporary studies point towards many interoperability issues and factual lack of data for sustainability assessment. In spite of the fact that several studies mention the interoperability financial impact, data about the actual costs of inadequate interoperability are not available. Additionally, there is a limited research on the practical incorporation of hygrothermal modelling into BIM. However, the automatic and effortless exchange of relevant building information between BIM and analytical applications, such as hygrothermal modelling, are vital to minimize the impact of buildings on the environment.

As discussed with Fraunhofer Institute for Building Physics IBP, Department of Hygrothermics Germany, the incorporation of hygrothermal modelling into BIM is not researched yet. There are software products available for calculations and modelling in the field of energy and hygrothermal performance assessment. However, a knowledge gap exists on the parameters and specifications needed for standardized data libraries, practical solutions for BIM and simulation models to be used as viable tools for effective decision-making process regarding sustainability and energy performance of the building. Fedorik et al. (2017), Romanska-Zapala et al. (2019), and others have recognized the need for the development of future BIM systems implementing the hygrothermal and mould growth risk analysis. The possibility and ability to make decisions about the quality and physical characteristics of the future construction in the early design stage will have many advantages. These improvements will contribute to the reduction of the life cycle costs, minimization of later claims, and enhance the quality and performance of buildings.

3.6 Summary

This chapter provides a review and analysis of factors affecting the indoor environment with a view to understand the consequences of underestimating hygrothermal relations in buildings and to investigate the integration of hygrothermal modelling into BIM. This research intended to demonstrate that BIM can be broadened in terms of sustainability assessment. If the hygrothermal modelling would agree with the measured control values one could apply modelling during the early stage of design to improve the durability and quality of the construction and prevent moisture related problems. Consequently, negative impacts on the environment and life cycle costs of a building can be minimized, and return of investment, energy efficiency, and indoor air can be improved.

The literature review inspects the theoretical and practical understanding for this objective by analysing reviewed papers and the background of building physics, BIM and hygrothermal modelling. After the broader description of the sustainability issues in the architecture, engineering, and construction (AEC) industry, the analysis narrows to the NZ construction industry. Next, this research inspects hygrothermal relations in the built environment and the potential of building materials for the regulation of RH. BIM and software interoperability constitute the fourth topic of the literature review. After the short description of BIM history and praxis worldwide and in NZ, the chapter focuses on the interoperability, particularly between BIM and hygrothermal modelling. The conclusions outline gaps in the knowledge and discuss a proposed holistic approach to the design process that takes cognizance of the benefits of BIM with respect to the hygrothermal performance of buildings.

Chapter 4 Data Collection and Analysis – Quasi-Experiment

This chapter deals with quasi-experiment which forms the first part of data collection and analyses. Chapter 5 contains the second part of data collection (simulation). After a description of the experiment and its settings, this chapter presents results in graphical and numerical form. The data analysis process consists of different statistical methods, such as descriptive statistics and analysis of covariant. This leads to a comparison of the results. Next, the text focuses on the limitations and challenges of the quasi-experiment. From the results are drawn conclusions and recommendations. In the summary section, the major points of this chapter are summarized.

4.1 Description

This research utilizes (as described in Chapter 2 above) a combined model of design using a combination of experimental and simulation design (Li et al., 2013; Mathy & Chekaf, 2018; Xing et al., 2018). Radon et al. (2018) used the combination of experimental and simulation study on long-term hygrothermal performance of different outer assemblies in passive houses. The difference between the Radon et al. (2018) study and this study comprises different climate (middle Europe), construction and materials, not controlled amount of released water vapour, and active mechanical ventilation.

Consequently, the research intention is to create a supportive environment for using both in-field experiment and simulation for the collection of data. With this combination of methods, the research demonstrates the importance of using simulation during the construction design process (Antretter, Klingenberg, et al., 2013; Bomberg et al., 2017). This way, existing differences between physical qualities of materials might be purposely used to enhance the hygrothermal performance of houses. The in-field experiment delivers data for the testing of the hypothesis and for the comparison to simulation data as described below. Therefore, for the collection of data experiment and simulation are selected.

The experiment's goal is to gain data for the following purposes:

- Monitor indoor humidity in two houses with different room settings/scenarios while introducing water vapour into the room to simulate occupancy.

- Compare relative humidity (RH) in the same room (size, position in the house, cardinal direction) by two houses. Where the only difference between them is that the control house (C-house) has traditional NZ exterior wall construction and the test house (T-house) has airtightness membrane and installation cavity on exterior walls.
- Compare RH levels while introducing new materials into the room.
- Compare the data with hygrothermal simulation results for the same scenarios.
- Test the hypothesis: "Materials used in the building envelope have a significant influence on the hygrothermal performance of the building."

For the testing, this study chooses RH, dew point, and temperature as parameters measured in one-hour step for consecutive 5 days (120 steps in total) for each scenario. Independent variables represent weather conditions, materials with different moisture buffering qualities, amount of water vapour released during every day in the 24-hour cycle, and different type of exterior walls. Weather conditions are described by outside RH, temperature, dew point, solar radiation, rain, wind, and atmospheric pressure. The study compares the measured data with data from the hygrothermal simulation. The hygrothermal modelling tool, WUFI Plus and the simulation are described in detail in Chapter 5 (p. 156).

For the understanding of this research, it is important to emphasize that RH represents the characteristic of the interest. The question of RH and indoor environment is addressed in Chapter 3 (p. 62) and further discussed in Chapter 7 (p. 202). Generally, under atmospheric conditions, RH is influenced by two significant factors: the absolute amount of water vapour in the air and temperature (Hens, 2017). This fact is demonstrated in scenario 1 where RH is periodically changing, although there is no additional moisture introduced to the room. The RH fluctuations are mainly caused by the change of the temperature as no water is evaporated into the room. However, as the exterior walls are not entirely sealed the researcher notices some influence of the exterior level of humidity and temperature too.

The research introduces interpolation functions to analyse the development of the RH level. For the relatively short time period (5 days) of each test, a lineal interpolation proves to be sufficient. Although being very simple, linear interpolation functions effectively demonstrate differences between tested scenarios. Nevertheless, as many times it has been proven (Bomberg, Kisilewicz, et al., 2015; Hens, 2017) that air saturation process with water is nonlinear this research introduces natural exponential functions also. Natural exponential functions express the relations of the air saturation process more accurately, therefore, they might be used for an extrapolation.

4.2 Settings

Data for the study are drawn from an experiment with real time measurements in real houses. The experiment ran from January 9th, 2018 till February 19th, 2018. The experimental set-up has been situated in two test buildings located for the time of the measurements in Auckland, New Zealand (-36.882533, 174.707651) as shown on the aerial photo (Figure 5).

Figure 5

Testing Houses Aerial Photo

Note. (R. Birchmore, personal communication, 11.04.2019). Reprinted with permission.

The houses have been constructed by students as a part of the Unitec carpentry programmes. They are single storied, relocatable, complete with electrical and plumbing fittings, without floor coverings or wall finishes. The C-house has been built using conventional New Zealand construction methods and the T-house using diffusion open airtightness membrane and horizontal battens creating an installation cavity on the indoor side of exterior walls (Birchmore et al., 2015). Figure 6 features its appearance.

Figure 6

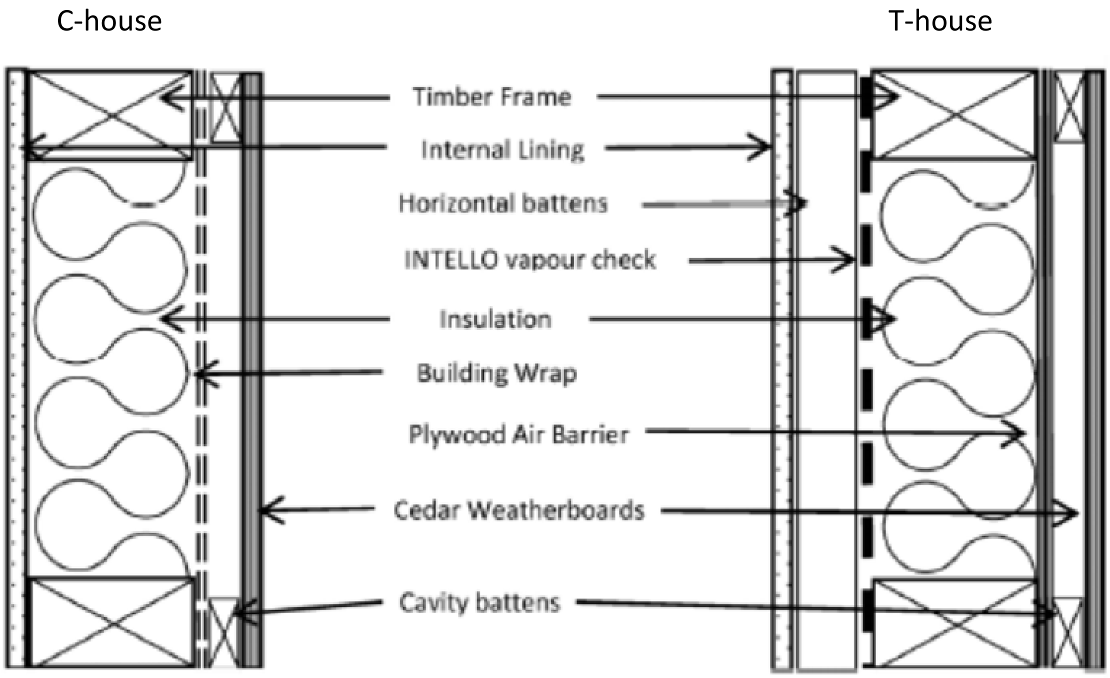
Photo of the T-House

Note. (R. Birchmore, personal communication, 11.04.2019). Reprinted with permission.

The C-house was constructed in 2011 and the T-house one year later. The purpose of this construction was to study the hygrothermal behaviour of air tight construction and building components under real climatic conditions in New Zealand (De Groot & Leardini, 2010). These houses are identical in size, orientation and layout. The only difference is in the exterior wall construction, as shown in Figure 7.

Figure 7

Comparison of Wall Construction in T-House and C-House

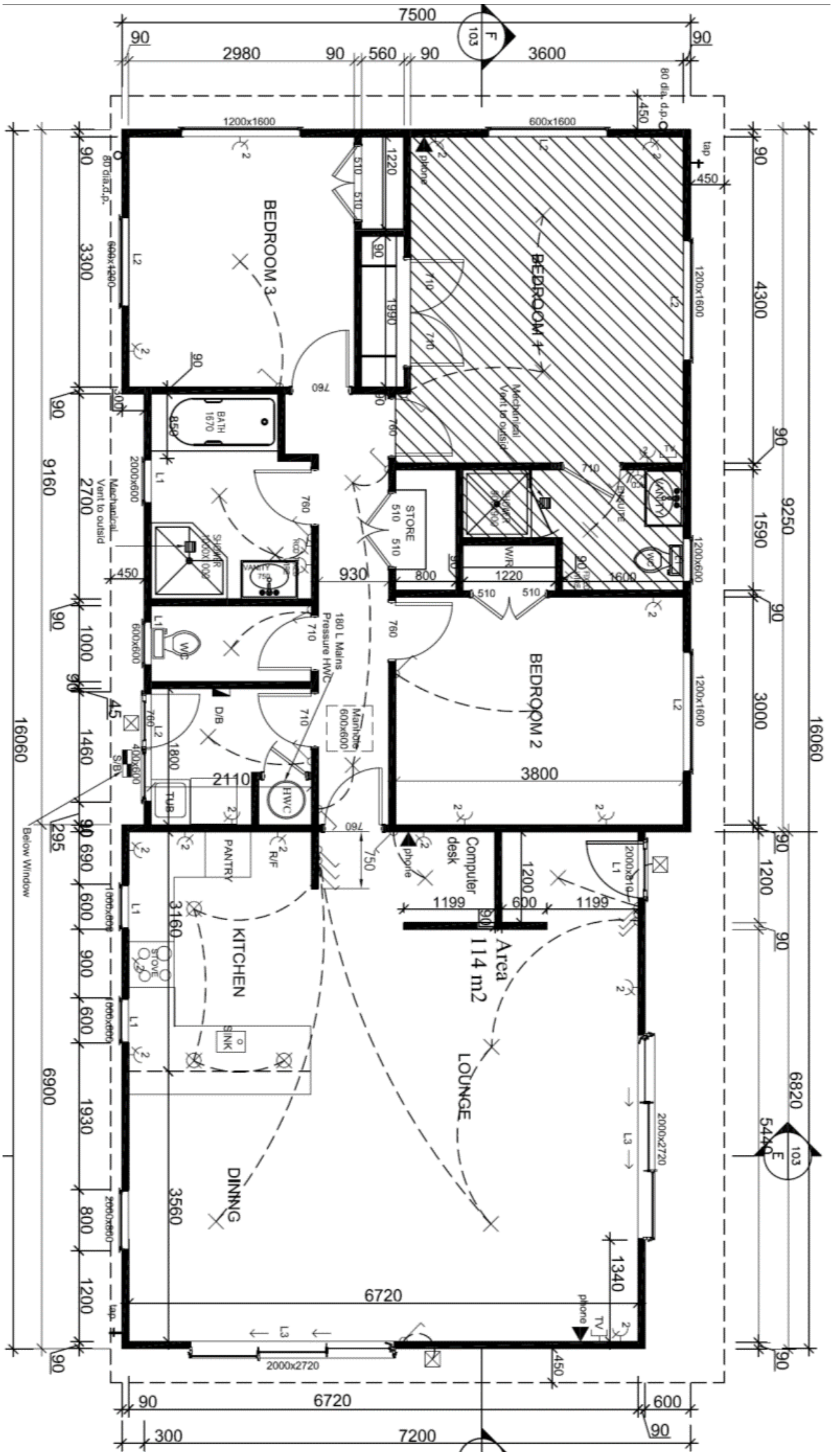


Note. The details depicting horizontal sections of the walls have been adapted from Birchmore et al. (2015, p. 181). Reprinted with permission.

For the testing chosen, a compartment consisting of a master bedroom and the enclosed en-suite bathroom contains a floor area of 19.46 m² in total. The floor plan of the houses and the location of the test area is shown in Figure 8 (R. Birchmore, personal communication, 11.06.2018). Reprinted with permission.

Figure 8

Floor Plan (not in Scale) With the Testing Room (Marked)



The orientation of the compartment is North (Azimuth 340°) with the longer exterior wall (6.16 m) and West (Azimuth 250°) with the shorter exterior wall (3.78 m). The indoor side with the total surface wall area of 43.8 m² and ceiling area of 19.46 m² is provided with unpainted plasterboard (10 mm).

The basic configuration of exterior walls in both houses consists of 90 mm timber frame with polyester insulation (90 mm) in between. From outside the load-bearing construction is sheathed with a building wrap by the C-house and with 7 mm thick plywood air barrier by the T-house. The plywood is treated to H3.2 CCA (Copper Chrome Arsenate) in accordance with AS/NZS 1604.3 (Standards New Zealand, 2012b) to meet AS/NZS 2269.0 (Standards New Zealand, 2012a). Both houses external wall cladding consists of cedar horizontal weatherboards fitted to cavity battens. The cavity is not vented, although fitted with cavity closer at the bottom of the wall in accordance with the NZ Building Code acceptable solution E2/AS1 Paragraph 9.1.8.3 (New Zealand Government, 2018a, p. 101). The cavity closer provides holes or slots between 3 mm and 5 mm with an area of opening of 1000 mm² per linear metre of wall in order to provide draining and venting of the cavity. However, as there is no opening on the top of the wall cladding, the cavity from building physics point of view has to be seen as not vented.

From inside of exterior walls is plasterboard fixed directly to the frame in the C-house. The composition of the inside of exterior walls in the T-house consists of an airtightness membrane fixed directly to the indoor side of the frame, followed by an installation cavity, and plasterboard. To minimize openings in the airtightness membrane, an installation cavity consisting of horizontal timber battens and plasterboard is implemented. All openings in the air tightness membrane are sealed with tape and special grommets. Both buildings' airtightness has been tested with Blower door test. The test results are shown in Appendix A and summarized in Table 7.

Table 7

Blower Door Test Results

Characteristic	T-house	C-house
ACH_{50} pressurised	1.93	8.20
ACH_{50} depressurised	2.37	8.28

Note. The complete blower door test results for T-house and C-house are in Appendix A.

There is no active mechanical ventilation running in the houses during the experiment. The mechanical ventilation is switched off and all ventilation outlets are sealed with a plastic foil cover. The reasons to switch the ventilation off are: existing mechanical ventilation is very simple with fluctuating velocity, the effect of humidification will be minor compared to the air volume exchanged, and most of the existing NZ residential homes do not have any mechanical ventilation. The entry door to the master bedroom is shut during the testing. However, the gaps around the door are not segregated. The reason for not sealing the door is that this test intends to simulate a situation in one compartment in an occupied house without any mechanical ventilation. This fact is included in the simulation under “interzone ventilation”.

Besides indoor measurements of temperature, RH, and dew point, the same exterior values are monitored continuously. This enables the research to provide an analysis of covariance, which is an interpolation (extension) of analyses of variance by adding metric independent variables (covariances) to the calculation. For more details, see section 4.4.3.

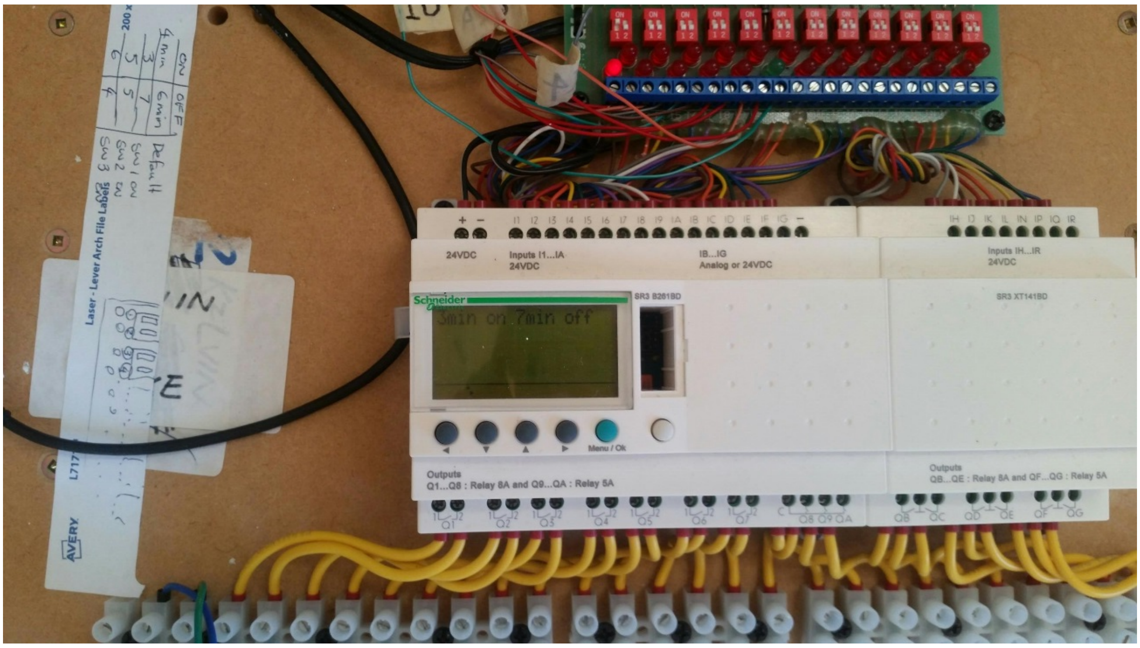
The RH, dew point, and temperature are measured every hour with “EasyLog”, Lascar EL-USB-2 humidity and temperature USB data loggers. The EasyLog measures and stores temperature (dry bulb air temperature in a range of −35 °C to +80 °C), RH (0% to 100%), and dew point (°C). Multiple sensors in each house identical positions are installed. Sensors are fixed to the ceiling by a builder’s twine at 1500 mm high above the floor level as outlined by Barley et al. (2005). The sensors used by the experiment are calibrated by placing them in the same room, one to another and measuring RH, temperature, and dew point for 2445 hours. The results of these measurements are analysed with descriptive statistics methods. Sensors deviate in their measurements in temperature with an absolute average deviation of 0.44 °C, and RH with an absolute average deviation of 2.55% RH. The arithmetic mean of deviation is by temperature -0.19 °C and by RH -1.48% RH. The deviation range was caused by only a few higher deviations, which is visible from the harmonic mean of deviation. The harmonic mean of deviation is by temperature 0.00 °C and by RH -0.50% RH. The results of the calibration are well within the accuracy stated for the sensors to be ±0.5 °C (Birchmore et al., 2015).

The relatively high measurement uncertainties by RH are common issues, not only by field testing but by laboratory testing as well. According to Desta et al. (2011) and Van Belleghem et al. (2011) improved accuracy (absolute deviation of less than 1.5% RH) is achievable by controlled conditions after calibrating the sensors. In long-term measurements, which are taken in uncontrolled and dynamic conditions, the response time of sensors has to be considered as well. Therefore, the uncertainty of ±5% RH and ±0.8 °C in field studies seems realistic (Labat et al., 2015, p. 138).

Additional humidity, in order to simulate inhabitancy, is provided by humiDisk10 with the maximal production of around 1 kg/h of atomized water. To assure the faultless functioning of the humidifier, the researcher uses distilled water during the experiment. HumiDisk utilizes an adiabatic humidification process by which liquid water is sprayed into a relatively dry, warm air stream in a tower. By this process, some water evaporates, the temperature of the air stream decreases and its moisture content increases. Required daily evaporation is controlled by a relay operating on switch on and off mode. A relay is "… an electrical device, typically incorporating an electromagnet, which is activated by a current or signal in one circuit to open or close another circuit" (Lexico, n.d.). To set up a correct amount of switching cycles, a calibration method based on a trial of different relay's settings is employed. The closest possible setting with given technical equipment is to run the HumiDisk daily for 12 hours from 7 pm till 7 am in a mode of 3 min turned on and 7 min turned off as shown in Figure 9.

Figure 9

Relay Setting



This allows for a simulation of an occupancy of two people based on Straube (2002) with the following calculation:

2 people	1.2 * 2	=	2.4 l
2 showers	0.5 * 2	=	1.0 l
Total			3.4 l/24 h

The only disadvantage of this type of evaporation is in the variation of the amount of water released each time. The humidifier diverts a portion of the water into an overflow container, which has to be refilled by the researcher into the supply container on a regular basis. The amount of daily evaporated water varies between 3.18 and 3.32 litres/24 hours, with an average of 3.28 l/24h and variance of 0.0227, as shown in Table 8. Variational span is 0,14 l. Although the actual amount of evaporated water is lower than the originally intended evaporation, the results are suitable for analyses. The reason for the good usability of the results is that this research intention is to demonstrate a tendential influence of different materials on the RH in real houses.

Table 8

Daily Evaporated Water (litre/24 hours) During Individual Tests

House	Scenario 2.	Scenario 3.	Scenario 4.
T-house	3.32	3.18	3.30
C-house	3.32	3.30	3.28

The investigations are carried out for five days on the following scenarios:

1. Existing plasterboard lining (unpainted) on the walls and ceiling without any additional humidification.
2. Existing plasterboard lining (unpainted) on the walls and ceiling with additional humidification as described above.
3. Three sheets of MgO (magnesium oxide) board additionally installed (fixed with stainless steel screws) to some of the walls in the room.
4. Natural earth plaster in a thickness of 2 mm approximately is applied to MgO board sheets as a wall finish. All residual walls remain unpainted.

The testing is done in a switching mode. This means that the testing of one scenario in one of the houses is followed by another testing in the next house. The switching mode allows for drying of the structure in the first house and vice versa.

The reasons for choosing the scenarios and the materials are based on the following facts:

- The number of scenarios depends on the number of tested materials plus one. The research tests the original plasterboards setting, the setting with the added MgO boards, and the setting with the applied plaster to the MgO boards. Therefore, three material scenarios plus one scenario for measurements of initial conditions, four in total, are tested.
- Materials have been chosen on the basis of availability, the alternative of traditional indoor materials, hygroscopic qualities, and the decision to use one basic material and one finishing material. The underlying basis of the researcher’s choice has been the decision to use interchangeable materials

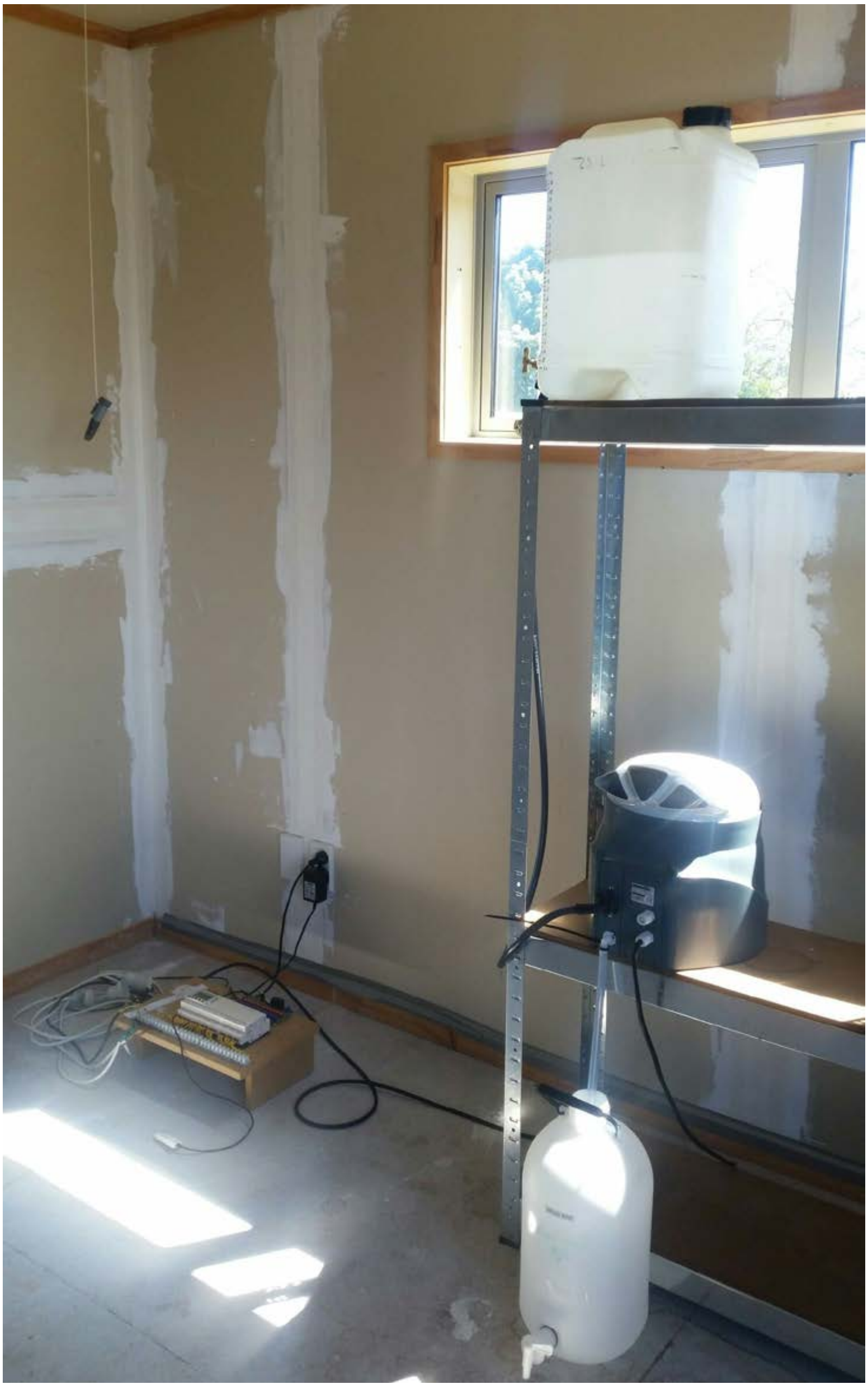
only. Consequently, the researcher intended to demonstrate the influence of realistic indoor materials on the room humidity level.

- The number and size of the MgO sheets have been determined by practical measures, such as the availability of suitable walls without any fittings or openings. The owner of the houses has not permitted any alterations to the construction. Therefore, the research was limited by the wall area, allowing for a direct sheet's installation without any wall variations. Additionally, the fact that the researcher had to install the materials by herself represents another restricting factor on the number of the installed sheets.

The complete experimental setting is shown in Figure 10.

Figure 10

Experimental Setting



The settings of each scenario are as following:

1. scenario

Before the actual testing of indoor humidity development comparison data is needed. Five days measurements of hourly indoor air temperature, RH, and dew point are monitored by existing plasterboard lining (unpainted) on the walls and ceiling without any additional humidification.

2. scenario

Five days measurements of hourly indoor air temperature, RH, and dew point are monitored by existing plasterboard lining (unpainted) on the walls and ceiling by additional humidification. The goal of this setting is to gain data about the development of indoor RH while releasing additional humidity to the room as-built.

3. scenario

Three sheets of Magnumboard (MgO - magnesium oxide) are additionally installed onto some of the walls in the room. One sheet on the North exterior wall, one sheet on the East internal wall, and one sheet on the South internal wall. The area of the MgO boards is 8.28 m^2 which covers 18.9% of the wall area in the room. Over five days, additional moisture is released into the room. The goal of this setting is to demonstrate that materials on the indoor side of walls have an influence on the level of indoor RH.

MgO board is sheathing board used for exterior and interior sheathing. However, under high outdoor humidity (above approximately 84%) the water droplets forming on the surface contain soluble chloride ions that might cause serious corrosion damage to nearby metal fixtures (Hansen et al., 2016). Therefore, the MgO boards are fixed with stainless steel screws according to the supplier's specifications (Health Based Building, 2017). Nghana and Tariku (2018) showed that the moisture buffering potential (MBP) of MgO boards may be comparable to MBP of gypsum boards.

4. scenario

Natural earth plaster in a thickness of 2mm is applied to MgO board sheets as a final wall finish. Prior to the application of plaster, the MgO boards have been primed with a resin diluted in water (1:5). The resin (Acrylbond) ensures the plaster's bonding to the board as specified by the manufacturer. All residual gypsum plasterboards during the fourth testing remain unpainted and unsealed. The study intention of the fourth scenario is to show that finishing materials have an influence on RH levels.

Acrylbond, used as a primer on the MgO boards, is a water-based co-polymer resin. In this application, the barrier properties of the resin are vital factors determining performance. Although this study does not include testing of any products, the researcher notices that the polymer has an effect on permeability. This effect of polymers coatings has been already described by Thomas (1991), who outlined the theory of diffusion of small molecules through polymer films and demonstrated the effect of such coatings. The permeability of polymer coatings is the product of both diffusivity and solubility. This means that the penetrant molecule solubilizes into the polymer matrix and diffuses through it (Thomas, 1991). Similarly, permeability is consequently reduced by nanofillers (Tan & Thomas, 2016) and surfactants (Gonzalez-Martinez et al., 2018).

4.3 Results

For the presentation of test results and the summary, this research utilizes IBM SPSS Statistics Software. Figure 11 and Figure 12 present the graphing depiction of measured results, which are significantly different for each house. The maximum reached RH level of each testing period in the T-house is higher than in the C-house although by each period initial RH level in the T-house is lower than by the C-house as shown in Table 9.

Table 9

Relative Humidity Levels by Humidification and Different Materials Added

House	**2. Scenario RH %**			**3. Scenario RH %**			**4. Scenario RH %**		
	Initial	**Min.**	**Max.**	**Initial**	**Min.**	**Max.**	**Initial**	**Min.**	**Max.**
T-house	67.0	66.5	92.0	56.0	55.5	87.0	61.5	55.0	90.0
C-house	76.0	70.0	85.0	62.5	61.5	85.5	74.5	73.5	87.5

In both houses, the most effective material for an increase of RH minimalization by the introduction of additional water vapour seems to be MgO board. The highest levels of

RH are reached by 2. Scenario (no adding any materials) in the T-house (Figure 11) and by 4. Scenario (MgO board with earth plaster) in the C-house (Figure 12). However, these absolute values might be partly influenced by the initial level of RH and by the outside weather conditions.

Figure 11

Measured RH in T-House

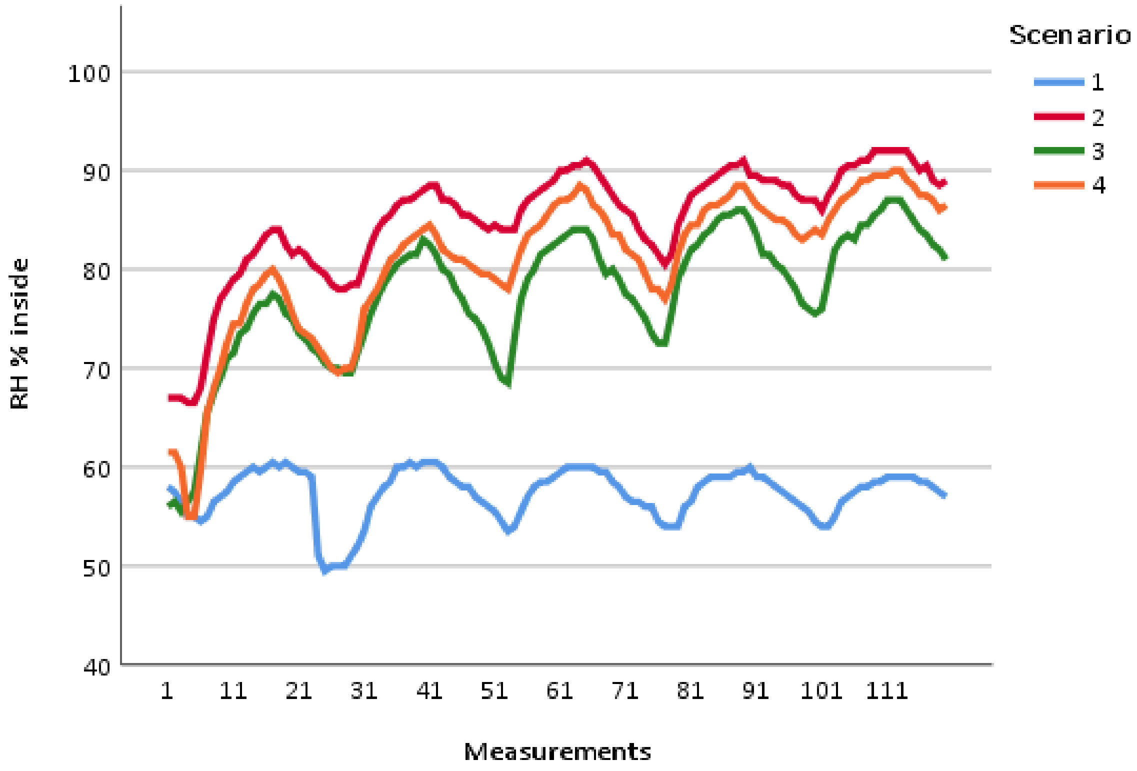
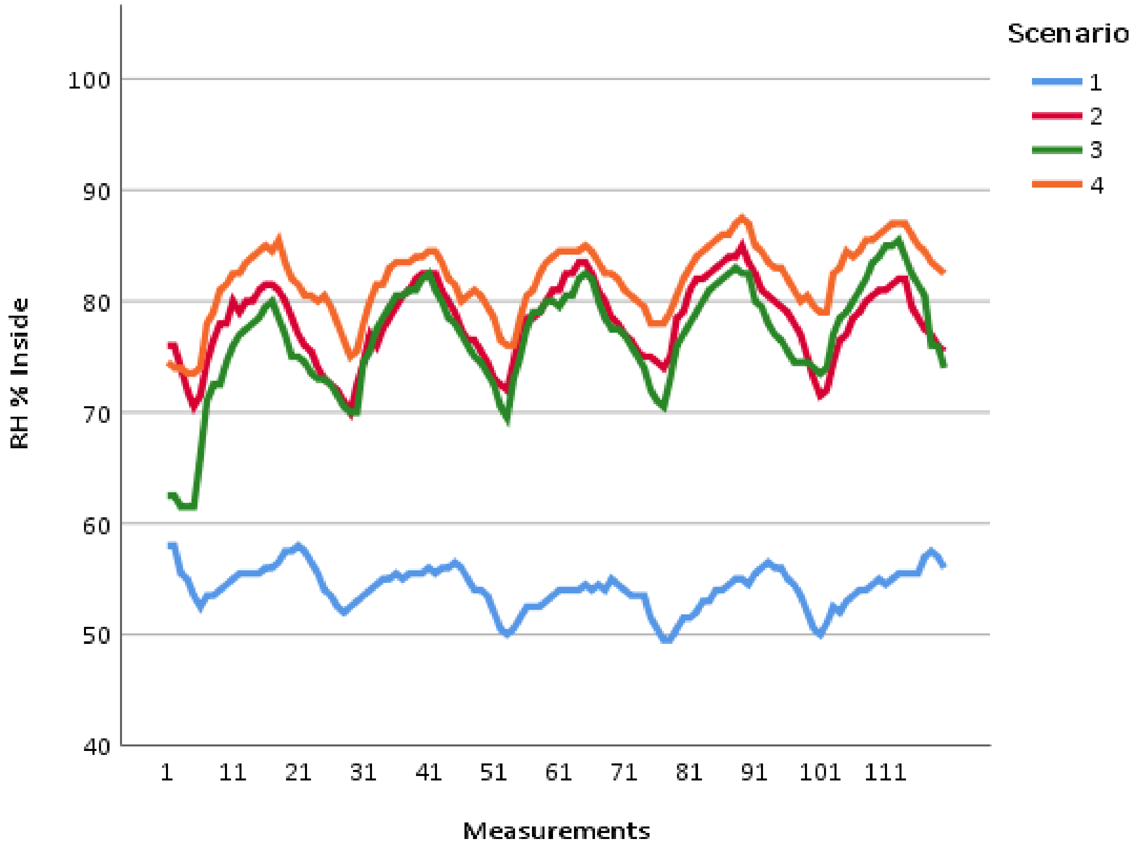


Figure 12

Measured RH in C-House



4.4 Data Analysis Process

For the analysis, the study uses Excel and the IBM SPSS Software. The study intention is to compare the groups of measured data (scenarios) on a metric variable (RH indoor). For such comparison normally, an analysis of variance (ANOVA) would be sufficient. However, in a quasi-experimental setting due to the not controlled environment, other factors might have an influence on the results. From this reason, the research implements a statistical calculation of interpolation combined with regression to control for the influence of exterior RH. The calculation of analysis of variance by adding metric independent variable(s) as covariate(s) is called an analysis of covariance (ANCOVA) (Ankarali et al., 2018). ANCOVA uses features from the analysis of variance and multiple regression (Rutherford, 2011). With other words, ANCOVA is an extension of the analysis of variance (ANOVA) in which main effects and interactions are assessed after dependent variable scores are adjusted for differences associated with one or more covariates. The covariate(s) are measured before or simultaneously to the dependent variable and are correlated with it. Therefore, ANCOVA is a way of controlling for initial individual differences that could not be randomized (Huitema, 2011). The focus is one of determining the effects of the independent variable on the dependent variable adjusted for the presence of covariate(s) in the model. Due to these characteristics, ANCOVA is often used in quasi-experimental research (Rutherford, 2011). Purposes for implementation of ANCOVA into the data analysis are:

- To increase the sensitivity of the test for main effects and interactions by reducing the error term. The error term is adjusted for, and hopefully reduced by the relationship between the dependent variable (DV) and the co-dependent variable(s) CV(s) (Ankarali et al., 2018).
- To adjust the means on the levels of DV itself to what they would be if all subjects scored equally on the CV(s). Differences between subjects on CV(s) are removed so that, presumably the only differences that remain are related to the effects of the grouping independent variable(s) IV(s). The CV(s) enhance prediction of the DV, but there is no implication of causality (Huitema, 2011).
- The adjustments depending on the relationship between CV(s) and DV are determined empirically from measured data (Rutherford, 2011).

From the visual analysis of measured data, the research assumes an influence of exterior RH on reached levels of indoor RH. To prove this assumption, an analysis of variance (ANOVA) and analysis of covariance (ANCOVA) are implemented. The research uses exterior RH as CV to control for the possible influence of exterior conditions on indoor RH.

4.4.1 Descriptive Statistics

The descriptive statistics include data in the form of mean, minimum RH, maximum RH, range, and counts (number of measurements) for each scenario calculated from the measured data. Comparing the data, the study found out that in each scenario the values for mean RH, maximum RH and the range are lower in the C-house (Table 11) than in the T-house (Table 10).

Table 10

Descriptive Statistics for Inside RH in T-House

Dependent variable: RH inside

Scenario	Mean	Minimum	Maximum	Range	Counts
1.	57.367	49.5	60.5	11.0	120
2.	85.050	66.5	92.0	25.5	120
3.	77.492	55.5	87.0	31.5	120
4.	80.746	55.0	90.0	35.0	120

Table 11

Descriptive Statistics for Inside RH in C-House

Dependent variable: RH inside

Scenario	Mean	Minimum	Maximum	Range	Counts
1.	54.200	49.5	58.0	8.5	120
2.	78.117	70.0	85.0	15.0	120
3.	76.746	61.5	85.5	24.0	120
4.	81.854	73.5	87.5	14.0	120

In descriptive statistics, another method for depicting groups of numerical data by their quartiles is a box plot, as demonstrated in Figure 13 and Figure 14.

Figure 13

Box Plot of Measured Data in T-House

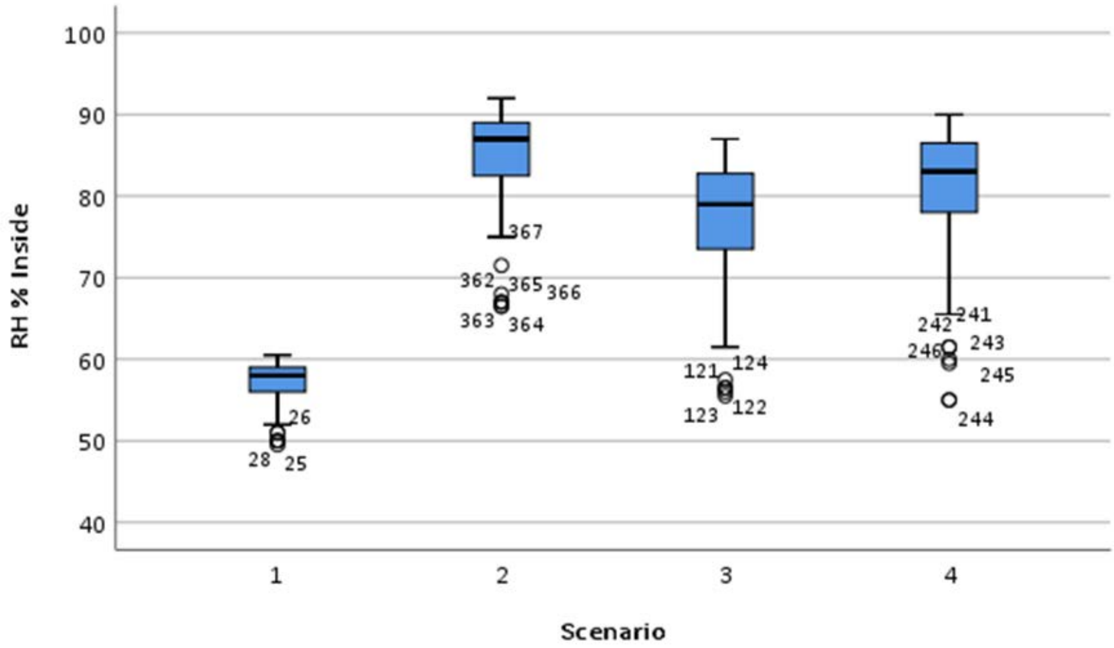
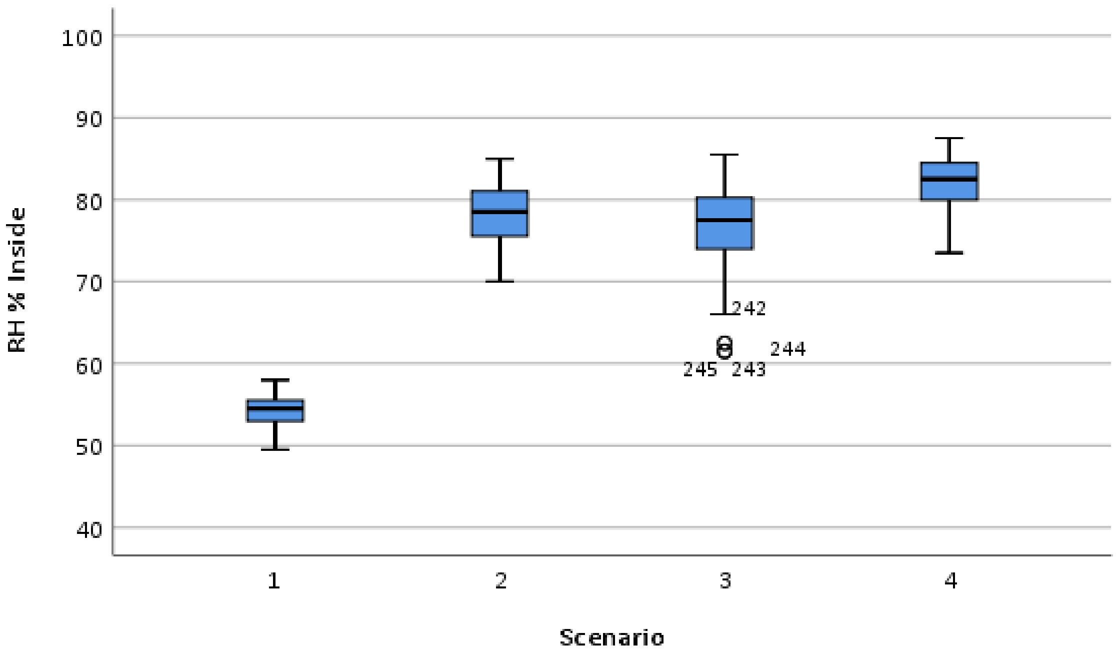


Figure 14

Box Plot of Measured Data in C-House



Box plots indicate variability outside the upper and lower quartiles by lines extending vertically from the main boxes. These lines, called whiskers display variation in samples. However, extremes are displayed as single points on the diagram. Therefore, the box plot is a visualisation of variation without making any assumptions of the underlying statistical distribution (Bruffaerts et al., 2014; Hubert & Vandervieren, 2008). The degree of spread of samples (range) is presented by spacings between the different parts of the box and the length of the whiskers (Praveen et al., 2017).

The visual analysis of box plots enables for a good overview of differences between the two tested construction types. The house with an airtightness membrane (T-house) compared with the house without any airtightness membrane (C-house) features higher mean RH and more spread variation of measures RH in each scenario.

4.4.2 Testing of ANCOVA Preconditions

The research follows the well proven practice to utilize ANCOVA in the quasi-experiment data analysis as described by Rutherford (2011). This way, the indoor RH (DV) is analysed by controlling the influence of outside RH (CV) on the DV. ANCOVA has similar assumptions with the general linear model, such as normality, linearity, homoscedasticity, and homogeneity of regression slopes (Ankarali et al., 2018). However, before applying ANCOVA, two necessary preconditions have to be tested:

1. CV is homogenous over the testing groups (scenarios).
2. Homogeneity of regression.

Testing of the First Precondition

The first precondition test uses an analysis of variance (ANOVA) for outside RH as DV. This test delivers information about homogeneity of outside RH over the testing scenarios and therefore, about the suitability of the outside RH as CV. The results for the first precondition test are shown in Table 12 for T-house and in Table 13 for C-house.

Table 12

Test for Homogeneity of Covariant (ANOVA for Outside RH) T-House

Dependent Variable: RH Outside

Source	Sum of Squares (Type III)	df	Mean Square	F-ratio	P-Value
Adjusted Model	37657.868[a]	3	12552.623	92.421	.000
Constant Term	2873165.901	1	2873165.901	21154.165	.000
Scenario	37657.868	3	12552.623	92.421	.000
Error	64650.481	476	135.820		
Total	2975474.250	480			
Total (adjusted)	102308.349	479			

Note [a]. R-Square = .368 (adjusted R-Square = .364).

Table 13

Test for Homogeneity of Covariant (ANOVA for Outside RH) C-House

Dependent Variable: RH Outside

Source	Sum of Squares (Type III)	df	Mean Square	F-ratio	P-Value
Adjusted Model	6542.442[a]	3	2180.814	13.186	.000
Constant Term	2347242.408	1	2347242.408	14192.255	.000
Scenario	6542.442	3	2180.814	13.186	.000
Error	78725.150	476	165.389		
Total	2432510.000	480			
Total (adjusted)	85267.592	479			

Note [a]. R-Square = .077 (adjusted R-Square = .071).

The purpose of implying ANOVA for the outside RH is to test the null hypothesis (0H) using the F-statistic. The F-statistic has P degrees of freedom for the numerator variance. P generally, in any statistics test determines the statistical significance, with other words, the likelihood of an effect being zero. The P-value for the scenario represents in this test the value of interest. The P-value is the probability that the test statistic will take on a value at least as extreme as the observed value if the null hypothesis is true. If the P-value is less than Tests Alpha value, set as 0.05 for 5%, the null hypothesis is rejected. If the P-value is greater than Tests Alpha value, then the null hypothesis is accepted.

In both cases, in T-house and C-house, the P = 0.000 which, is smaller than 0.05. This means that the null hypothesis (0H) that no significant statistical differences in outside RH exist is not true. Therefore the 0H is rejected. With other words, this means that the outside, exterior RH might have an influence on the inside, indoor RH.

Testing of the Second Precondition

The second precondition tests homogeneity of regression slope. This test is done by applying ANCOVA while determining the terms and interactions of sources. For the purposes of this test, the research defines the scenario, RH outside, and the interaction of scenario and outside RH as sources. To test the second precondition, the researcher analyses results of Levene's test of homogeneity of variances, F-Test of heteroscedasticity, and the test of between-subjects effects.

The Levene's Test, as shown in Table 14 and Table 15, proves the 0H that the variance of DV errors in all groups (scenarios) remains the same. The fact that P-value for both houses is less than 0.05 (P = 0.000) leads to a rejection of the 0H. Therefore, the conclusion from the Levene's test is that the variances of inside RH are not equal. Nevertheless, as the sample sizes are absolutely equal in each scenario, the RH variance does not need to be equal to get valid ANCOVA results.

Table 14

Levene's Test of Homogeneity of Variances for T-House

Dependent Variable: RH Inside

Levene Statistic (F)	**df_1**	**df_2**	**P-Value**
28.175	3	476	.000

Note. Design: Constant Term + Scenario + RH Outside + Scenario * RH Outside.

Table 15

Levene's Test of Homogeneity of Variances for C-House

Dependent Variable: RH Inside			
Levene Statistic (F)	**df_1**	**df_2**	**P-Value**
19.287	3	476	.000

Note. Design: Constant Term + Scenario + RH Outside + Scenario * RH Outside.

The research proves with the following F-Test the null hypothesis that the variance of errors does not depend on independent variables (IVs). The P-values for testing the null hypothesis in T-house (Table 16) P = 0.001 and in C-house (Table 17) P = 0.007 are less than 0.05. Therefore, the 0H is rejected for both houses, and a conclusion can be drowned that the DV (RH inside) is influenced by independent variables, such are a scenario (used materials) and exterior RH.

Table 16

F-Test of Heteroscedasticity for T-House

Dependent Variable: RH Inside			
F	**df_1**	**df_2**	**P-Value**
11.338	1	478	.001

Note. Design: Constant Term + Scenario + RH Outside + Scenario * RH Outside.

Table 17

F-Test of Heteroscedasticity for C-House

Dependent Variable: RH Inside			
F	**df_1**	**df_2**	**P-Value**
7.452	1	478	.007

Note. Design: Constant Term + Scenario + RH Outside + Scenario * RH Outside.

The following test is for estimating the effect size in interaction terms. For testing this effect, the research presents the test of between-subjects effects (Table 18 and Table 19). In the test, the research is particularly interested in the results for the effects of the exterior RH and scenario interaction. Both main effects (scenario and outside RH) and the interaction between them are statistically significant as indicated by P-value. The P-value indicates the likelihood of this effect being zero. A zero effect in the interaction source would mean that all indoor RH means are exactly equal for the combined outdoor RH and scenario. This is not true because the P-value for this source is equal to P = 0.000 in both houses.

Table 18

Two-Way ANOVA Tests of Between-Subjects Effects T-House

Dependent Variable: RH Inside

Source	Sum of Squares (Type III)	df	Mean Square	F-ratio	P-Value	Partial Eta Squared
Adjusted Model	57442.191[a]	7	8206.027	276.854	.000	.804
Constant Term	23139.590	1	23139.590	780.680	.000	.623
Scenario	341.400	3	113.800	3.839	.010	.024
RH Outside	2039.439	1	2039.439	68.806	.000	.127
Scenario * RH Outside	590.591	3	196.864	6.642	.000	.041
Error	13990.221	472	29.640			
Total	2783220.250	480				
Total (adjusted)	71432.412	479				

Note [a]. R-Square = .804 (adjusted R-Square = .801).

Table 19

Two-Way ANOVA Tests of Between-Subjects Effects C-House

Dependent Variable: RH Inside

Source	Sum of Squares (Type III)	df	Mean Square	F-ratio	P-Value	Partial Eta Squared
Adjusted Model	58103.542[a]	7	8300.506	831.857	.000	.925
Constant Term	61501.881	1	61501.881	6163.574	.000	.929
Scenario	919.315	3	306.438	30.711	.000	.163
RH Outside	1232.663	1	1232.663	123.535	.000	.207
Scenario * RH Outside	407.668	3	135.889	13.619	.000	.080
Error	4709.750	472	9.978			
Total	2601788.500	480				
Total (adjusted)	62813.292	479				

Note [a]. R-Square = .925 (adjusted R-Square = .924).

4.4.3 Analysis of Covariant – ANCOVA

Huitema (2011, p. 134) states that "… the purpose of ANCOVA is to test the null hypothesis that two or more adjusted population means are equal." The research investigates the effects of diverse materials on the development of indoor RH in two steps. In the first step, the researcher would like to find out what influence has the fixed factor, scenario on the dependent variable (DV) without controlling for the exterior RH. Therefore, the research applies simple ANOVA calculations. In the second step, the research investigates for the influence of the scenario on the indoor RH by controlling the influence of exterior RH using analysis of covariance ANCOVA.

ANOVA

The results of the one-way ANOVA are shown in Table 20 and Table 21. The T-house and the C-house significance P is 0.000, which is smaller than 0.05. Therefore, 0H is not confirmed. This means that the scenarios and therefore, the used materials have a significant influence on indoor RH. Without correction for the exterior RH, the partial eta-squared indicates how much the indoor RH is influenced by scenarios representing a combination of used materials and other factors. The scenarios in this sense influence the indoor RH by 76% in the T-house (Table 20) and by 90% in the C-house (Table 21).

Table 20

One-Way ANOVA Tests of Between-Subjects Effects T-House

Dependent Variable: RH Inside

Source	Sum of Squares (Type III)	df	Mean Square	F-ratio	P-Value	Partial Eta Squared
Adjusted Model	54126.356[a]	3	18042.119	496.245	.000	.758
Constant Term	2711787.838	1	2711787.838	74587.242	.000	.994
Scenario	54126.356	3	18042.119	496.245	.000	.758
Error	17306.056	476	36.357			
Total	2783220.250	480				
Total (adjusted)	71432.412	479				

Note [a]. R-Square = .758 (adjusted R-Square = .756).

Table 21

One-Way ANOVA Tests of Between-Subjects Effects C-House

Dependent Variable: RH Inside

Source	Sum of Squares (Type III)	df	Mean Square	F-ratio	P-Value	Partial Eta Squared
Adjusted Model	56610.529[a]	3	18870.176	1448.097	.000	.901
Constant Term	2538975.208	1	2538975.208	194840.960	.000	.998
Scenario	56610.529	3	18870.176	1448.097	.000	.901
Error	6202.762	476	13.031			
Total	2601788.500	480				
Total (adjusted)	62813.292	479				

Note [a]. R-Square = .901 (adjusted R-Square = .901).

ANCOVA

The results of the ANCOVA are summarized in Table 22 and Table 23. The T-house and the C-house significance P-value is equally 0.000, which is smaller than 0.05. Therefore, 0H is not confirmed. This means that the used materials (scenario) have a statistically significant influence on the indoor RH. The partial eta-squared indicates that the T-house inside RH is influenced by 67% by scenario and by 16% by outside RH (Table 22). The partial eta-squared indicates that the C-house inside RH is influenced by 91% by scenario and by 18% by outside RH (Table 23).

Table 22

ANCOVA Tests of Between-Subjects Effects T-House

Dependent Variable: RH Inside

Source	Sum of Squares (Type III)	df	Mean Square	F-ratio	P-Value	Partial Eta Squared
Adjusted Model	56851.600[a]	4	14212.900	463.015	.000	.796
Constant Term	37118.386	1	37118.386	1209.208	.000	.718
RH Outside	2725.244	1	2725.244	88.780	.000	.157
Scenario	29069.993	3	9689.998	315.672	.000	.666
Error	14580.812	475	30.696			
Total	2783220.250	480				
Total (adjusted)	71432.412	479				

Note [a]. R-Square = .796 (adjusted R-Square = .794).

Table 23

ANCOVA Tests of Between-Subjects Effects C-House

Dependent Variable: RH Inside

Source	Sum of Squares (Type III)	df	Mean Square	F-ratio	P-Value	Partial Eta Squared
Adjusted Model	57695.874[a]	4	14423.968	1338.836	.000	.919
Constant Term	64839.027	1	64839.027	6018.374	.000	.927
RH Outside	1085.345	1	1085.345	100.742	.000	.175
Scenario	49910.985	3	16636.995	1544.250	.000	.907
Error	5117.418	475	10.774			
Total	2601788.500	480				
Total (adjusted)	62813.292	479				

Note [a]. R-Square = .919 (adjusted R-Square = .918).

Although the influence of outside RH is statistically significant, the major factor affecting the development of inside RH remains in both houses the scenario (used materials). However, these factors are not the only two sources of RH differences between the houses. The research suggests that apart from investigated factors, existence or non-existence of airtightness membrane and the quality of the membrane might have a significant impact on the hygrothermal performance of the building.

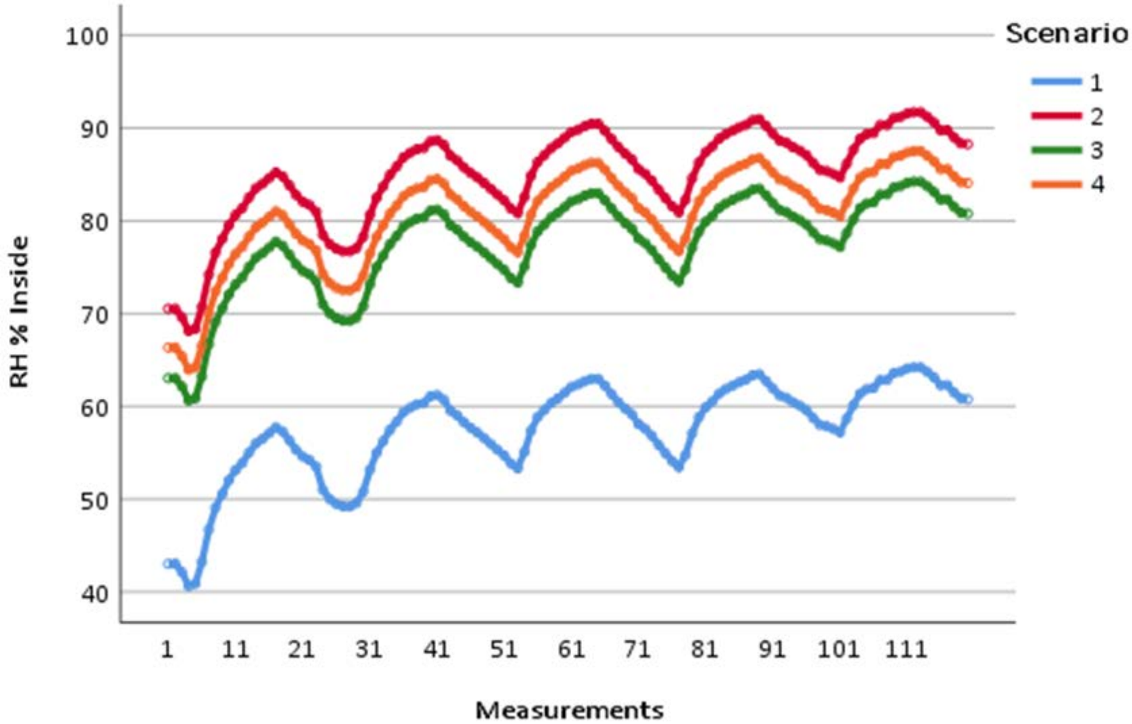
The analysis of measured data delivers new knowledge about the development of inside RH in houses. The research found out that the scope of indoor materials influence is different depending on the exterior walls' construction. The indoor RH in the house with a variable moisture vapour transmission rate airtightness membrane (T-house) is influenced by used indoor materials by 76% (without correction for outside RH) and by 67% (with the correction for outside RH). However, the indoor RH in the house without an airtightness membrane (C-house) is influenced by used indoor materials by 90% (without correction for outside RH) and by 91% (with the correction for outside RH). Additionally, in general, the indoor RH in the T-house reached higher levels than in the C-house in identical conditions (scenarios) as demonstrated in Table 9. The research assumes that these differences are due to the airtightness membrane.

Figure 15 and Figure 16 depict the profile diagrams of ANCOVA results. The diagrams illustrate the estimated marginal means by controlling for the outside RH. The estimated marginal means are predicted scores representing the mean DVs if the CV mean would remain the same as the grand CV mean (Huitema, 2011). Therefore, the ANCOVA calculates for what would the indoor RH means be for each scenario, if the exterior RH would stay the same. The grand CV mean for T-house is 77.37% RH and for the C-house is 69.93% RH. The difference between the grand CV is due to the different testing periods for each house.

From a comparison of Figure 15 and Figure 16, the different development of RH in both houses is evident. In the C-house the estimated marginal means of inside RH are following a stable pattern and the increase of maximal reached RH is lesser than by the T-house. In the T-house the maximal RH level exceeds in scenario number two the benchmark of 90% RH what on the contrary, does not happen in any scenario in the C-house. Descriptive statistics indicate these tendencies, as shown in Table 10 and Table 11.

Figure 15

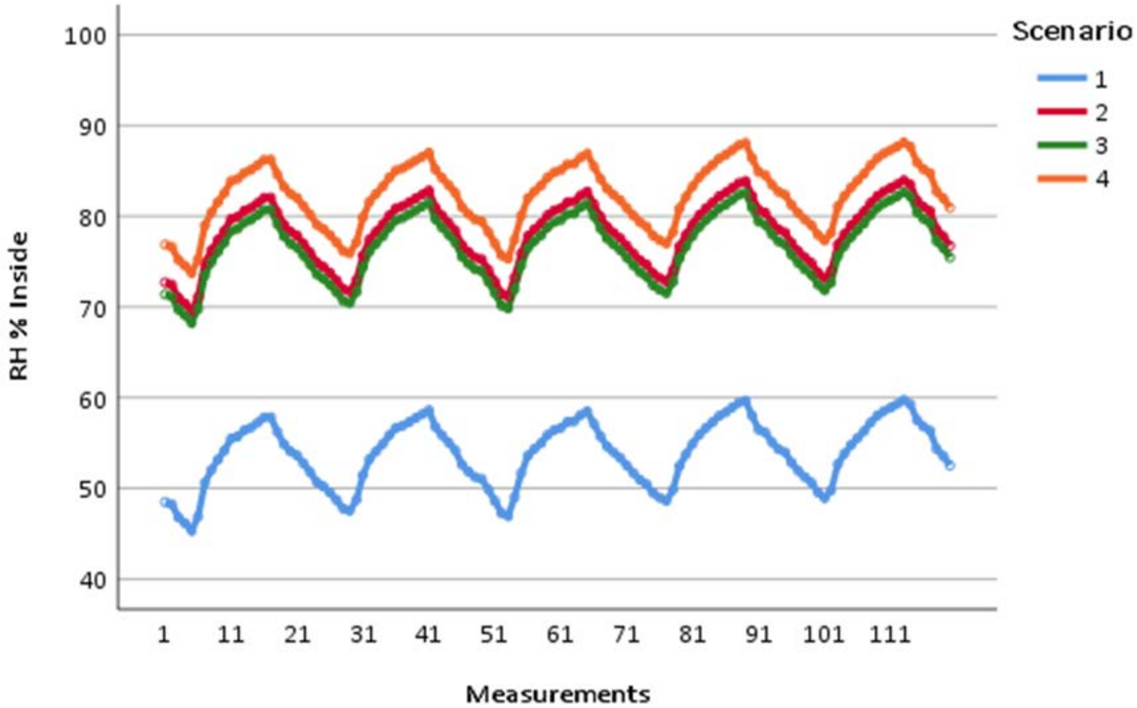
Estimated Marginal Means of Inside RH by the Elimination of Exterior RH in T-House



Note. Covariant in the model has been calculated by exterior RH = 77.368%.

Figure 16

Estimated Marginal Means of Inside RH by the Elimination of Exterior RH in C-House



Note. Covariant in the model has been calculated by exterior RH = 69.929%.

Comparing the analysis of measured data and the analysis of covariance, where the influence of exterior RH development is controlled, the ranking of materials' effectiveness stays the same. The most effective material for minimalization of increase of RH is MgO board in both houses. The highest levels of RH are by no adding any materials in the T-house (Figure 11 for measured data and Figure 15 for estimated data) and by MgO board with earth plaster in the C-house (Figure 12 for measured data and Figure 16 for estimated data).

The analysis of covariance delivers different results by the elimination of exterior influence for each house. However, for the first scenario without any humidification nor added materials, this study prefers to use the original data without covariance. The reason for this decision is that the measurements are done in the same period of time with identical exterior conditions as there is no need for the switching mode by the testing. In the first scenario, the study observes the average RH in the C-house to be lower (3.17 percentage points) than in the T-house. Initial RH levels are different too.

In C-house the initial RH is 54.8% and in T-house 56.9%. The percentage difference is 2.1 percentage points (Table 10 and Table 11). For the 5 days-period the measured data could be described using linear regression:

T-house: $y = 0.007x + 56.943$

C-house: $y = -0.0106x + 54.842$

The negative slope of the interpolation function of the C-house data in the first scenario is a depictive representation of drying out of the indoor space. As the first layer of materials from inside of the house is identical by both houses, the difference is assumed to be influenced by several factors, such as the existence of airtightness membrane and infiltration rate. The airtightness membrane installed in the T-house is a humidity-variable vapour control layer with a vapour resistance between an Sd of 0.25 m and 10 m according to the direction of heat flow and the RH between both sides of the membrane (British Board of Agrément, 2015). The lower vapour resistance in the summer allows moisture to pass through the membrane from the wall back into the room. As the quasi-experiment proceeds during summer, this might explain the higher RH level in the T-house by the first scenario when no additional water vapour is introduced. Besides this feature of the membrane, the infiltration rate (natural air movement) in the T-house is four times lower than in the C-house (see Table 25). Although the vapour resistance of the airtightness membrane is in the time of the experiment (summer) relatively low, the in-wall materials are still less available for adsorption than in the C-house. The in-wall materials in the T-house are therefore, partly blocked and the natural infiltration rate is low due to the airtightness membrane. This would explain the higher level of reached RH (Table 10 and Table 11) and a significantly higher slope of the interpolation functions (Table 24) in the T-house compared to the C-house by each scenario.

Table 24

Interpolation Functions by Humidification in T- and C-House as Measured

Scenario No.	Linear Interpolation		Exponential Interpolation	
	T-house	C-house	T-house	C-house
2	y = 0.1299x + 77.192	y = 0.0255x + 76.576	$y = 77.043e^{0.0016x}$	$y = 76.493e^{0.0003x}$
3	y = 0.1415x + 68.931	y = 0.0721x + 72.383	$y = 68.703e^{0.0019x}$	$y = 72.183e^{0.001x}$
4	y = 0.1721x + 70.331	y = 0.0467x + 79.031	$y = 70.142e^{0.0022x}$	$y = 78.972e^{0.0006x}$

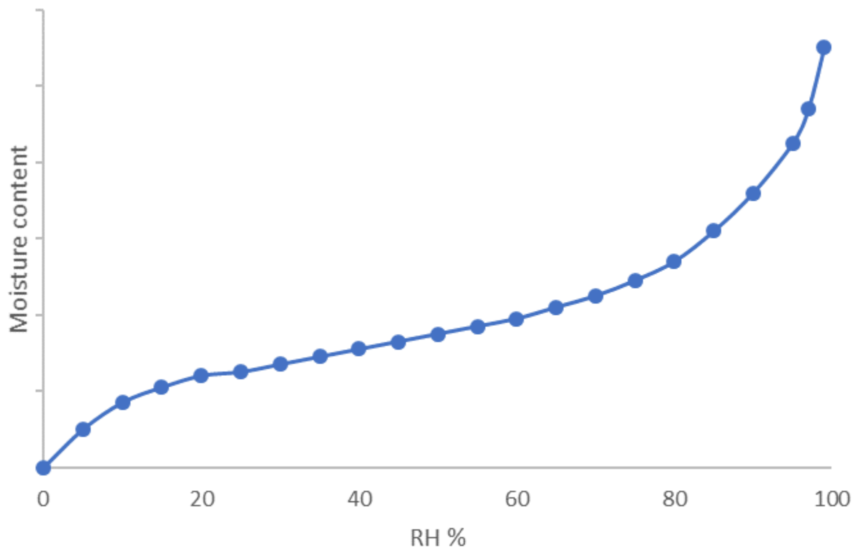
The research uses linear interpolation (regression) functions as one way to analyse and compare measured data. Rutherford (2011) defines the simple linear regression as:

> Simple linear regression examines the degree of the linear relationship … between a single predictor or independent variable and a response or dependent variable, and enables values on the dependent variable to be predicted from the values recorded on the independent variable (p. 4).

The interpolation of the measured data reflects the tendency of the air saturation process. The slope of the interpolation function determines how fast the saturation of the indoor air would be reached if the hygrothermal conditions would continue the same. A negative slope signalizes a drying process. However, it is important to emphasize that it is not possible to use these interpolations for an estimate (extrapolation) of the saturation process. The water vapour saturation process in porous materials follows a non-lineal growth called sorption curve (J. Berger et al., 2018; Luikov, 1964). Additionally, the design of the quasi-experiment combines two processes in a repeating cycle. A part of the cycle contains humidification which might be described by a sorption curve and another part represents the drying process without any additional moisture. The second part might be described as the desorption process.

Figure 17

Illustration of a Sorption Curve Example



A sorption curve depicts the relation between RH and moisture content. The development of RH for an indoor space is dependent on moisture sources and hygroscopic qualities of sorption active surfaces of installed materials (Hens, 2012). Measurements of sorption isotherms represent a crucial task for accurate calculations of heat and mass transfers (Lakatos, 2014). Although every material depicts different sorption isotherm, the sorption curve might be generally illustrated by an S-shape, as shown in Figure 17. Therefore, the sorption curve might be replaced by a linear regression for RH between 20% and 80% (Hens, 2017).

Consequently, for the short time of the testing, the analysis of the slope by the linear function is sufficient. The linear interpolations show similar results to the analysis of exponents in the exponential interpolations. Both of these characteristics signalize how quickly the air would be saturated with water vapour until a benchmark of 80-85% RH. However, by RH above 80%, the saturation process is non-linear and increases very fast. The y-intercept in the linear interpolation specifies the level of humidity at the beginning of the testing. This factor might be influenced by exterior conditions, initial interior conditions, and by the immediate effect of moisture buffering.

Alternatively, and more accurate for the description of the development of indoor RH by normal conditions might be an exponential interpolation of the air saturation process. Exponential interpolations are often used by modelling of physical processes (Ammar et al., 1991). The exponential functions for the first scenario are:

T-house: $y = 56.834e^{0.0001x}$

C-house: $y = 54.814e^{-2E-04x}$

These exponential functions and the functions for scenarios with humidification, as shown in Table 24, are derived from measured data. This means that the potential influence of exterior weather is not eliminated or controlled. This would explain the extremely low exponent by the second scenario without any added material in the C-house. The researcher notes that the testing of this scenario was done during dry and hot weather in comparison to the other testing.

4.5 Limitations and Challenges of the Quasi-Experiment

The researcher is aware of limitations related to the accuracy of the quasi-experiment data. Due to or coming from available technical equipment, and limitations related to uncontrollable factors, such as weather.

The major challenge of the experiment is the equipment, its inaccuracy, and technical malfunctions occurring during testing. In the input data on the humidification process simulating occupancy, the study has to rely on technical equipment supplied by a sponsor. Initially, there were two identical humidifiers. However, after a simultaneous trial measurement in both houses, the researcher ascertained some technical problems causing unreliable outputs. One of the humidifiers was evaporating uncontrollable and irregular quantities of water. Therefore, it is not suitable for further testing. As a result, the research has to change the setup of the experiment from simultaneous to switching mode experiments. While testing one scenario in one of the houses, the other is on hold. The consequence of the switching mode is that each test runs under different weather conditions.

Although indoor RH is the entity of interest, the complete assessment of the hygrothermal performance of the house/compartment inclusive in-wall RH measurements would be required to guide design decisions. Nevertheless, the results of the experiment have proven that even small variations of the first layer from the inside have a significant influence on the hygrothermal performance of the building in real life situations.

4.6 Conclusion and Recommendations

Every building during its whole life span has an impact on the environment. This study shows that even small changes in material specification can engender a significant influence on indoor air quality and therefore, on the whole ecosystem. RH in houses is influenced by several factors. Statistical analyses in this research demonstrate that one of those factors are materials used in the first layer from inside of the house. The study compares maximal reached RH in different settings in two houses while simulating occupancy. The RH increase in each setting in the T-house (with airtightness membrane) is significantly higher than in the C-house (without membrane), although, the initial RH levels in the T-house are lower than in the C-house (see Table 9). This is a new finding of the research.

Estimated marginal means of inside RH by the elimination of influence of fluctuations in exterior RH reached by simulation of the habituated house the lowest level by adding MgO boards. The highest level of RH was reached in the T-house with its original construction of unpainted plasterboard and in the C-house by the addition of MgO boards with earth plaster. These results might be influenced by the different exterior wall structure and/or by the different infiltration rate. Airtightness membrane prevents direct water vapour transport into the exterior wall. This means that for the moisture buffering the most available layer/s are the sorption active surfaces in direct contact with the indoor air. These facts would explain the generally lower levels of maximum reached RH in the C-house by each scenario. This maximum of RH can mistakenly be interpreted as a disadvantage of the airtightness membrane. However, without testing the drying process in exterior walls and an assessment of complete thermal and hygrothermal house performance, this statement would not be correct. As this study has not done any testing of the drying/wetting process inside of the walls, the evaluation of the airtightness membrane is not a part of this research.

From the visual analysis of the development of RH, the conclusion might be drawn that the span between maximal and minimal reached RH each day by different scenarios is higher in the T-house than in the C-house. This fact emphasizes the need for a thorough hygrothermal assessment of the construction, especially of the first layer from inside. Air open structures need more energy for heating and cooling the indoor due to the infiltration. This is not viable because of the energy saving needs. The solution would be a holistic approach to the combined heat, air, and moisture (HAM) flow already in the design process.

Acknowledging the complexity of buildings' hygrothermal performance, it is crucial to note that this research covers only a segment of the whole. The study evaluates the assessment of the first layer from the inside as an essential part of the design decision process. Other parts leading to an integrated solution of HAM flow include but are not limited to suitable ventilation, airtightness, the orientation of the house, use of passive solar energy, shading, passive cooling, or thermal insulation.

The quasi-experiment confirmed the hypothesis: "Materials used in the building envelope have a significant influence on the hygrothermal performance of the building." From the findings, a conclusion might be derived that the materials used as the first layer from the inside of the house might loom large in the hygrothermal performance of the building. Therefore, the research, especially in airtight houses, recommends a hygrothermal simulation as a vital part of the design process.

For further research, this study recommends repeating the experiment with more precise humidifiers allowing for simultaneous tests of each scenario in both houses to eliminate different weather conditions. However, even by such configuration of the experiment, there would be still different weather conditions for each scenario. The industry would also benefit from knowledge about long term complete hygrothermal performance inclusive in-wall processes in NZ houses.

4.7 Summary

The study's data collection and testing the hypothesis consist of two parts. The first part, described in this chapter, comprises the experiment in the form of in-field experiment (quasi-experiment). The second part described in Chapter 5 comprises simulation. The quasi-experiment confirmed the hypothesis: "Materials used in the building envelope have a significant influence on the hygrothermal performance of the building."

New knowledge brought by this study could benefit the industry and supports the suggestion of the importance to implement hygrothermal modelling into the design of buildings. With real house measurements, this study demonstrates the differences between diverse materials used as the moisture buffering. This research is based on the theory of sorption (Hens, 2017; Woods & Winkler, 2018). The findings of RH development in real houses in New Zealand, demonstrating the influence of different materials in diverse construction types are new knowledge.

The study investigates the difference of RH development in two identical houses with diverse wall structures. The materials introduced to the indoor side of the walls have a diverging influence on the indoor environment in each house. With other words, the effect of used materials depends on each situation. A building in its functions works as a coherent entity (system) with interconnected parts. If one part is altered or changed, other parts are affected. Therefore, the study emphasizes the viability of hygrothermal analysis as a part of the BIM process.

The following Chapter 5 is dedicated to the second part of data collection. The chapter investigates the simulation of the experiment described above. Therefore, these two chapters form a database for proving the hypothesis and demonstrating the importance of hygrothermal modelling beyond static models of the literature discussions.

Chapter 5 Modelling of the Quasi-Experiment With WUFI Plus

This chapter deals with the description of the second part of data collection and analysis. This chapter is devoted to the simulation. After a description of heat and moisture numerical models, particularly WUFI Plus, and simulation settings modelling results are presented in graphical and numerical form. These results are analysed and compared with the results of quasi-experiment addressed in Chapter 4 above. From the analysis process, conclusions and recommendations are drawn. In the summary section, the major findings of this chapter are outlined.

5.1 Description

As already described in the previous chapter, this research utilizes a combined model of design using a combination of experiment and simulation for the collection of data. This chapter deals with the simulation using hygrothermal modelling tool WUFI Plus provided by Fraunhofer Institute, Germany.

5.1.1 WUFI Plus Settings

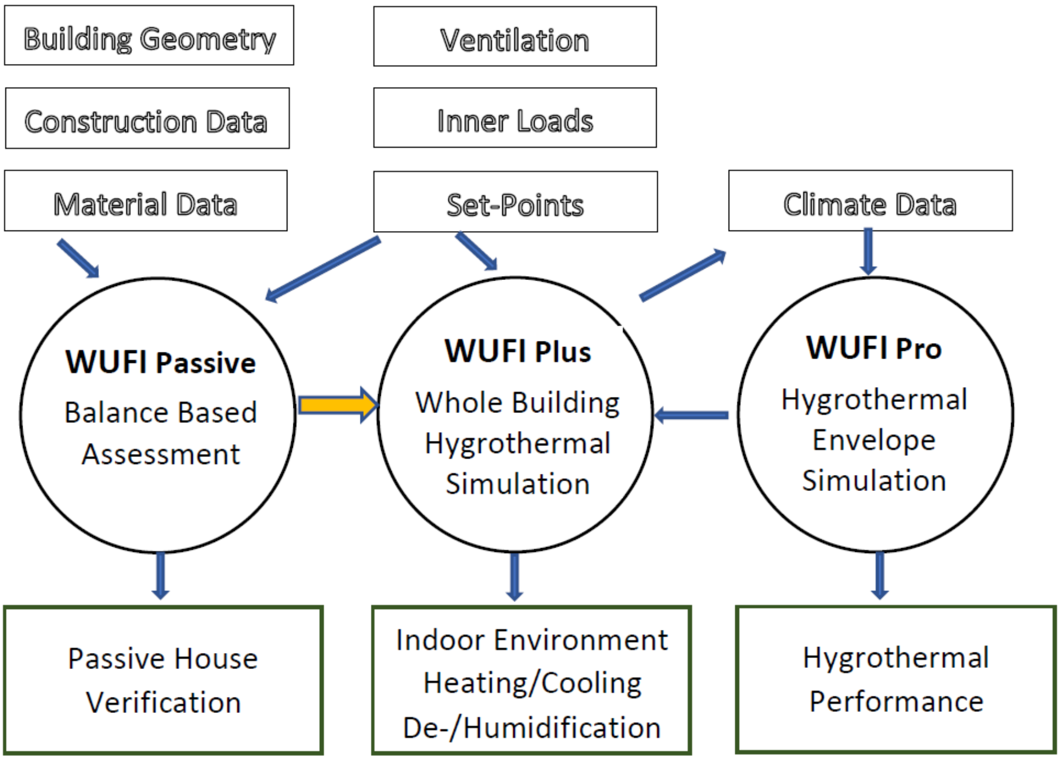
Heat and moisture transport in porous materials was first described in the 1950's and 1960's (Luikov, 1964; Philip & De Vries, 1957). Since Künzel (1994) applied the knowledge of the heat, air and moisture (HAM) physical phenomena to building materials, diverse hygrothermal models have been developed (Mendes et al., 2016; Woloszyn & Rode, 2008). For instance, WUFI (IBP, 2019), HAM-Tools (Kalagasidis, 2004), Passys (Rode & Grau, 2010), and Delphin (Bauklimatik, n.d.). HAM simulation tools are developed and used for analysis and prediction of physical processes of heat and moisture transfers in buildings. Therefore, they serve the AEC industry in the analysis and prevention of moisture related issues in existing and most important future buildings (Busser et al., 2019).

WUFI Plus is a dynamic hygrothermal building simulation tool commercially available for practitioners in the field of analysis of heat and moisture in buildings (Fraunhofer Institute for Building Physics, n.d.-e). WUFI Plus consists of a combination of a whole building energy calculations model and HAM transfer model (Woloszyn & Rode, 2008). Therefore, WUFI Plus is suitable for numerical modelling and analysis of HAM performance of the whole building or separate zones in the building. WUFI Plus is in accordance with the requirements of the EU-initiated heat and moisture standards development-project (HAMSTAD, 2000-2002). This aims to standardize HAM-modelling procedures (Adan et al., 2004). Consequently, HAM models are engineering tools for the analysis and optimization of the hygrothermal performance of the building components, and, as in the case of WUFI Plus, of the whole building and its zones. In WUFI Plus, the user can choose between SI and US-IP units for data input, computation, and output of results. The WUFI Plus user interface itself can be switched between the following languages: German, English, Polish, Italian, and Chinese.

Prior to the practical use of any energy and moisture analysis numerical model, the program has to be tested. WUFI Plus is used in multiple countries. Therefore, the WUFI Plus evaluation process involves not only German standards but American as well. WUFI Plus validation with The Association of German Engineers (VDI) (2001) is described by Schöpfer et al. (2010) and the evaluation with ASHRAE (2017a) by Sauer (2011). An overview of the validation process for WUFI Plus delivers Antretter et al. (2011). WUFI Plus, as an essential member of “WUFI family” (Figure 18), focuses on a room and/or the whole building, including building components, interactions between the building envelope and indoor air, and the building envelope and outer climate.

Figure 18

Combination of WUFI Simulation Tools



Note. Adapted from "*All-in-One Design Tool Solution for Passive Houses and Buildings - Monthly Energy Balance and Hygrothermal Simulation*" (Antretter, Klingenberg, et al., 2013, p. 8).

WUFI Plus calculations account for precipitation, solar radiation, local weather data, air exchange, window ventilation, HVAC, inner moisture loads, the orientation of walls, and construction details. Therefore, WUFI Plus provides dynamic building energy simulations based on realistic calculations of the transient hygrothermal behaviour of multi-layer building components exposed to natural climate conditions. Consequently, the calculations enable for a comfort analysis on a room by room basis as per the requirements of ASHRAE (2017b). By these calculations, the interaction with the room combines two components - hygrothermal with thermal.

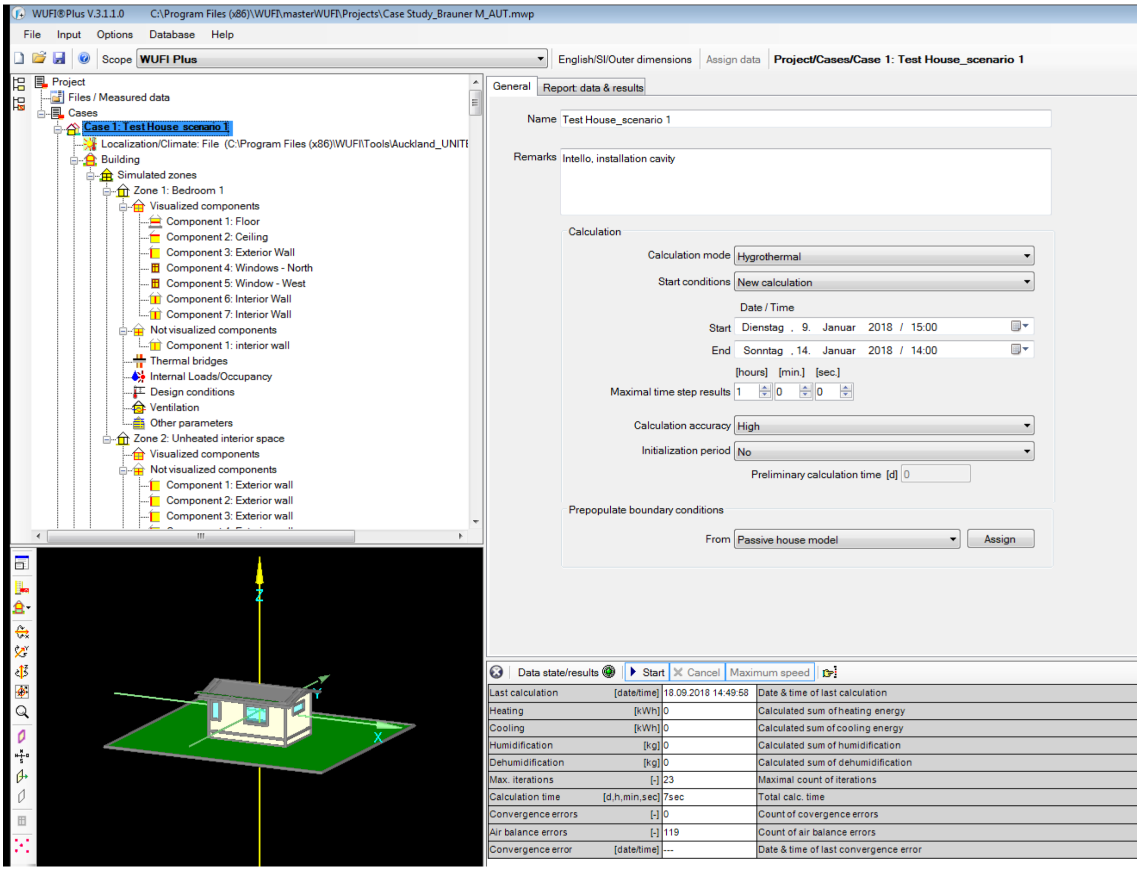
WUFI Plus contains different calculation scopes, such as WUFI Plus, DIN 4108-2 Thermal Protection / Building Simulation, and Passive House Verification. The switching between these calculation scopes is possible at any time while building inputs are carried automatically from one scope to the other. The German thermal protection standard DIN Standards (2013) describes verification methods, such as thermal building simulations, to achieve thermal protection and the energy economy in buildings (Krone et al., 2015). The part 2 of this standard defines minimum requirements to thermal insulation in order to minimize thermal bridges or to reduce overheating during summer (Maas et al., 2013).

WUFI Plus is a user-friendly software with built-in assistance for missing or incorrect data (Fraunhofer Institute for Building Physics, n.d.-e). Its advantages lay in the uniqueness of a complete analysis for thermal and hygrothermal relations. Subsequently, WUFI Plus enables for predictions of moisture damages, indoor climate and energy demand (Antretter, Klingenberg, et al., 2013). The energy analysis contains an energy flow and loss evaluation, which might benefit the design optimization process. Additional features of WUFI Plus are ventilation analysis and an option to evaluate dampness and mould growth (Antretter et al., 2017). Therefore, WUFI Plus simulations require detailed building envelope data and additional information, such as internal loads, set points, ventilation, and mechanical systems. For the building data input, WUFI Plus offers two possibilities. Building Wizard, as a part of WUFI Plus, supports building geometry input where a pre-set basic geometry might be used. Alternatively, the geometry import is enabled from SketchUp or gbXML (e.g., from Revit) (Antretter et al., 2017). The additional information input is provided by "User interface". The subdivision of the user interface enables customized entry or built-in databases. Consequently, realistic mechanical systems profiles and daily usage might be simulated. Alternatively, in a situation of unknown values, pre-set standard schedules, internal loads, and engineering system components might be used for the simulation (Fraunhofer Institute for Building Physics, n.d.-e).

The layout of WUFI Plus is divided into 4 windows/sections: a tree structure, input mask, 3D preview of the building, and output window as shown on a project example in Figure 19.

Figure 19

WUFI Plus Tree Structure, Input Mask, 3D Preview of Building, and Output Window



The tree structure allows for the management of the project, its description, division of the project into cases, and data files, such as measured data input. Each project's case is described by location/climate, building, and HVAC. Building components are subdivided into simulation zones, attached zones, 3D-Objects, and remaining elements. Each simulated zone is specified by visualized components, not visualized components, thermal bridges, internal loads/occupancy, design conditions, ventilation, and other parameters.

The input mask structure enables case specific data entry and case related results. All components of the building require a definition of structure, material, and environment. Each component description consists of a general description, assembly, surface, initial conditions, numerics, and report data/results. General description of a component informs about the name of the component, type (opaque-walls, transparent-windows, opening-not relevant), attachment to the interior and exterior side of the component, area, inclination, orientation, perimeter, and essential physical parameters, such as U-factor and thermal resistance. The section about internal loads/occupancy enables for periodic day profiles or use of external files with measured data. The internal loads represent heat (divided into convective and radiant), moisture, CO_2, and human activity. The internal loads are allocated to specific periods during the 24-hour cycle. Ventilation is determined by natural ventilation, such as infiltration due to air leakages, mechanical ventilation, and interzone ventilation, such as gaps under internal doors. All these features allow for a specific determination of hygro- and thermal conditions of the building. That way, the program is well suited for research and calculation of project alternatives.

5.1.2 The Simulation Process

This chapter describes the carefully planned series of full-scale simulations with the goal of generating data. The data can be used for testing the hypothesis, comparison with the field experiment results under real climatic conditions, and analysis of the requirements for integration of HAM models into BIM. The test case in this study is unique in its complexity, configuration, and purpose. The experimental set up, as described in Chapter 4, represents the input into the simulation program. This study simulates the hygrothermal processes in the compartment with real boundary conditions reflecting the real house settings. The intention is to create a supportive environment for using both, in-field experiment and simulation. With this combination of methods, the research demonstrates the importance of using simulation during the construction design process. Consequently, existing differences between the physical qualities of materials might be purposely selected to enhance the hygrothermal performance of the house. The simulation delivers data for both, the testing of the hypothesis and the comparison with in-field experiment data. Therefore, the simulation represents a vital part of the data collection.

The study chooses RH and temperature as dependent variables calculated in one-hour intervals for consecutive 5 days (120 measurements/counts in total) for each scenario. Independent variables consist of weather data, different materials with different physical properties, water vapour released during every day in the 24-hour cycle, and different type of exterior walls. Weather conditions are described by outside RH, temperature, and solar radiation. For the calculation, this research uses real measured weather data in the form of an exterior weather data file.

5.2 Experimental Settings

The experimental set-up follows the description of the quasi-experiment above. Therefore, the simulation setting reproduces the actual situation. However, WUFI Plus enables diverse determinations and consequent visualizations of the simulated compartment. The tested area might be specified as a zone in the whole building or as a compartment only. In the second option, the compartment's boundary conditions have to be specified accordingly (Antretter et al., 2017). Therefore, the remaining indoor space has to be determined as not visualized attached zone with not heated indoor conditions. After careful evaluation of the advantages and disadvantages of these options, the researcher decided to visualize the compartment only. This option allows for an exact specification of the location and orientation of exterior walls, area, wall properties, ventilation, solar radiation into the room, and initial conditions. The visualization of the tested compartment is shown in Figure 19.

The actual simulation process contains eight cases where for each of the two houses, four scenarios are calculated. Each case consists of two simulated zones. The visualized zone represents the tested compartment with a user-defined net volume of 46.7 m^3 and floor area of 19.46 m^2. The not visualized zone represents the remaining indoor space of the house with the net volume of 226 m^3 and a floor area of 94.85 m^2. The simulation in each case runs simultaneously for the tested compartment and for the remaining indoor space as a "not visualized" zone. This way, the whole building hygrothermal and thermal performance is calculated. The settings of the scenarios are as follows:

<u>1. Scenario</u>

In the first scenario, the development of RH is simulated in the existing compartment without any changes of materials or any humidification. The results are used for comparison with the measured data and as the initial data before any changes are made. For the same five consecutive calendar days as in the in-field experiment, the RH and indoor temperature are simulated in the one-hour step by existing plasterboard lining (unpainted) on the walls and ceiling without any additional humidification.

2. Scenario

The second scenario uses the identical specification of materials as the first scenario. The difference consists of changes in internal loads. The humidification is set in a periodic day profile under "Moisture" with the hourly release of 276.67 grams of water into the indoor air in the time between 7 PM and 7 AM. This way, the sum of water released in 24 hours is 3.32 l, which corresponds with the quasi-experiment situation. The twelve-hour cycle imitates inhabited space. The goal of this setting is to gain data about the development of the indoor RH while releasing additional humidity to the room as-built.

3. Scenario

For the third scenario, changes in components are required. As only a part of the walls is covered with MgO sheets, the researcher uses "not visualized components" section to specify the material added to the walls, its placement and orientation. One sheet of MgO board is installed on the North exterior wall and two sheets on the internal walls. The area covered with MgO boards of 8.28 m^2 represents 18.9% of the total wall area in the compartment. The humidification is identically set as in the second scenario in a periodic day profile under "Moisture" with the hourly release of 276.67 grams of water into the indoor air for twelve hours in the time between 7 PM and 7 AM. The goal of this setting is to show how the last layer of installed materials influences the level of the indoor RH.

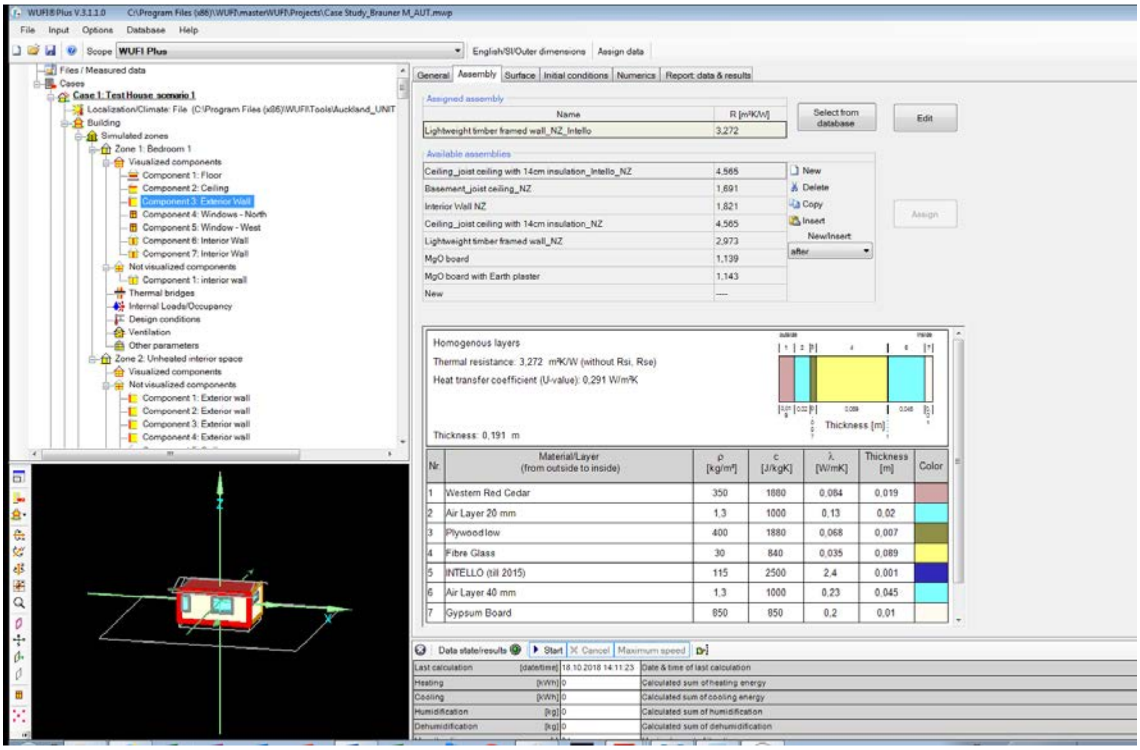
4. Scenario

Earth plaster (Rockcote) in a thickness of 2mm is applied to MgO sheets as a final wall finish. Prior to the application of the plaster, MgO boards have been primed with a diluted (1:5) water-based co-polymer resin to assure bonding as per manufacturer's specification. In this application, the barrier properties of the resin represent the key performance determining factor. Although this study does not include testing of any products, the researcher notices that the polymer has an effect on permeability. This effect of polymer coatings has been described by Thomas (1991) and reviewed by Tan and Thomas (2016). They outlined the theory of diffusion of small molecules through polymer films and demonstrated the effect of such coatings. The study intention of the fourth scenario is to show that finishing materials have an influence on indoor RH levels. Therefore, the permeability of such finishes has to be considered during the specification process.

In order to receive correct simulation results, the detailed determination of all building components is necessary. For this reason, WUFI Plus requires each component to be described by the assembly, surface, and initial conditions. The assembly is specified by homogenous layers from outside to inside where every material layer is described by thickness, thermal resistance, heat transfer coefficient, equivalent air layer thickness Sd, and other physical properties. The WUFI Plus assembly of homogenous layers is shown on an example of north-facing exterior wall in Figure 20.

Figure 20

WUFI Plus Specification of Homogenous Layers in the Exterior Wall by T-House



After all homogenous layers are specified, WUFI Plus automatically calculates the total thermal resistance and the heat transfer coefficient for the assembly. In the simulation, the building component “Exterior wall” in the T-house has thermal resistance 3.272 m²K/W and heat transfer coefficient (U-value) 0.291 W/m²K. In comparison, the same component in the C-house has thermal resistance 2.973 m²K/W and U-value 0.318 W/m²K.

The researcher is aware that the determination of all layers in the assembly is crucial for the simulation. However, as no moisture dependent hygrothermal properties of the primer nor the earth plaster are available, some adjusting decisions have to be made. Therefore, in these layers, the study uses available data from other sources to substitute for missing acrylic primer data. The data sources are published testing results of water-based acrylic paints (Giosuè et al., 2017), polymers coatings (Tan & Thomas, 2016; Thomas, 1991), and the design thermal values for materials in general in building applications, as stated in BS EN 12524:2000 (British Standards, 2000). The physical properties of earth plaster are replaced by the suitable physical characteristics of similar material - clay plaster, which is provided by WUFI material data.

The next part of the settings consists of ventilation data. As mechanical ventilation is out of order for the time of the experiment, the only air exchange sources represent the infiltration and the interzone ventilation. The infiltration rate determines the air flow through the exterior walls, floor, and roof space. In other words, the air exchange through the building envelope between inside and outside. The air flow through the building envelope measurements are provided by Blower door test. Consequently, the research estimates the infiltration values (air change rate) from the Blower door test results (see Appendix A). According to the recommendation of BRANZ, the natural air change rate is possible to calculate using the following formula (McNeil et al., 2015; Quaglia & McNeil, 2012):

$$ACH_{nat}=ACH_{50} / 20,$$

Where ACH_{nat} represents the natural air change rate and ACH_{50} the air change rate by 50 Pa air pressure difference, as measured in Blower door test. The results are shown in Table 25.

Table 25

Blower Door Test Results Summary and Air Infiltration Rate Calculation

Characteristic	Test House	Control House
ACH_{50} pressurised	1.93	8.20
ACH_{50} depressurised	2.37	8.28
ACH_{nat} estimation	0.1	0.4

5.3 Limitations and Challenges of the Simulation

Generally, model prediction of RH development using a classic diffusive model may be devoid of accuracy, since numerical equations underestimate the nature of the adsorption process by diverse moisture levels. Therefore, some phenomena, such as nonequilibrium behaviour between water vapour and bound water or transport by air convection, are neglected (Busser et al., 2019). The research results demonstrate this limitation, primarily due to the use of hygroscopic fibrous materials, such as MgO board and wood-based products.

The major challenge of the research represents unknown values of some data. For example, the infiltration rate has to be set to allow for the specification of the natural air movement between the indoor of the building and the outside air caused by leakages. The infiltration values in the form of the natural air change rate have been estimated as described above and shown in Table 25. Configuration of real exterior weather data for the time of the experiment, conversion of permeance to water vapour resistance factor, interzone ventilation rate, and material properties depict the next challenges this research deals with.

For exterior weather data, the researcher created a new data set comprising temperature, RH, and solar radiation. The measured weather data for the period of the experiment have been kindly provided by Unitec. However, the data supplied in the Excel sheet are not suitable for the WUFI calculation. WUFI's webpage describes in detail the weather file formats which WUFI can read (Fraunhofer Institute for Building Physics, n.d.-a). For newly created weather data, WUFI recommends WAC format. The WAC format is flexible with respect to the number of contained weather elements. Thus, only weather elements which are needed for the concrete simulation are required and therefore sufficient. Furthermore, directional weather elements, such as radiation and rain, are automatically converted by WUFI for the orientation and inclination of the component to be simulated.

The hygrothermal properties of the MgO boards have been provided in the form of testing results from an independent laboratory. However, the testing results are not directly suitable for the simulation as they are available for different board thicknesses and in Perms only. Therefore, the research needs to proceed with a conversion calculation of permeance into water vapour resistance factor µ-value ("mu-value"). For the measures conversion, the researcher created a conversion table (Table 26) based on BS 5250:2002 Annex E (British Standards, 2002).

Table 26

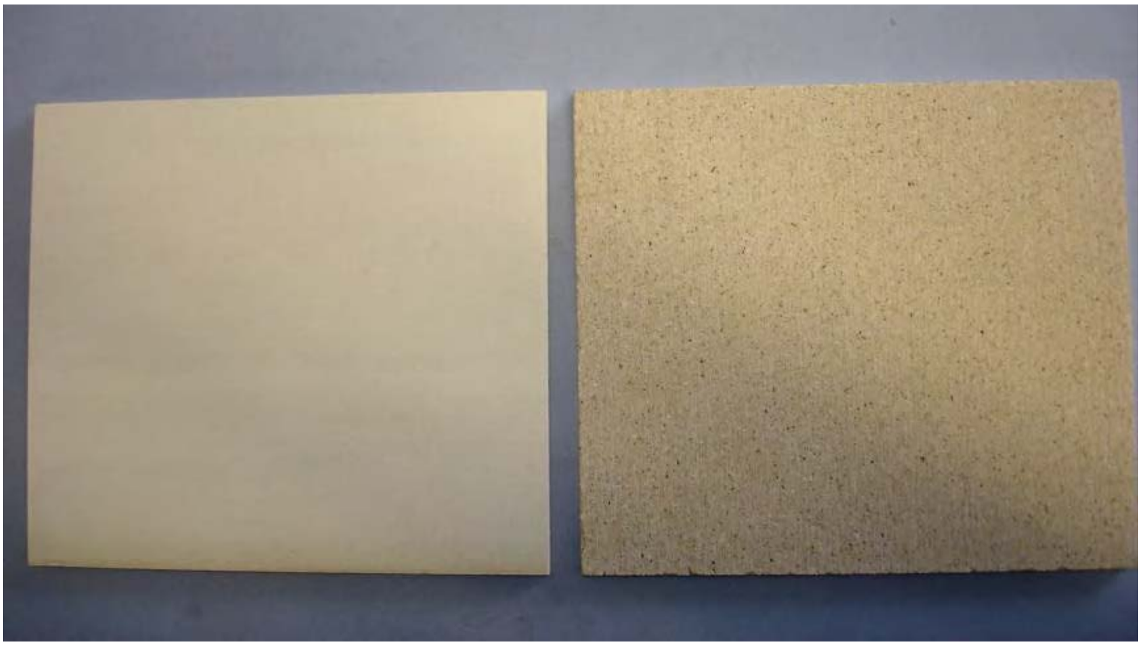
Conversion Table of Diverse Hygrothermal Measures

Measure	Symbol	Units	Conversion to µ-value	Conversion to S_d-value
Vapour resistance		MNs/g	– multiply by 0.2 gm/MNs – divide by thickness of material in metres	– multiply by 0.2 gm/MNs (equivalent air layer thickness)
Vapour resistivity		MNs/gm	– multiply by 0.2 gm/MNs	– multiply by 0.2 gm/MNs – multiply by thickness of material in metres
Water vapour resistance factor	µ			– multiply by thickness of material in metres
Equivalent air layer thickness	S_d	m	– divide by thickness of material in metres	
Permeance	US perm	grains/(ft²·h·inHg)	– multiply by 0.0572 – reciprocate 1/result – multiply by 0.2 – divide by material thickness in meter	– multiply by 0.0572 – reciprocate 1/result – multiply by 0.2
Permeance	Metric perm	g/(m²·24h·mmHg)	– multiply by 0.0968 – reciprocate 1/result – multiply by 0.2 – divide by material thickness in meter	– multiply by 0.0968 – reciprocate 1/result – multiply by 0.2
Permeance (SI equivalent)		ng/sm²Pa	– multiply by 0.001 – reciprocate 1/result – multiply by 0.2 – divide by material thickness in meter	– multiply by 0.001 – reciprocate 1/result – multiply by 0.2

The laboratory test results are available for two MgO boards' thicknesses: 3 mm and 18 mm. The samples for the testing have been derived from bigger pieces of the material supplied by the manufacturer as representative samples. The MgO boards' water vapour transmission has been tested in the laboratory in accordance with ASTM E96 / E96M-05 (ASTM, 2005). The current version of the Standard Test Methods for Water Vapor Transmission of Materials is ASTM E96 / E96M-16 (ASTM, 2016). For the full test results, see Appendix B. Although the water vapour resistance factor μ-value is a bulk material property, the results from the conversion of permeance for the different board thicknesses into water vapour resistance factor are not equal. The water vapour resistance factor μ, resulting from permeance's conversion by 3 mm board equals 131 and by the 18 mm board equals 57. The reason for such a significant difference in μ-value is unknown to the researcher. Although the importer/producer of the MgO boards states that the boards are not coated or treated, it seems that the moisture-related hygrothermal property of the boards depends on their thickness. A possible explanation of this phenomenon might be the different density across the board, which is apparent from the visual examination of the boards. The increased material density towards the front side of the MgO boards might be caused by the nature of the boards' production process. The boards are fabricated in a process consisting of following procedures: forming of a mould, separating the panel from the mould, drying of the panel, and sanding to the required board thickness. Due to this process, the face side of the boards is denser and smoother than the back side, as shown in Figure 21.

Figure 21

Magnum Board Photo Showing Both Sides of the Sheet Material



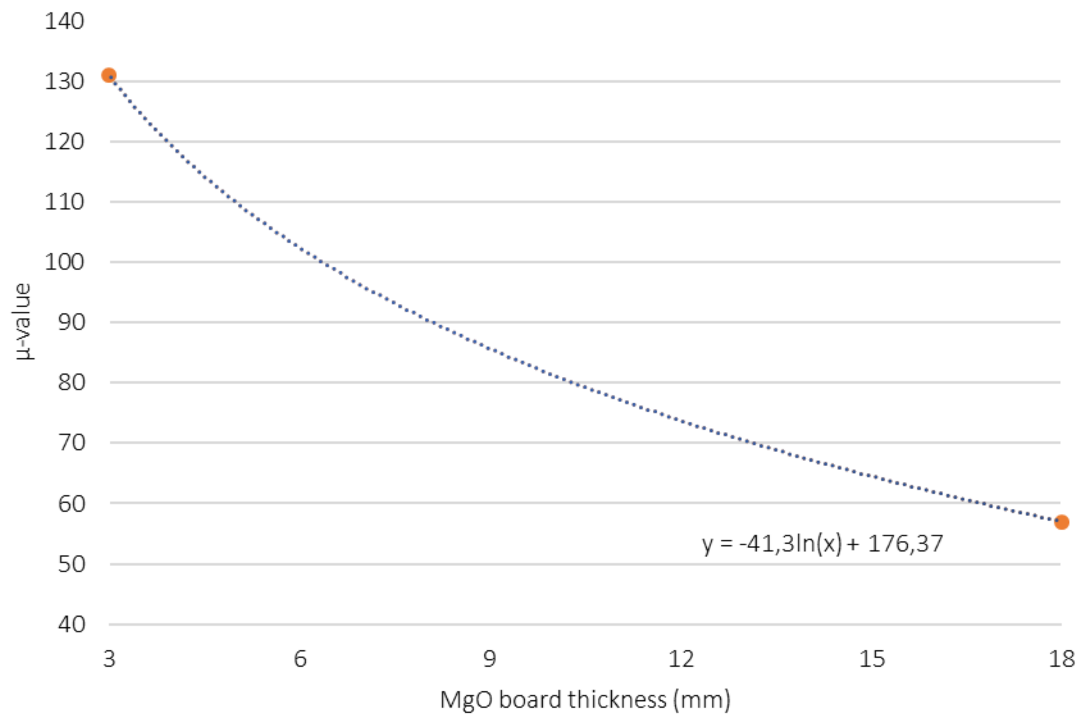
Note. The wall lining board is made from a fibre-reinforced magnesium oxide base. Reprinted from *Magnum Board Technical Information* (Version 1.0, p.9), Copyright 2017 by Health Based Building. Reprinted with permission.

As already mentioned earlier, the hygrothermal data is not available for the 9 mm MgO board. To estimate the water vapour resistance factor μ the research uses a natural logarithmic derivation function: $\mu = -41.3 \ln(x) + 176.37$, where x represents the thickness of the board in millimetres (Figure 22). The calculation of the μ-value for the 9 mm board is as follows:

$$\mu = -41.3 \ln(9) + 176.37 = 85.62$$

Figure 22

Water Vapour Resistance Factor μ-Value Extrapolation for MgO Boards



The next challenge of the simulation represents the interzone ventilation. Especially for the scenarios with humidification, in a situation when no airflow measurements inside of the house are available, setting up the correct interzone ventilation rate influences the numerical outcomes. The interzone ventilation is mainly due to gaps around the closed internal door and gaps in the internal walls between the tested compartment and remaining indoor area. This research uses an estimate of 0.01m^3/h based on available literature (Maas, 1992; McNeil et al., 2015) and trial calculations for the first scenario.

Another issue arises when comparing the simulation results to quasi-experiment data. Numerical predictions often underestimate the adsorption process on one side and overestimate the desorption process on the other side. Therefore, the simulated moisture front rushes slower than the measured experimental moisture (Berger, Gasparin, et al., 2017).

5.4 Results

Results from WUFI Plus simulation are available in the form of numerical calculated results and graph curves for each case. The results from the simulations are shown in Figure 23 for the T-house, and in Figure 24 for the C-house.

Figure 23

T-House Simulated RH Values

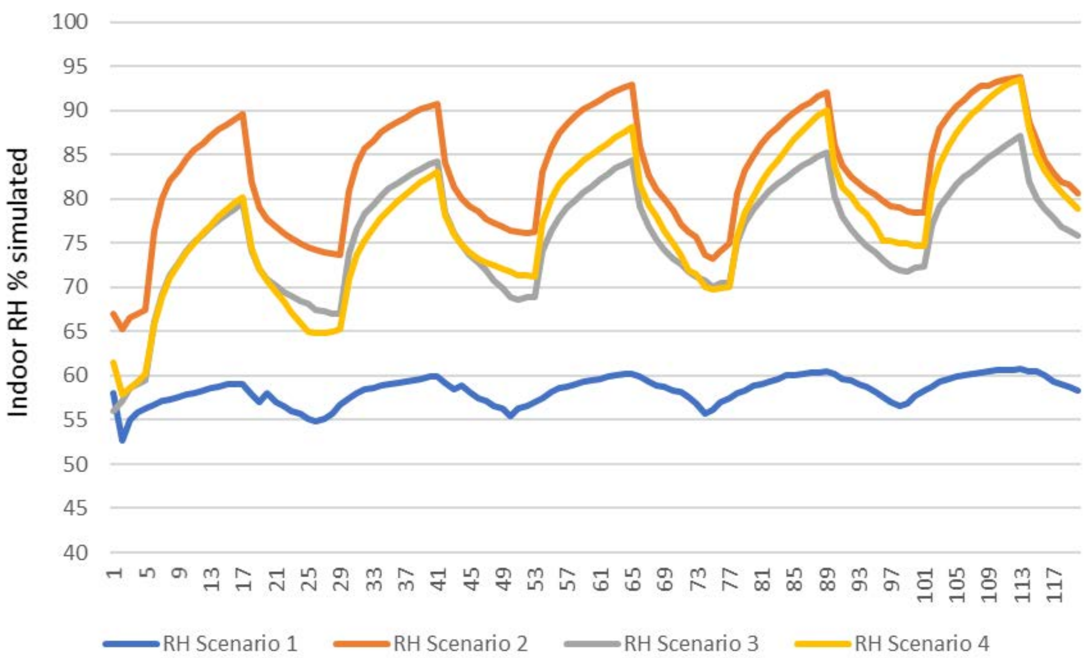
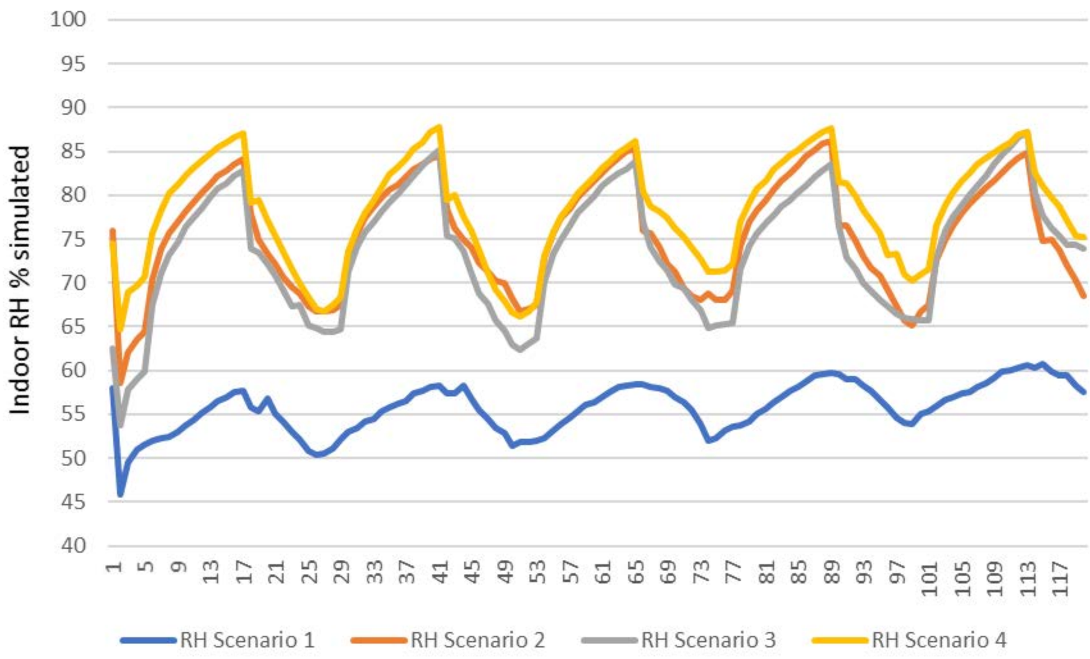


Figure 24

C-House Simulated RH Values



5.5 Analysis

The simulation results demonstrate the differences in the indoor RH levels while testing various scenarios. For the analysis of the data, the study uses IBM SPSS descriptive statistics.

5.5.1 Descriptive Statistics

The descriptive statistics include data in the form of mean, minimum RH, maximum RH, range, and counts for each scenario calculated from simulated data. Comparing the data, the study found out that in scenario number one, two, and three the values for mean RH are lower in the C-house (Table 28) than in the T-house (Table 27). The simulation results for scenario number four show that maximum reached RH is higher in T-house however, the mean RH is higher in C-house.

Table 27

Descriptive Statistics for Simulated Inside RH in T-House

Dependent variable: RH inside

Scenario	Mean	Minimum	Maximum	Range	Counts
1.	58.365	52.7	60.8	8.1	120
2.	83.100	65.3	93.8	28.5	120
3.	75.883	56.0	87.1	31.1	120
4.	77.606	57.8	93.4	35.6	120

Table 28

Descriptive Statistics for Simulated Inside RH in C-House

Dependent variable: RH inside

Scenario	Mean	Minimum	Maximum	Range	Counts
1.	55.773	45.8	60.7	14.9	120
2.	75.396	58.6	86.3	27.7	120
3.	73.778	53.8	87.3	33.5	120
4.	78.157	64.8	87.8	23.0	120

In descriptive statistics, another method for depicting groups of numerical data by their quartiles is a box plot, as demonstrated in Figure 25 and Figure 26. Box plot and its meaning is described in section 4.4.1. The visual analysis of box plots enables for a good overview of the differences between the two simulated construction types. The house with an airtightness membrane (T-house) compared with the house without any airtightness membrane (C-house) features mostly higher mean RH and more spread variation of measures RH in two scenarios.

Figure 25

Box Plot of Simulated Data in T-House

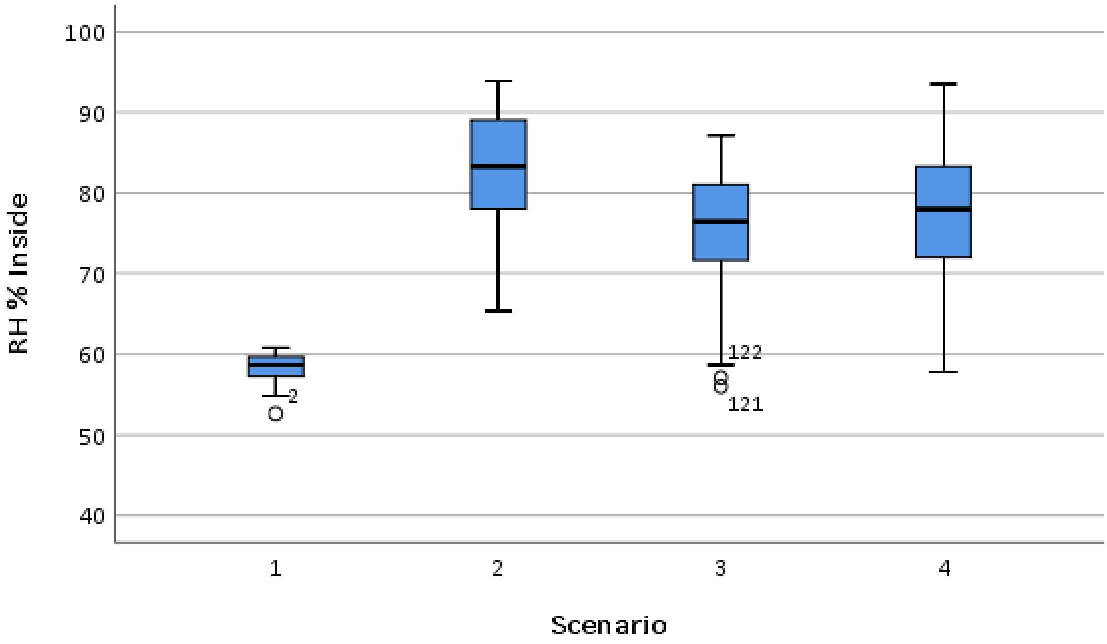
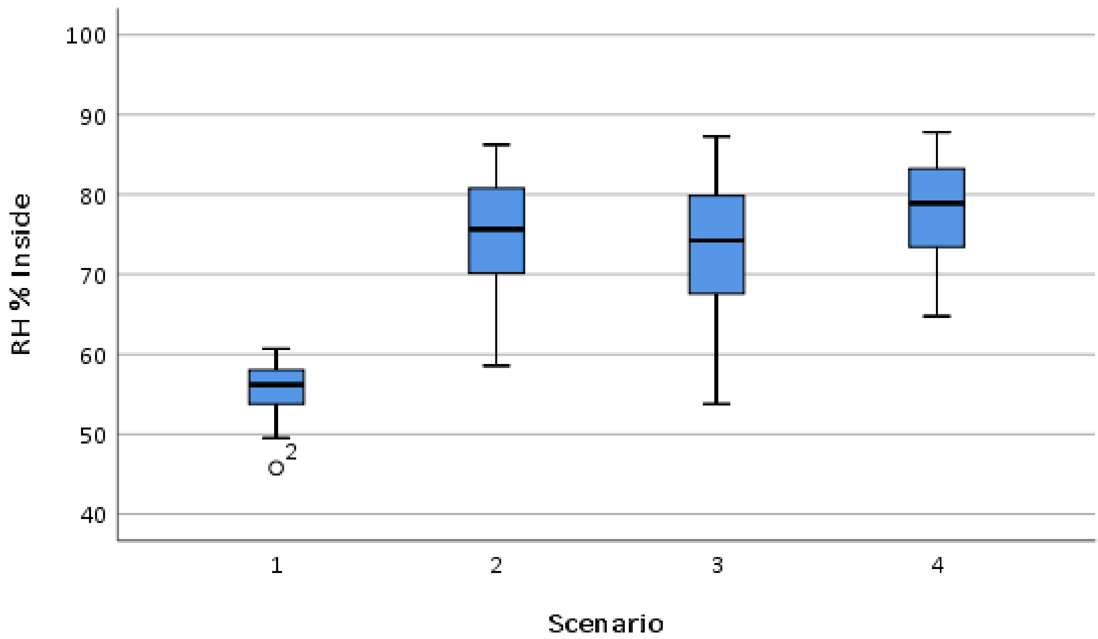


Figure 26

Box Plot of Simulated Data in C-House



The descriptive statistics of simulated data reveal that the most effective material by humidification is MgO (scenario number three). Although the ranking of numerical model results is identical to measured results, the mean, minimum, maximum, and the range of data are not the same. The possible reasons for that are addressed further in this chapter and Chapter 7 (p. 202).

5.5.2 Comparing Simulation and Quasi-Experiment Data

Another issue arises when comparing the numerical model results and experimental data. The study results correspond with the previous studies facing the problem that hygrothermal models do not precisely reproduce the measured RH levels under dynamic load, especially by the presence of hygroscopic materials (Colinart et al., 2016; James et al., 2010; Labat et al., 2015). The results of the simulation seem to underestimate the adsorption process and/or overestimate the desorption process, while additional humidity is introduced to the room (J. Berger et al., 2018). This means that the simulation predicts slower moisture transport than measured during the in-field experiment. This phenomenon is illustrated in the example of the third scenario discrepancies as depicted in Figure 27 in the T-house and Figure 28 in the C-house.

The differences in the standard deviation and mean values found between quasi-experiment and simulation are presented in Table 29. From the data, it is possible to derive a conclusion that the differences between the measured and simulated data are higher in the C-house. Nevertheless, all differences in the standard deviation and mean values are within the range of 5% error from the measured values. The highest differences the research experiences in scenario number four, where the error from measured mean is 3.9% in the T-house and 4.5% in the C-house.

Table 29

Differences Between Measured Data and Simulation

House	Differences in RH (measured – simulated)	Scenario			
		1	2	3	4
T-house	Mean value	-1.00	1.95	1.61	3.14
	Standard deviation	0.73	-1.32	0.11	-0.72
C-house	Mean value	-1.57	2.72	2.97	3.70
	Standard deviation	-0.83	-2.39	-2.15	-2.44

Figure 27

Illustration of the Discrepancies Observed by Scenario 3 When Comparing Experimental Data to Results From the Simulation With WUFI Plus in T-House

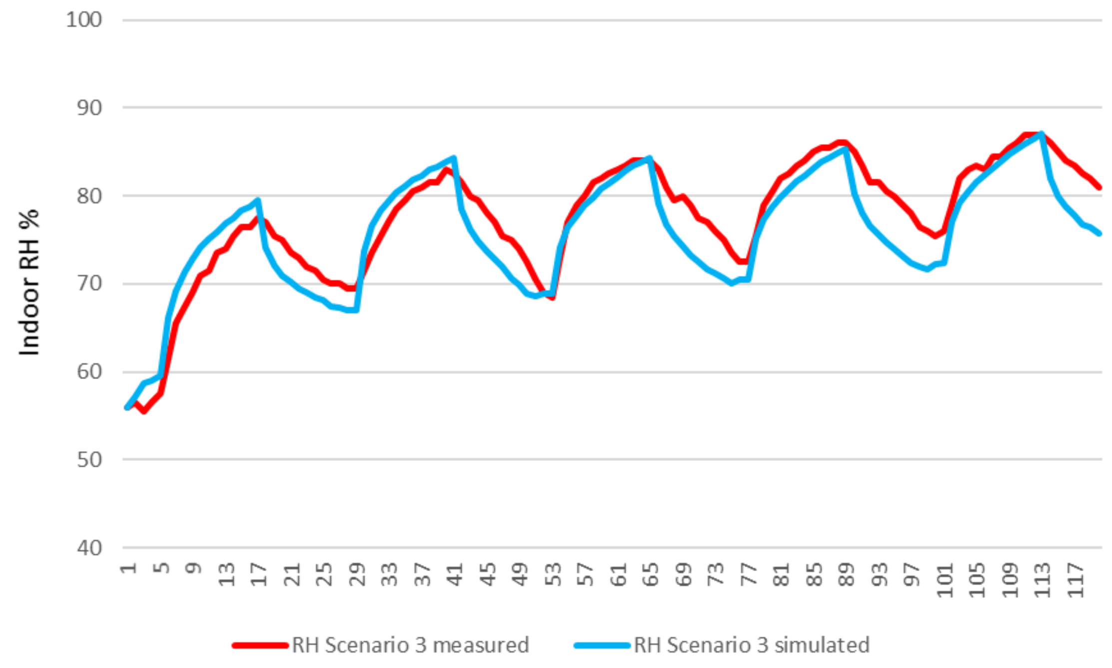
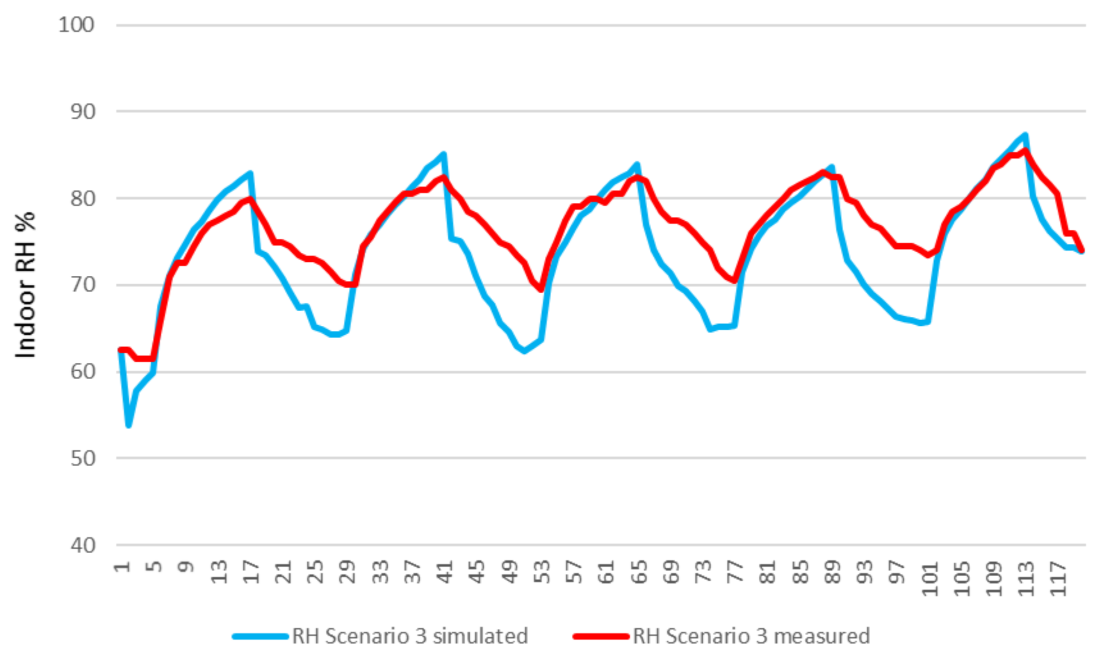


Figure 28

Illustration of the Discrepancies Observed by Scenario 3 When Comparing Experimental Data to Results From the Simulation With WUFI Plus in C-House



The divergences found between experimental measurements and simulation results might have their source within the difficulty to estimate the correct air change rate between the modelled zone and the rest of the indoor space in the house. As the air change is caused by unknown air channels between the rooms, the calculation of the air change, as described above, is addressed in pre-processing (Schmidt et al., 2012, p. 1145). Another reason for the divergences might be the estimated moisture dependent material properties.

5.6 Conclusions and Recommendations

The key findings of the simulation are similar to the quasi-experiment results. Despite the above described limitations, the results from the dynamic hygrothermal simulation confirm the hypothesis: "Materials used in the building envelope have a significant influence on the hygrothermal performance of the building." In the simulated cases, the most effective material for the regulation of the inside RH is the MgO board. However, in each house, the highest level of RH is reached in a different scenario. In the T-house, the maximum of 93.8% RH is reached in scenario number two with the original construction of unpainted plasterboard. In contrary, in the C-house the maximum of 87.8% RH is reached in scenario number four with the addition of MgO boards covered with earth plaster.

From the findings, a conclusion might be drawn that the materials used as the first layer from the inside of the house influence the hygrothermal performance of the whole building. Therefore, the research recommends the hygrothermal simulation as a vital part of the design process.

For further research, this study recommends repeating the simulation with accurate and not estimated hygrothermal measures of the used materials. Generally, for any simulation, it is crucial to use laboratory tested material data. Therefore, the study recommends creating a data bank with moisture related physical data for every material used in construction.

5.7 Summary

This chapter deals with the description of the second part of data collection and analyses - modelling of the quasi-experiment. For the purposes of the simulation, the study utilizes the dynamic hygrothermal building simulation tool WUFI Plus. The simulation set-up is identical with the quasi-experiment settings. Therefore, the actual simulation process contains eight cases where for each of the two houses, four scenarios are calculated. The assembly of the boundary components is specified by homogenous layers from outside to inside where every material layer is described by thickness, thermal resistance, heat transfer coefficient, μ-value, and other physical properties. The ventilation data represents the next vital part of the simulation settings. As the mechanical ventilation is switched off for the time of the experiment, the only air exchange sources consist of the infiltration and the interzone ventilation.

In both houses, the most effective material by the introduction of additional water vapour seems to be MgO board (scenario number three). The highest levels of RH are reached in scenario number two (unpainted plasterboard lining) in the T-house and scenario number four (MgO board with earth plaster) in the C-house. After analysing the simulation results, this chapter provides a comparison of the numerical model and experimental data. Although the ranking of scenarios in the numerical model results is identical to measured results, the mean, minimum, maximum, and the range of data are not the same. The differences in the standard deviation and mean values found between quasi-experiment and simulation are higher in the C-house. Nevertheless, all differences are within the range of 5% error from the measured values.

The results of the simulation confirmed the results of the experiment. Therefore, the study recommends the hygrothermal simulation as a suitable tool for an early materials' assessment and for the targeted specification of building materials. The following chapter focuses on the incorporation of the hygrothermal simulation into BIM. Primarily, the various possibilities of the interoperability between two virtual tools, such as Revit and WUFI Plus, are investigated.

Chapter 6 Interfacing BIM With Hygrothermal Modelling

The research understands BIM as a process to achieve higher productivity in the construction, sustainability, and quality of buildings. This chapter deals with requirements for interoperability between architectural models and building hygrothermal models in BIM. These requirements are based on the study of the interoperation between BIM tools in general, modelling/simulation tools assessing the hygrothermal performance of buildings, and on the in-field experiment. BIM and the state-of-the-art BIM interoperability are analysed historically in Chapter 3, section 3.4. The requirements for interfacing BIM with hygrothermal modelling in this chapter are specifically related to Revit and WUFI Plus, as two representative tools widely used in construction. After a description of the interoperability, the research dedicates the next part of the chapter to an analysis of settings in Revit and material properties in WUFI Plus, followed by the limitations and challenges of the BIM interoperability. At the end of this chapter, the research draws conclusions and recommendations for future research and summarizes the main findings.

6.1 Interoperability

This chapter addresses interoperability between the BIM architectural and hygrothermal models. The online Oxford English Dictionary (n.d.) defines interoperability in computing as “The ability of two or more computer systems or pieces of software to exchange and subsequently make use of data.” The construction industry implements computer-based information management and modelling at an increasing rate. Therefore, interoperability is becoming a matter of vital concern. “Interoperability is the fundamental characteristic of tools that are designed to work together as part of an integrated system to complete complex tasks” (Smith & Tardif, 2009, p. 146).

The subject matter of interoperability, as already described in section 3.4.4, represents a bottleneck in the BIM process (Ghaffarianhoseini, Tookey, et al., 2017). BIM adoption requires an exchange of information between diverse stakeholders (Dixit et al., 2019; Georgiadou, 2019). The inefficient data interoperability (Grilo & Jardim-Goncalves, 2010) together with the lack of software compatibility (Sun et al., 2017), and the lack of available skilled personnel (Georgiadou, 2019) are the significant risk factors for BIM projects. These three factors and ten others are identified by Chien et al. (2014) as critical risk factors related to the technical, management, personnel, financial, and legal aspects of BIM adoption.

Intelligent system performance depends not only on the smart system design and smart system lifecycle but on the interoperability of the system components from multiple vendors (Horst et al., 2011). Therefore, measuring the interoperability failures and risks might mitigate interoperability problems (Panetto et al., 2016). Unfortunately, not many data on interoperability ROI (return of investment) are available, nor unified guidance on the cost and risk uncertainty estimation (Horst et al., 2011). For an illustration of the magnitude of the interoperability impact, information published by the National Institute of Standards and Technology (NIST) might be used. The cost of inadequate data interoperability in the U.S. capital facilities industry has been estimated by NIST to be $15.8 billion per year (Gallaher et al., 2004; Sacks et al., 2018). Additionally, besides the interoperability issues, the fast-growing field of building simulation tools and their complexity is overwhelming to most architectural practitioners (Attia et al., 2012; Charron et al., 2005; Georgiadou, 2019).

The specification of the interoperability requirements between BIM and hygrothermal modelling forms one of the four research objectives described in section 1.4. The first research objective is to examine the hygrothermal performance of New Zealand housing construction, focusing on internal envelope materials. The second research objective is to identify the challenges associated with undertaking effective hygrothermal assessments during the early design stage of housing in New Zealand. The third research objective, relevant to this chapter, is to specify requirements for integration of hygrothermal simulation into BIM to improve building sustainability. The fourth research objective is to develop a framework for designers to provide warmer, drier, and healthier houses for the New Zealand context.

BIM, as a process, is a set of operations for constructing the digital building model using BIM tools. Consequently, the BIM tools are object-based parametric models with a set of properties. These properties are usually set to a minimal default level allowing for an extension. The extensions provided by users or an application, enable a specific type of simulation, analysis, data exchange, or interoperability of information (Sacks et al., 2018). The current BIM generation tools are well suited for cost estimation, life cycle management (Sacks et al., 2018), and some of them for energy analysis (Treeck et al., 2018) and lighting (Mendes & Mendes, 2019). To suit the requirements for interoperability, properties may be adjusted/added for diverse sets of applications. One way for specifying the material properties is to use object libraries for predefining properties (NATSPEC and Masterspec, 2018). However, the researcher notices that the predefined properties, although being convenient to use, might not be suitable for some hygrothermal assessments. Therefore, the second option, the addition of properties by the user while creating the design model (Busser et al., 2019) allows for project-specific data adjustments. This corresponds with the IFC model approach. IFC define material characteristics in two ways: as static attributes within the schema and as dynamic properties. The dynamically created properties in the form of subclasses of IFC-Property can be defined and added freely without limitations on their number (Borrmann, Beetz, et al., 2018). Another option for enhancement of interoperability represents an automatic assignment of properties during the exportation to a simulation tool (Sacks et al., 2018).

Although theoretical requirements for interoperability are well-known, the practical application of using BIM generated models for more specialized functions is still not an easy task. For example, the environmental analysis (Kent & Becerik-Gerber, 2010; Motawa & Carter, 2013) and the structural analysis (Lee et al., 2012) face many challenges. Similarly, analysis of building thermal performance (Gao et al., 2019; Negendahl, 2015; Schlueter & Thesseling, 2009) or hygrothermal performance. These challenges are generated by the reliability of the technology, cost-related issues, cyber security, client demand, and organizational culture in the AEC industry (Georgiadou, 2019; Ghaffarianhoseini, Tookey, et al., 2017; Lu et al., 2017; Migilinskas et al., 2013; Oduyemi et al., 2017). The reasons for this might be a high initial investment for software and staff training representing a financial risk for the company (Chien et al., 2014; Georgiadou, 2019). Other reasons might be the factual lack of software compatibility (Migilinskas et al., 2013; Porwal & Hewage, 2013), or lack of interest in long-term gains due to typical AEC industry contracts (Zheng et al., 2019). The significance of the financial barrier of the BIM adoption is reported from 51 per cent of UK organizations participating in the National BIM Report (NBS, 2019).

A deeper analysis of these reasons reveals that most of the hindrances to interoperation are due to the stakeholders' prevailing interest in short-term investment returns only and no client demand on BIM (Georgiadou, 2019; Zheng et al., 2019). Nevertheless, a successful enhancement of interoperability in BIM requires a driving force, especially from stakeholders. Similar to environmental issues, the behaviour is not rectified until an actual need for action has been developed due to severe climate changes (Travers, 2019). Consequently, in today's financially driven world, people need to realize what impact a low-quality building has on, but not limited to, living costs, health, and environment (Child Poverty Action Group, 2015; De Groot & Leardini, 2010; Stats NZ, 2019; Yarbrough et al., 2019).

With the growing requirements for sustainability, CAD (computer-aided design) is no longer sufficient because necessary building performance evaluation warrants the additional time, personal input, and costs (The British Standards Institution, 2018). BIM has the potential for automation of such processes and therefore, for contribution to sustainable design (Autodesk, 2006). As a significant participant in the total world energy consumption, the AEC industry needs to follow sustainability requirements (Bomberg et al., 2016). Therefore, this research recommends an adaptation of a holistic approach to the construction process. BIM can contribute to economic, social, and environmental sustainability parameters in many ways. Through enabling specialized examinations, such as energy modelling, daylight analysis, or life cycle assessment (Dastbaz et al., 2017).

Interoperability in BIM enables direct use of physical material properties in simulation and diverse analyses of buildings during the design process (Borrmann, König, et al., 2018). Therefore, the relevant physical properties and the capability of their modification constitute a part of BIM. However, this research found out that the moisture related hygrothermal material properties are often missing. Although WUFI offers product libraries (Fraunhofer Institute for Building Physics, n.d.-b), many building products and their physical data are not available. This situation makes the simulation process challenging. The results might not reproduce the current project situation due to incorrect or insufficient material data. Coherent product libraries and sharing structured product data represent crucial stipulations of continuous processes in the AEC industry. Open BIM formats offer a solution to the requirements of the better workflow. However, the existing proprietary data formats or viewable data formats in PDF are often not suitable for the automatic data-flow (Palos et al., 2014). Additionally, this research found out that the data formats often comprise non-consistent naming of physical properties, attributes, or non-unified value range. Product libraries very seldom consist of IFC-compatible library objects as defined in ISO 16739-1:2018 (ISO, 2018b). This means that the data can only be used with software accepting their formats (Palos et al., 2014). The lack of data conformity hinders a broader application of analytical and simulation tools in the construction industry.

Another hindrance in interfacing BIM with hygrothermal simulation exists in the requirements for simplification of BIM data to envelopes and zones (Antretter et al., 2017). Current WUFI Plus hygrothermal simulation tool supports building geometry input by a built-in Building Wizard, or by geometry import from SketchUp or gbXML (e.g., from Revit) (Fraunhofer Institute for Building Physics, n.d.-e). The Green Building XML schema (gbXML) allows disparate 3D BIM models and engineering analysis software to share information. “XML, eXtensible Markup Language, is a type of text-friendly computer language that allows software programs to communicate information with little to no human interaction” (gbXML, n.d.).

According to the WUFI Plus 3.1 Manual “… gbXML-files can be imported with an external program, found in the Tools-folder of the WUFI Plus main installation folder” (Antretter et al., 2017, p. 97). However, the researcher’s attempt to transfer the 3D model of the test houses from AutoCAD Architecture into WUFI Plus, using gbXML format was not successful. Therefore, the researcher entered the geometry of the building, its orientation, and used materials in WUFI Plus manually. This process is very time consuming and requires extensive knowledge of the software and material properties. Consequently, the researcher examined “Software List - Software Tools That Integrate With gbXML” (gbXML, 2019). The list of BIM authoring and analysis software tools that integrate with gbXML confirms that the listed software successfully imports or exports gbXML. However, this research found out that AUTODESK Revit and AutoCAD software are on the software list, but WUFI Plus is not.

Based on the study of IFC standard (Borrmann, Beetz, et al., 2018), presupposition for interoperability between the building and hygrothermal model would be an implementation of the basic entity of the properties, such as IfcPropertySingleValue with identical attributes in both models. To this static value can be dynamically added by the placeholder entity IfcProxy semantic extensions for hygrothermal analysis. This way, the building model would incorporate independent hygrothermal property value sets. Each IfcPropertySingleValue would have allocated nominal value and unit. However, the suggested (from this research) implementations need to be provided by software vendors. Therefore, the proposed changes are possible in a cooperation between software providers only.

Another option for interoperability between Revit and WUFI Plus might be an integration of the hygrothermal simulation in Revit using an Application Programming Interface (API) platform. The general areas where the API is suitable are stated in Table 30 based on Autodesk (n.d.-c).

Table 30

The General Areas Where the API is Suitable in Autodesk Revit

Add-ins improving Revit	Add-ins improving interoperability
To automate repetitive tasks in the user interface.	To extract project data for analysis and to generate reports.
To enforce project design standards by checking for errors automatically.	To import external data for creating new elements or parameter values.
To create Revit project documentation automatically.	To integrate other applications, including analysis applications, into Revit products.

As programming skills are required to use the API effectively, this research concentrates on the setting of parameters needed for the interoperation of Revit and WUFI Plus only. Functionality through external applications might be added to Revit in the form of an Add-In (Autodesk, n.d.-a). However, the research only makes suggestions for further research or programming without testing the feasibility of such applications. Integrating WUFI Plus analysis application as an Add-In into Revit would enable to run the hygrothermal analysis automatically as a part of the optimization process during the early design stage.

6.2 Settings in Revit and WUFI Plus

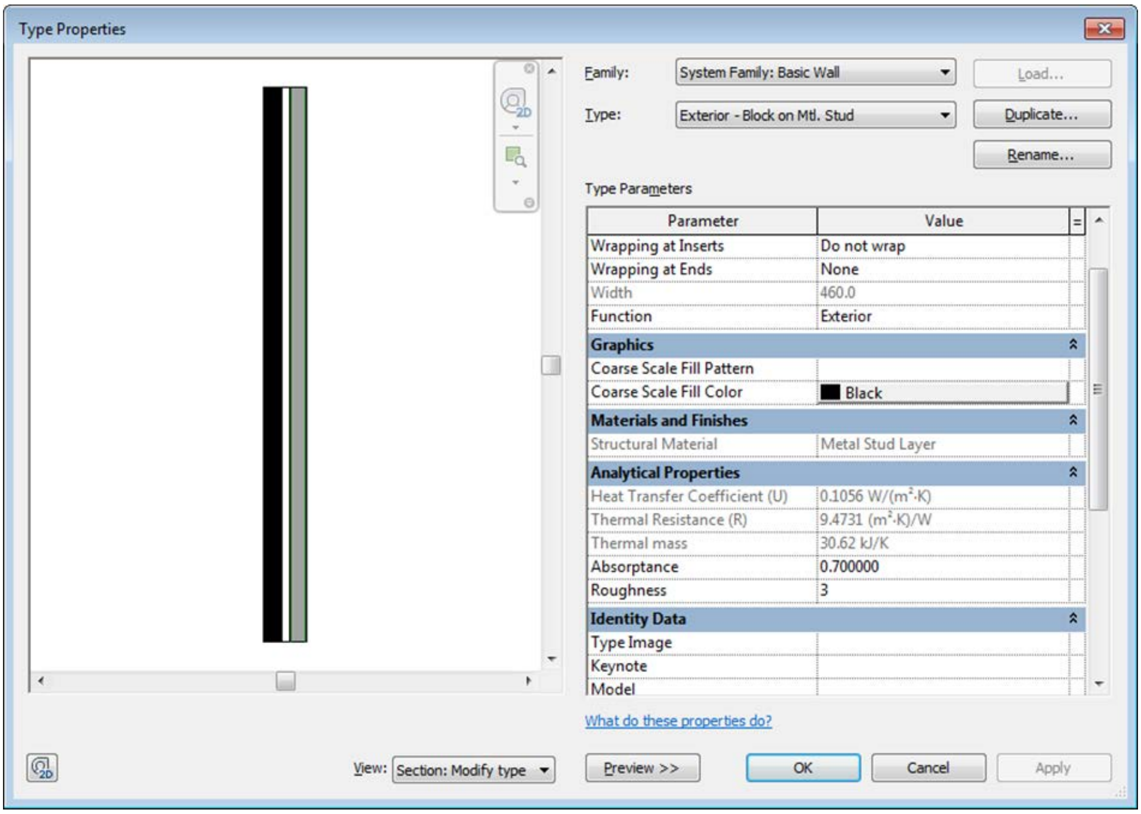
Similar to energy data settings, already existing in Revit2019, this research suggests including the hygrothermal data settings into the Revit material properties. This way, the necessary data for hygrothermal analysis will be incorporated into the BIM model. The aim is to enable hygrothermal analysis informing the design stage of construction to improve the thermal and hygrothermal performance of the building. The study demonstrates the influence of diverse building materials on hygrothermal performance. Furthermore, the study suggests a way on how to avoid future problems related to high moisture, such as condensation, mould, dampness, polluted indoor environment, and premature construction faults.

6.2.1 Revit Settings

Revit settings allow for the specification of materials and their physical properties. Existing type properties show analytical properties, such as heat transfer coefficient (U) in W/m²K, thermal resistance (R) in m²K/W, thermal mass in kJ/K, and absorptance (Figure 29).

Figure 29

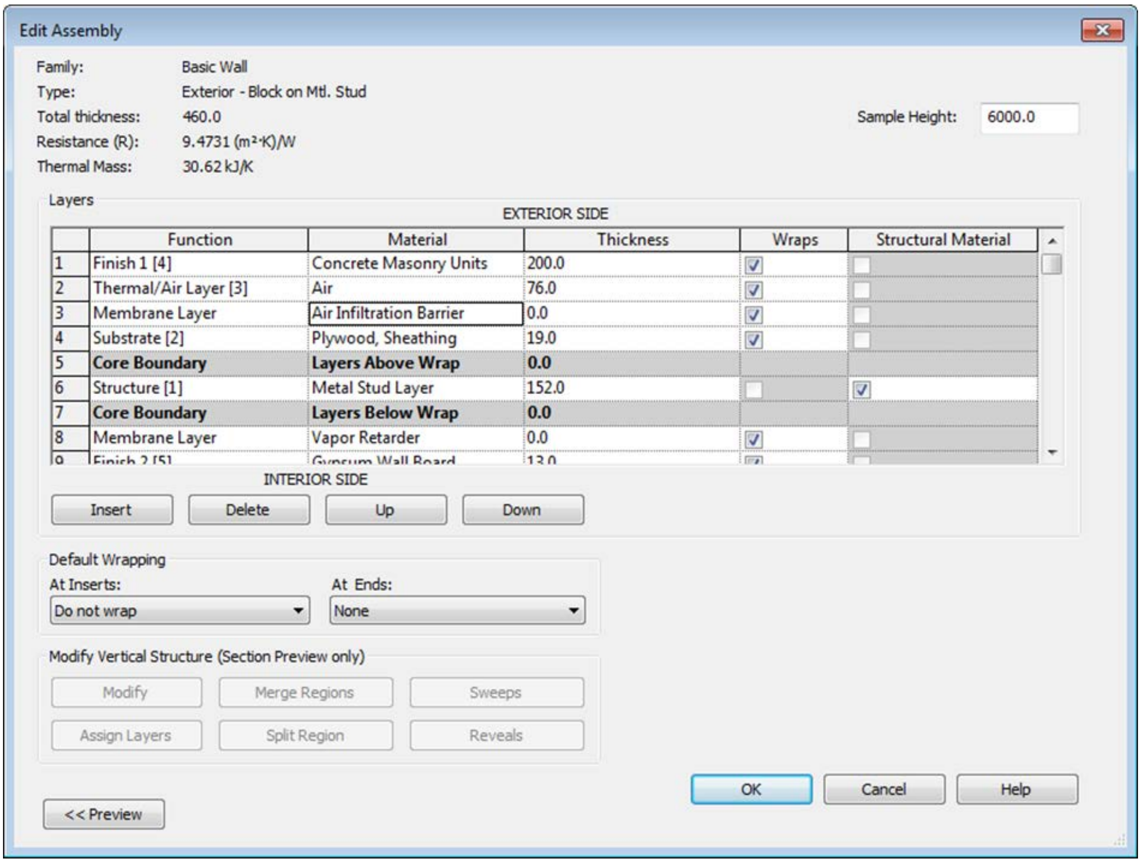
“Type Properties” in Revit2019 on an Example of a System Family “Basic Wall”



The Revit function "Edit Structure" allows for editing the assembly, as shown in Figure 30. The edit function enables for the specification of each layer in the structural and architectural assembly. After describing each layer from the exterior side to the interior side (by function, material, and the thickness) and ticking if the layer is a wrap or a structural material, physical properties might be set.

Figure 30

"Edit Assembly" in Revit2019 on an Example of a System Family "Basic Wall"



The Revit offers in the "Edit Assembly" window an option for a two-dimensional preview of the assembly, as shown in Figure 31. In the preview, each layer is pictured in relation to its position and thickness. Additionally, this function enables to add/remove layers, change the material or its thickness. This way, it is possible to create own material assemblies. The researcher notes the specification of each layer and the whole assembly is very similar to the WUFI Plus requirements, as shown in Figure 32.

Figure 31

"Edit Assembly" With a Preview in Revit2019 on an Example of a System Family "Basic Wall"

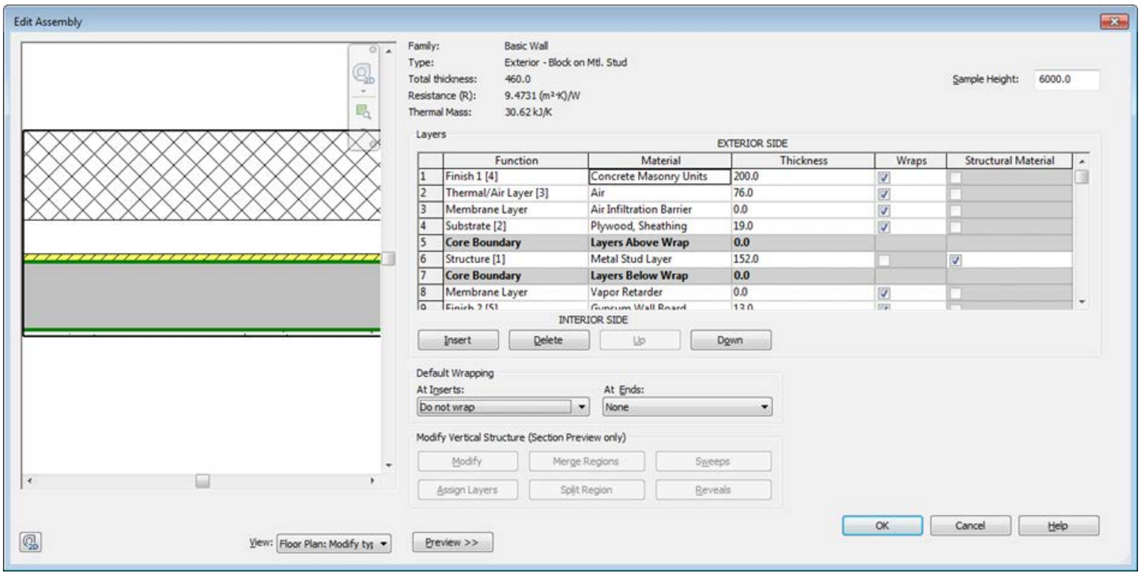
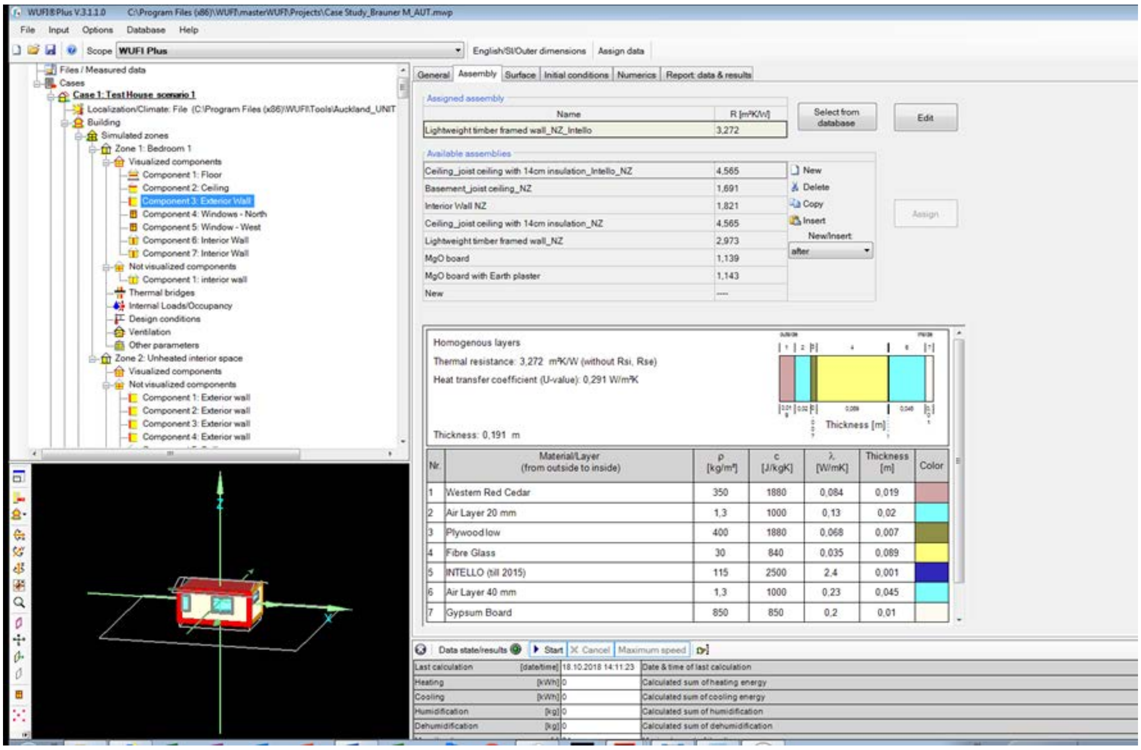


Figure 32

"Assigning Assembly" in WUFI Plus on an Example of an Exterior Wall



The allocation of materials in Revit during the design stage of the project occurs in an interface, where all the material properties are set. In the "Material Browser" menu, it is possible to identify each material, describe its graphic and appearance, plus most relevant to the hygrothermal simulation, set physical and thermal properties. Using the material browser (Figure 33), the designer has the opportunity to evaluate materials and specify them accordingly. Examples of thermal properties in project material browser are shown in Figure 34 for vapour retarder and in Figure 35 for building paper. After all layers in the assembly are specified, the program calculates the total thickness, R-value, and thermal mass of the whole assembly.

Figure 33

"Identity" of Vapour Retarder as Shown and Specified in the "Material Browser", Revit2019

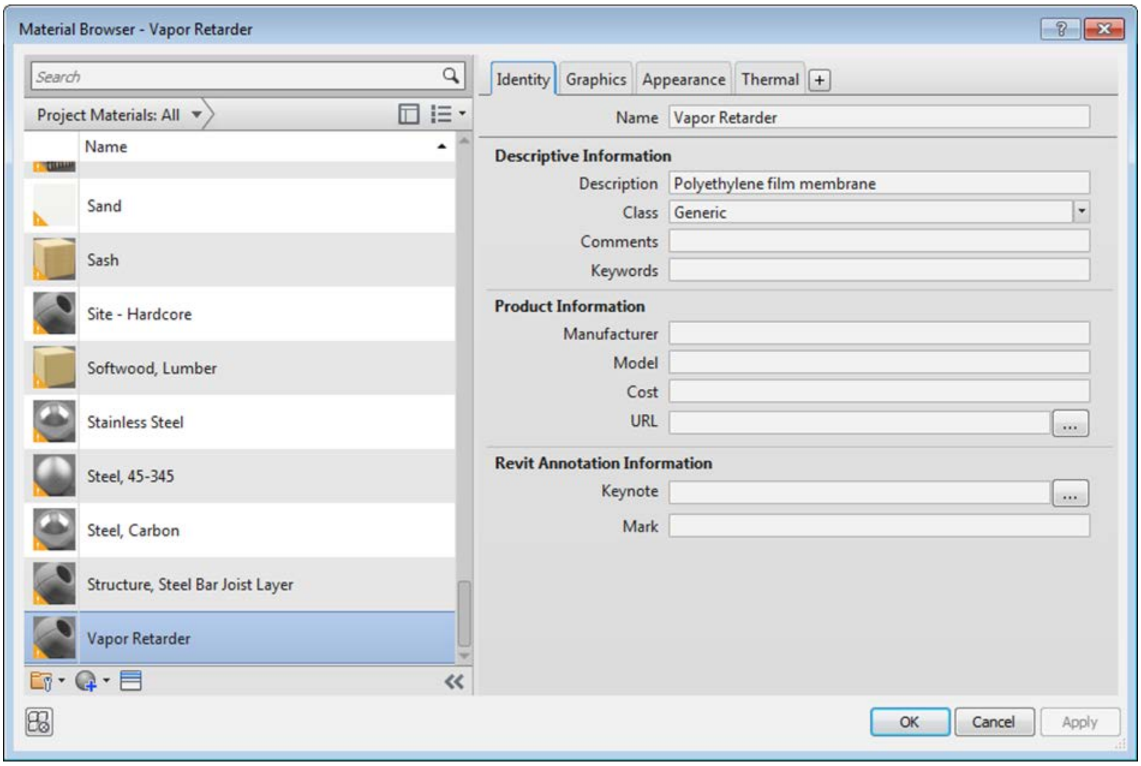


Figure 34

Thermal Properties of Vapour Retarder as Shown and Specified in the "Material Browser", Revit2019

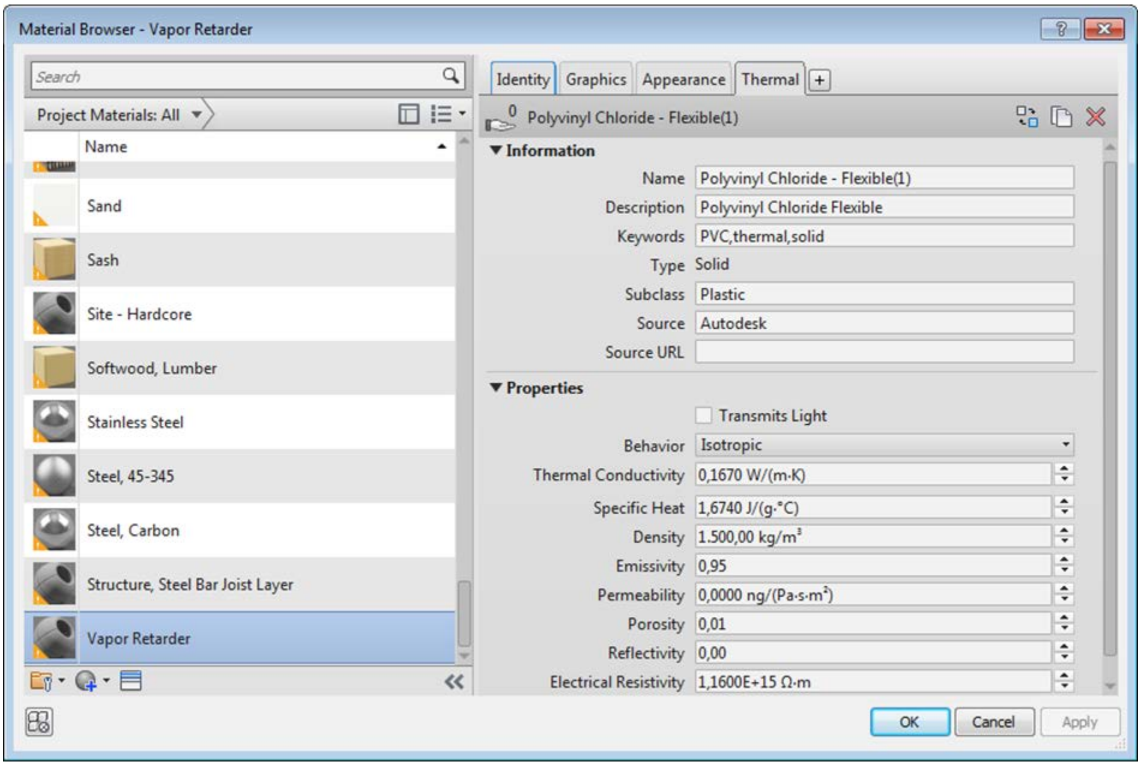
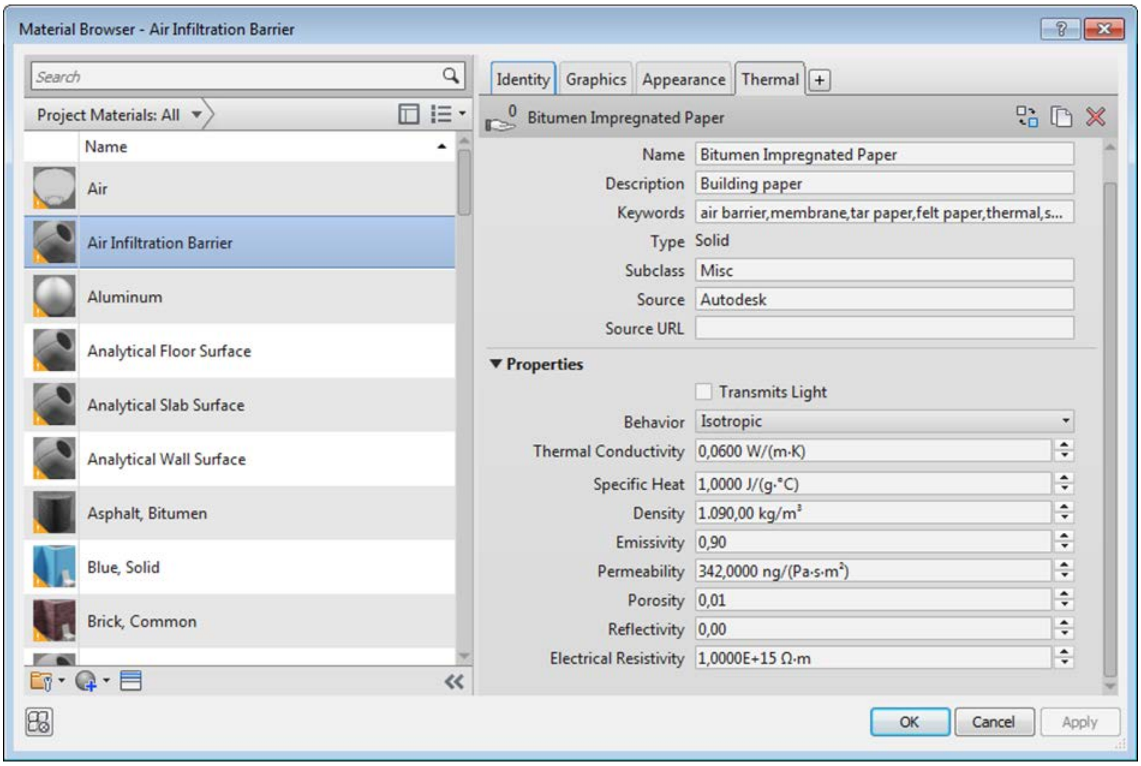


Figure 35

Thermal Properties of Building Paper as Shown and Specified in the "Material Browser", Revit2019



The evaluation of settings in Revit reveals the opportunity for an extension of the material properties, to include the moisture related physical properties essential for hygrothermal calculations. Examples of the moisture dependent physical properties are the water vapour diffusion resistance factor μ, moisture storage function, and the typical built-in moisture to name a few. The material browser of the current Revit version (Revit2019) already contains thermal properties in the main task bar. Additionally, the task bar is prepared for further tasks. Therefore, similarly to the thermal properties, a new task "Hygrothermal Properties" might be set. This is a new finding of the research.

Finally, to enable interoperability, the research suggests coordinating the thermal and hygrothermal properties and their definitions and units between BIM and hygrothermal modelling. This would allow for direct use of material data from the architectural program (e.g., Revit) for hygrothermal calculations. On the contrary, the diverse names for specific physical properties and/or diverse units cause failures in the calculation or render the interoperability impossible.

Revit Energy Settings

The energy settings, as an integrated part of Revit, control the process of the energy model creation and the use of the material and thermal space properties. Therefore, the energy settings specify parameters for the direct generation of the energy analytical model from the architectural model. Energy settings consist of energy analytical model parameters and advanced energy settings. The energy analytical model parameters are mode, ground plane, project phase, analytical space resolution, analytical surface resolution, perimeter zone depth, and perimeter zone division (Autodesk, n.d.-b).

Energy Analytical Model Parameters

Although Revit offers three modes for creating the energy model, it is recommended to use the "Conceptual Masses and Building Elements" mode (Autodesk, n.d.-b). This mode accepts models with only masses or only building elements, and it supports the mixing of both types of elements. For the energy model correct function, the designer has to specify in the ground plane the level which is in the direct contact with the ground. This information is necessary for the calculation of heat transfer. In the case where buildings are set partly underground, the ground plane forms the floor with the most exposure to the ground.

The project phase information determines the specified phase and earlier building phases included in the energy analysis. The analytical resolutions, such as space and surface, represent important information necessary for the energy model algorithm. These parameters influence the energy model accuracy and processing time. Therefore, some adjustments, according to the size, complexity, and quality of the Revit model, may be needed to regulate the accuracy-processing time relation. Generally, for every computer-based model, higher settings of analytical resolution lead to more accurate model results but increase the calculation time. The next parameter, perimeter zone depth, should always be used in conjunction with the perimeter zone division setting. These settings are important for the determination of the building envelope area influenced by external weather conditions. A typical perimeter zone depth, especially for large open plans is between 4 and 5 meters. Generally, the perimeter zoning allows for passive solar energy analysis and results in more accurate energy consumption simulation (Autodesk, n.d.-b).

Advanced Energy Settings

The advanced energy settings relate to the mode specified by the energy analytical model parameters. In the default mode “Use Conceptual Masses and Building Elements” the architectural designer might specify the following parameters: building data, room/space data, and material thermal properties. However, the changes to the building data affect the BIM setting and therefore, should be done only after performing the initial energy analysis (Autodesk, n.d.-b).

The building data, such as building type, building operating schedule, HVAC system, and outdoor air information, have an impact on the energy optimization for Revit. The building type data are provided in the form of tables determining assumptions about occupancy schedule, amount of people per 100 m², people sensible and latent heat gain, lighting and equipment load density [W/m²], infiltration flow rate (ACH), ventilation flow per person [l/s] and per area [m³/h], and unoccupied cooling set point [C°]. The Revit default assumptions are based on ASHRAE 90.1 (2016b), ASHRAE 90.2 (2018), ASHRAE 62.1 (2019b) standards, Commercial Buildings Energy Consumption Survey, and other surveys (Autodesk, n.d.-b). The researcher suggests that although these assumptions are provided for energy analysis or heating and cooling loads analysis, they are equally suitable for hygrothermal analysis.

The room/space data contains the export category setting determining which room or space information is utilized in the analysis. However, these elements are only needed if the architectural model contains the distinction between rooms and spaces residing within analytical areas of the energy model. Otherwise, the room elements or space elements are not essential for an energy model (Autodesk, n.d.-b).

The material thermal properties might be specified in three combinable ways. The conceptual types represent the default thermal properties for typical mass construction assemblies, such as exterior and internal walls, roof, slab, floor, glazing, and skylights. Additionally, the conceptual types offer mass shades and overhangs to reduce cooling loads, minimize solar heat gains, and increase comfort. The mass openings conceptual type enables to include voids in surfaces that are exposed to climatic conditions into the energy model. The conceptual types define default thermal properties, such as R-value, density, and heat capacity in imperial (IP) and metric (SI) values (Autodesk, n.d.-b). The values are the composite of individual material layers per unit of the construction area.

The second way on how to define thermal properties is to specify schematic types during schematic design. The researcher notes that Revit applies the default conceptual types in any element categories not overridden by the schematic type. However, the schematic and conceptual types might be overridden by material-based thermal properties defined in the detailed elements option. The detailed elements represent the third way to specify material thermal properties of building elements for the energy analysis (Autodesk, n.d.-b).

6.2.2 WUFI Plus Settings

WUFI Plus settings' description consists of a part of Chapter 5 (p. 156).

6.2.3 Physical Properties of WUFI Hygrothermal Calculations

Material data needed for WUFI hygrothermal calculations might be divided into two categories. The first paragraph lists the indispensable data, which is vital for a WUFI calculation. Without these data, no hygrothermal calculation is possible. The second paragraph lists and explains additional data, such as moisture storage function, liquid transport coefficients, moisture dependent heat conductivity, and moisture dependent diffusion resistance factor. The additional data, as listed in the second paragraph, may be optional for some calculations, but may be necessary for another, depending on the intention of the calculation (Fraunhofer Institute for Building Physics, n.d.-c).

Indispensable Data

One of the major requirements for interfacing BIM with hygrothermal modelling is the coupling of physical material data with materials in assemblies. Indispensable physical data for hygrothermal calculations are:

Bulk Density

Symbol: ρ

Units: kg/m³

Definition: Mass divided by volume occupied by the material (Radu et al., 2012, p. 15).

Bulk density serves to calculate the specific heat value by volume. According to the Fraunhofer Institute for Building Physics (n.d.-c), the hygrothermal simulations do not depend sensitively on the bulk density value. Therefore, the bulk density value does not need to be of high accuracy.

Porosity

Symbol: ξ

Units: m^3/m^3

Definition: Total volume of voids in the unit volume of porous material.
The porosity is described using a formula, in the form of the following algebraic expression:

$$\varepsilon = 1 - \frac{\rho - \rho_s}{\rho - \rho_g} \quad (6)$$

Where ρ is the apparent density of the material, ρ_s is the density of the solid matrix and ρ_g is the density of the gas in the voids (Radu et al., 2012, p. 28).

Heat Capacity

Symbol: C_o

Units: J/(kg·K)

Definition: Specific heat capacity of dry material – Heat added or removed when changing the temperature of a unit mass of dry material by 1 K (Radu et al., 2012, p. 19).

Heat/Thermal Conductivity Dry

Symbol: λ

Units: W/(m·K)

Definition: The Heat conductivity dry is the heat conductivity of the material in a dry condition as defined by Radu et al. (2012):

The thermal conductivity of a material is the density of heat flow rate per one unit of the thermal gradient in the direction of the flow. That definition stems from Fourier's law for heat conduction:

$$\vec{q} = -\lambda \cdot grad\ T \quad (7)$$

Thermal conductivity is a scalar for isotropic materials and a tensor for anisotropic materials. Its value depends on density, temperature, moisture content and sometimes age (as an indicator of changes in the material structure or composition) of the layer considered (p. 35).

Water Vapour Resistance Factor

The water vapour resistance factor (μ-value) is called by WUFI diffusion resistance factor dry.

Symbol: μ

Units: -

Definition: Water vapour diffusion coefficient in the air (D_a in m^2/s) divided by the water vapour permeability (δ_v in m^2/s) of a porous material:

$$\mu = \frac{Da}{\delta v} \quad (8)$$

It can also be defined as (9):

$$\mu = \frac{\delta p,a}{\delta p} \quad (9)$$

Where $\delta p, a$ is the water vapour permeability in the air in kg/(m·s·Pa) and δp is the water vapour permeability with regard to partial water vapour pressure in kg/(m·s·Pa). The water vapour resistance factor indicates how much larger the resistance of a porous material is against diffusion compared to an equally thick layer of stagnant air at the same temperature (Radu et al., 2012, p. 40).

Optional Material Properties

Some physical properties are not indispensable for WUFI Plus simulations, but are beneficial for the accuracy of some calculations, especially by the very high moisture contents.

Moisture-Dependent μ-Value

In some cases, the dependence of the diffusion resistance factor on RH should be considered. This dependency of the water vapour transmission rate on RH can be determined by a combination of test methods described in ASTM E96 / E96M-16 (2016). WUFI can, in these cases, employ a table resulting from dry cup tests with three chamber RH levels at 50%, 70% and 90% RH. Consequently, WUFI interpolates linearly between the table entries. However, for hygroscopic materials, the description of moisture transport as diffusion dependent on moisture is not correct. Therefore, by diffusion determination, additionally to using the moisture independent diffusion resistance factor, the moisture influence has to be calculated by using liquid transport coefficient (Krus, 1996).

Moisture Storage Function

The moisture storage function is for practical reasons (limitations of measuring methods) composed from sorption isotherms and pressure plate measurements (Krus, 1996). The adsorption isotherm reflects the equilibrium moisture content in a material by RH from 0 to 90% RH. Depending on the material, determination of the sorption isotherm might be a very long process, as reaching the equilibrium moisture content by hygroscopic materials takes up to 60 days for each measured RH (ASTM, 2016). Determining moisture storage characteristics above 95% RH belongs to the capillary water region. Therefore, by RH above 90%, where the storage function represents the relation between capillary pressure and water content, the capillary transport coefficient is determined.

A capillary-active material takes up water until it reaches a free saturation w_f. The free saturation w_f represents the value of the moisture storage function at 100% RH. However, porous materials are able to uptake water above the free saturation w_f until they reach the maximum water content w_{max}, which is determined by the porosity. Another standard measure determined by materials represents the "practical moisture content" w_{80} that corresponds to the equilibrium moisture content at 80% RH (Fraunhofer Institute for Building Physics, n.d.-c).

Heat/Thermal Conductivity, Moisture-Dependent

Symbol: λ_w

Units: W/(m·K)

Definition: Heat conductivity, moisture-dependent is the heat conductivity of the material by particular moisture content. Therefore, WUFI can employ a table with the relevant data and interpolates linearly between the entries using the formula (10):

$$\lambda_w = \lambda_0 \cdot \left(1 + \frac{b \cdot w}{\rho s}\right) \qquad (10)$$

Where λ_w is heat conductivity of moist material, λ_0 is heat conductivity of dry material, w [kg/m³] is water content, ρ_s [kg/m³] is the bulk density of dry material, and b is moisture-induced heat conductivity supplement.

The supplement b gives the fractional increase [in %] of the heat conductivity per mass-% moisture. Its value depends on the material; in hygroscopic materials, however, it is largely independent of their bulk density (Fraunhofer Institute for Building Physics, n.d.-c).

Liquid Transport Coefficient

Symbol: $D_{w(w)}$

Units: m^2/s

Definition: Since the capillary action in porous materials cannot be measured directly, the effects of these tractive forces in the form of a gradient in water content depicts the liquid transport in capillary porous materials. Although it is basically a convective phenomenon, the liquid transport in pore spaces might be depicted in the following diffusion equation (11):

$$g_w = -D_{w(w)} \cdot \frac{dw}{dx} \qquad (11)$$

Where g_w [kg/m²s] is liquid transport flux density, $D_{w(w)}$ is liquid transport coefficient, w [kg/m³] is water content, and x [m] is the spatial coordinate (Krus, 1996, p. 24).

Although the knowledge about moisture content in materials is crucial for accurate simulation of hygrothermal performance, the fact is that the determination of water distribution is difficult. Therefore, various test methods are implemented, such as measurements of electrical resistance, measurements of thermal conductivity, measurements of electrical capacity, ultrasound analysis, kiln method, tracer method, X-ray analysis, microwave method, gamma-ray attenuation, neutron scanning, and nuclear magnetic resonance. These analytical methods, their suitability for the liquid transport coefficient determination, and their pros and cons are introduced and described in detail by Krus (1996, pp. 32-38).

6.3 Limitations and Challenges of the Interoperability

The direct import of CAD data into WUFI Plus represents one of the challenges of this research. Even though, according to the Fraunhofer Institute for Building Physics (n.d.-e) building geometry input into WUFI Plus is supported by geometry import from gbXML, the import of the research project data was unsuccessful. The import of gbXML-files is dependent upon an external program 'gbXML project import.exe' which is allocated in the tools-folder of the WUFI Plus main installation folder. This tool converts gbXML project files into WUFI Plus XML project files. However, the instructions in the *WUFI Plus Manual* (Antretter et al., 2017) are not very helpful: "Always check your analytical gbXML Project model export via your CAD software. If the analytical model is not well prepared, the tool cannot import a usable model" (p. 97). Nevertheless, the researcher is unsure of what a "well prepared" model means. Therefore, the researcher conducted an internet search with the key-words "gbXML files into WUFI", and found out in the WUFI Forum that there are similar issues described with the direct data import. However, only one answer in the online WUFI Forum is available:

> The tool should give some feedback about the information found in the gbxml file and converted to the WUFI passive project file. Mostly it tries to import the geometry and this sometimes need some model geometry adaptions. The tool only imports raw gbxml information and doesn't check, or change the model. (by mpazold, Sun Aug 09, 2015 10:52 pm)

The analytical gbXML project model export from AutoCAD or Revit follows the current gbXML schema of green building XML. Since January 2017, the current schema is the Version 6.01 (gbXML, 2017). Revit offers two methods for exporting to gbXML in order to perform energy analysis using other software. The first method comprises the use of energy settings, as described above. The second method uses volumes as defined in the building model based on rooms/spaces in the model. However, the room/space volumes may not be as accurate as the energy analytical model. Either way, the resulting gbXML file contains energy information for the model depending on the gbXML file structure. Therefore, the gbXML schema should help building designers to gain energy related information about the building project (Treeck et al., 2018). The new finding of this research in the form of suggested Revit extension, as described in this chapter, might enable to perform hygrothermal analysis and optimization.

Another challenge to the successful interoperability represents the lack of hygrothermal data for building materials. Except for the most common materials/products, used in Germany and the USA, and listed in the WUFI materials library, the moisture related data are not available. Next challenge consists of solving the issues of building model extension in the way that it simultaneously contains all necessary information, and does not unnecessarily slow its implementation.

6.4 Conclusions and Recommendations

Resulting from the research, one of the significant requirements for interfacing BIM with hygrothermal modelling is the coupling of moisture related material data with materials in assemblies. To enable an automatic assignment of properties during exportation to a hygrothermal model, these properties have to be either already contained in the object libraries in the architectural program, such as Revit, or be added by user/architectural designer while creating the design model. The content, inclusive predefined units and structure of the properties, have to be congruent to allow for the direct use after the exportation into the hygrothermal simulation tool.

In order to improve the effectivity of the hygrothermal data administration and actualization process, this research recommends creating open, standardized external product library based on extended IFC model. Other option would be to use the "Semantic Web" external library (Szeredi et al., 2014). Thus, both software, Revit and WUFI Plus will make direct references to material properties in the external library classification.

The other requirement for interfacing BIM with hygrothermal modelling is the interoperability, allowing automatic transfer of geometry of the building (such as with gbXML files or extended IFC model) and all necessary material data. Therefore, this research is recommending software adjustments similar to the already existing energy model creation in Revit as described above. That way, the newly created "Hygrothermal Settings", as an integrated part of the building model, would control the process of the hygrothermal model creation, and the use of the material and hygrothermal space properties for each space or zone. Therefore, the hygrothermal settings specify parameters for the direct generation of the hygrothermal analytical model from the architectural model. The recommended hygrothermal settings consist of hygrothermal analytical model parameters and advanced hygrothermal settings. The suggested hygrothermal analytical model parameters are mode, case, location/climate, HVAC, building, project phase, analytical space resolution, analytical surface resolution, visualized components, not visualized components, thermal bridges, internal loads/occupancy, design conditions, ventilation, and other parameters. Consequently, this research recommends establishing a new bar "Hygrothermal Properties" in the Revit material browser. The generation of the hygrothermal properties and the hygrothermal settings are new findings of this research.

For future research, the study recommends analytical studies of hygrothermal analysis influence on diverse areas in NZ. Studies especially oriented on the economic, environmental, and sociological influences of hygrothermal analytical modelling on the design process, energy optimization process, indoor air quality improvements, building durability, and therefore, on the long-term costs and sustainability.

6.5 Summary

This chapter focuses on the possible improvements of interoperability between BIM and hygrothermal modelling. The comparison of settings in Revit and WUFI Plus reveals several feasible ways to enhance BIM with the hygrothermal analytical model creation. Apart from the main intention to enhance the software compatibility and achieve interoperability, the important condition constitutes the necessary creation of coherent product libraries. One other way of interfacing BIM with hygrothermal modelling might be the integration of WUFI Plus into Revit by using the Application Programming Interface (API).

The process of necessary simplification of BIM data to envelopes and zones might proceed similarly to the energy model creation in Revit. Therefore, the study recommends the establishment of hygrothermal properties in the Revit material browser. Additionally, the newly suggested hygrothermal settings, as an integrated part of Revit, would control the process of the hygrothermal model creation, and the use of the material and hygrothermal space properties. The generation of the hygrothermal properties and the hygrothermal settings are new findings of the research.

The new finding of this research, in the form of suggested Revit extension, might enable to perform hygrothermal analysis and optimization during the design stage of the construction process. Improving interoperability between Revit and WUFI Plus provides for the use of hygrothermal simulation as a tool for an early materials assessment and targeted specification of building materials. The critical interest of the research is an improvement and higher efficiency of the informed design process. The diverse themes related to the matter of this research are discussed in the following Chapter 7.

Chapter 7 Discussion

The discussion chapter depicts the most significant results of the first part of the thesis in a broader context of possible causes and effects. The findings of the study are described in detail in Chapter 4 (p. 132), Chapter 5 (p. 171), and Chapter 6 (p. 179). In this context, the researcher examines the wider meaning of the findings for different ways of understanding and the different but related fields of work. Consequently, the researcher assesses the findings against existing literature and evaluates the contribution to the field.

The ontological position of this research is objectivism and the epistemological perspective is based on integral theory. Despite the fact that this research implements causal reasoning, which is fundamentally qualitative (Shadish et al., 2002), the used methods for testing the hypothesis are quantitative. This research utilizes a model of research strategy where experimental and simulation design are combined. Through this combination of methods, new knowledge has been gained. The quasi-experiment delivers data for the testing of the hypothesis as well as for a comparison to simulation data. This chosen research strategy has proven to be valid because the applied approach and methods demonstrated the importance of using simulation during the construction design process. Therefore, the incorporation of hygrothermal modelling into BIM would have an impact on the optimization of the hygrothermal performance of buildings. This way, the combination of two data collections served the aim of this research; to demonstrate that the broadening of BIM in terms of hygrothermal assessment of materials, applied during the early stage of design, might prevent moisture related problems and improve durability and quality of the construction. Consequently, the proposed framework for designers (Chapter 8 below), which includes hygrothermal modelling, might improve the quality of NZ houses.

Energy savings requirements lead to more insulation and improved airtightness. However, this reduces the temperatures at the exterior layers of the building envelope and increases indoor RH (Lacasse et al., 2016). Therefore, the buildings are at higher risk of interstitial condensation. Nevertheless, the control of the hygrothermal performance of buildings during the design stage can prevent moisture problems (Künzel, 2014). In spite of the fact that investigations on hygrothermal performance of timber constructions have been carried out by several researchers (see section 3.3), the in-field measurements of indoor RH by diverse constructions and materials, particularly in NZ climate, are lacking.

An experimental lightweight frame house with several wall assemblies, unoccupied but with a laboratory controlled indoor environment was tested in France (Labat et al., 2015; Piot et al., 2011). However, these studies have examined coupled hygrothermal phenomena in different wall assemblies but not the influence of these assemblies on the indoor RH. The authors have used simulation software HAM-Tools for modelling one-dimensional (1D) coupled transfer in the walls. Nevertheless, their results demonstrate the importance of temperature-driven moisture diffusion in wall materials.

Another in-field study on long-term moisture performance of building envelopes was carried out in the USA by Glass et al. (2015). Glass et al. (2015) maintained RH and temperature in two test houses with humidifier and heater to investigate the hygrothermal performance and water content in diverse structures with two different orientations. The results have been compared with WUFI Pro 1D simulation. The difference between this study and Glass et al. (2015) is that the USA study investigated RH in building envelopes by constant indoor RH and temperature, and this study explored indoor air RH by a controlled amount of released water vapour (WV).

A third similar, in-field long-term experimental study researched hygrothermal performance and durability of the envelope assemblies in a passive house in Poland (Radon et al., 2018). Although temperature and RH were measured and simulated (using WUFI Plus) in the rooms, no testing on the influence of diverse materials on the RH in the same room was carried out. The testing was provided in a habituated house with active heating and mechanical ventilation without controlled humidification or dehumidification. Therefore, the released WV to the indoor air was unknown. Although the Polish study tested diverse envelope constructions, they stayed unchanged during the whole experiment.

Therefore, this research makes a significant contribution to the knowledge because none of the mentioned studies tested and simulated the influence of used materials on the development of indoor RH by controlled humidification. The following discussion is about the implications of the research for existing knowledge and research questions generally. Thus, the following three main sections of this chapter are corresponding to the research objectives (1. – 3.) and related questions, as stated in Chapter 1 (p. 6). The fourth research objective will be addressed in Chapter 8 (p. 220) because of the objective and related questions associate with the second part of this thesis dealing with a system approach. The first section of this chapter examines the hygrothermal performance of NZ housing construction by means of a quasi-experiment. In the second section, the researcher identifies the challenges associated with undertaking effective hygrothermal assessments during the early design stage of housing in NZ. Therefore, the second section contains a discussion about hygrothermal simulation and the differences between real measurements and simulation results, inclusive the possible reasons for such. The third section focusses on the requirements for integration of hygrothermal simulation into BIM in order to improve building sustainability and performance.

7.1 Quasi-Experiment – Hygrothermal Performance Examination

This study shows that even small changes in material specification can engender a significant influence on the hygrothermal performance of the building and therefore, on indoor air quality. Several factors, such as materials used in the first layer from inside of the house and airtightness membrane influence RH in houses. The findings bring new knowledge about moisture relations in NZ housing relating to the construction of the building envelope and used materials. Therefore, this paragraph discusses the results of the quasi-experiment and their implications for existing knowledge and research questions.

7.1.1 Levels of Relative Humidity in Different Settings

The study compares maximal reached RH in different settings while simulating occupancy in two test houses, T-house with airtightness membrane and C-house without airtightness membrane. The statistical analysis reveals that the maximal reached RH level in each setting was noticeably higher in the T-house than in the C-house. However, the initial RH levels in the T-house have been lower than in the C-house (Table 9). ANOVA test indicates that the materials influence the indoor RH by

76% in the T-house (Table 20) and by 90% in the C-house (Table 21). Additionally, the results show that the daily span between maximal and minimal reached RH in each scenario is higher in the T-house than in the C-house. These are new findings of the research.

The approach applied in this study is based on the sorption-active thickness theory (Hens, 2017) described in Chapter 3 (p. 88). The quasi-experiment manifested RH changes in relation to minor alterations of indoor materials (less than 20% of the total wall area). The results are summarized in Table 10 for the T-house and in Table 11 for the C-house. For example, by additionally covering an area of 8.28m² with MgO boards (18.9% of the total wall area), the level of average RH dropped at 7.56 percentage points in the T-house and 1.37 points in the C-house. The situation changed noticeably with the application of an acrylic primer and earth plaster as an interior finish to the same area. In spite of the fact that RH compared to 2. scenario in the T-house still dropped (4.30 percentage points), the C-house level of the average RH increased (3.74 percentage points). This newly discovered knowledge from the research demonstrates the influence of indoor materials and the airtightness layer on indoor RH.

The highest levels of RH are reached in the 2. scenario (no adding any materials) in the T-house (Figure 11) and in the 4. scenario (MgO board with earth plaster) in the C-house (Figure 12). These findings deliver an answer to the research question: What levels of RH are reached in occupied NZ houses by different internal envelope materials? In both houses, the most effective material for the minimalization of the RH increase by the simulated inhabitancy seems to be the MgO board. However, the measured values might be partly influenced by the initial levels of RH and by the outside weather conditions. As F-statistics confirmed the later, the research implemented an additional statistical analysis - ANCOVA to eliminate the influence of the outside RH. Therefore, the ANCOVA calculates for what would the indoor RH means be for each scenario, if the exterior RH would stay the same.

ANCOVA tests confirmed that used materials have a statistically significant influence on indoor RH. This fact answered the research question: What is the impact of different building materials used on the indoor side of walls on the hygrothermal performance of a building? The analysis of eta squared indicates the impact of introduced material on inside RH by controlling for the outside RH. Based on this analysis, the research estimates the influence to be 67% in the T-house (Table 22) and 91% in the C-house (Table 23). However, for the holistic evaluation of the impact, the maximal reached RH levels, and the development of temperature should be considered simultaneously. Therefore, the research suggests that despite the statistically higher importance of used materials in the C-house, the T-house might be more vulnerable to introduced materials. This statement is based on visual evaluation of graphed values for measured and calculated results and supported by a partial increase of RH based on eta squared for each house.

Another difference between the two houses is evident in the development of estimated marginal means of inside RH. In the C-house (Figure 16), RH is following a stable pattern and the increase of maximal reached RH is lesser than by the T-house (Figure 15). In the T-house, the maximal RH level exceeded in 2. scenario the benchmark of 90% RH what in the contrary, did not happen in any scenario in the C-house. Therefore, the analysis of measured data delivers new knowledge about the development of inside RH in NZ houses. The research found out that the scope of indoor materials influence is different depending on the exterior walls' construction. The indoor RH in the house with an airtightness membrane (T-house) is influenced by used indoor materials by 76% (without correction for outside RH) and by 67% (with the correction for outside RH). However, the indoor RH in the house without an airtightness membrane (C-house) is influenced by used indoor materials by 90% (without correction for outside RH) and by 91% (with the correction for outside RH).

Additionally, in general, the indoor RH in the T-house reached higher levels than in the C-house in identical conditions (scenarios). Although the influence of used indoor materials on the development of indoor RH is in the T-house statistically smaller, the significance of these materials seems to be high. This statement is supported by the noticeably higher RH differences between the scenarios in the T-house than in the C-house. The described findings delivered answer to the research question: How do RH levels differ in NZ houses based on the presence/absence of airtightness membranes?

However, the question remains why those differences occur? The researcher assumes that these differences are due to the airtightness membrane and infiltration rate.

Based on the existing building physics knowledge, the researcher suggests that the natural air exchange due to air leakages influences humidity removal from indoor space. However, this still would not clarify where the water vapour goes. It is known that the airflow carries the moisture into walls (Yarbrough et al., 2019). As this experiment has not assessed the situation inside of the walls, the research makes no conclusions regarding airtightness or drying process inside of the walls.

Nevertheless, the experience from built houses has proven that persisting high humidity affects the wall structure and causes serious damages in the construction, such as rust of metal parts or rotting of the structural timber (Harriman, 2012; Strangfeld & Kruschwitz, 2018). Therefore, the missing airtightness layer has an impact on the insulation quality, thermal transmittance, transient thermal response, and moisture tolerance of the construction (Hens, 2016). The fact that the average RH and the maximum reached RH in the C-house by each test have been lower than in the T-house indicates a movement of moisture into the C-house's walls. Consequently, the lower levels of maximum reached RH might be wrongly interpreted as an advantage of houses without a membrane. Therefore, the following text discusses the influence of an airtightness layer.

7.1.2 The Influence of an Airtightness Layer

The airtightness membrane installed in the T-house is a humidity-variable vapour control layer with a variable vapour resistance according to the direction of heat flow and RH between both sides of the membrane (British Board of Agrément, 2015). Therefore, the lower vapour resistance in summer allows moisture to pass through the membrane from the wall back into the room. This fact, together with a much lower infiltration rate due to the airtightness, might explain the higher RH levels and the significantly higher slope of the interpolation functions in the T-house (Table 24). Additionally, to account for the indoor RH differences, the research uses for the explanation of the RH development the Theoretical Moisture Penetration Depth (TMPD) model. The daily TMPD of gypsum board is 0.064 m (Wan, Xu, & Li, 2017, p. 6). As the gypsum board installed in the test houses is only 0.01 m thick, the WV penetrates the board on the first day, and the amount of the absorbed WV during the following days drops (Wan et al., 2019). The airtightness membrane restricts the VW movement through the wall. Consequently, more WV remains in the T-house indoor air in contrast to the C-house in which the VW moves freely to the next layer in the wall.

Although the vapour resistance of the airtightness membrane is in the time of the experiment (summer) relatively low, the in-wall materials are still less available for adsorption than in the C-house. The in-wall materials in the T-house are therefore partly blocked, and the natural infiltration rate is low due to the airtightness membrane. This explains the lower eta-square results for the influence of materials on the indoor RH in the T-house. Despite this statistical fact, the differences between maximal reached RH demonstrate that by an airtight construction, the inside layers (before the membrane) have a much higher influence on the inside humidity levels than in the house without any membrane.

In spite of the fact that the influence of outside RH is statistically significant, the major factor affecting the development of inside RH remains in both houses the used materials. However, these factors are not the only two sources of RH differences between the houses. Therefore, the research suggests that apart from investigated factors, existence or non-existence of airtightness membrane and the physical characteristics of the membrane might have a significant impact on the hygrothermal performance of the building. Consequently, the exterior wall structure and/or the infiltration rate influence the level of indoor RH. Airtightness membrane prevents direct water vapour transport into the exterior wall. This means that for the moisture buffering, the most available layer/s are the sorption active surfaces in direct contact with the indoor air. These facts would explain the generally lower levels of maximum reached RH in the C-house by each scenario. The researcher is aware that the higher levels of reached RH in T-house might mistakenly be interpreted as a disadvantage of the airtightness membrane. However, without testing the drying process in exterior walls and an assessment of complete thermal and hygrothermal house performance, this statement would be not correct. As this study has not done any testing of the drying/wetting process inside of the walls, the evaluation of the influence of the airtightness membrane contains not a part of this research.

Despite the sorption theory, structures without airtightness membrane are prone to be impacted by moist air due to the accessibility of materials inside of the wall's structure (Boudreaux et al., 2018). This would explain why, by the addition of acrylic primer and clay plaster, the inside RH develops differently. The level of RH changes in the 4. scenario not identically in both houses although the plastered MgO boards have higher Sd value, and therefore, their moisture buffering capabilities are limited. In the T-house, where the air movement through the building envelope is reduced, the priming and plastering of the MgO boards seems not to have such a remarkable influence. The RH in the T-house still dropped (4.30 percentage points) when compared with the situation without any additional materials. However, the C-house level of average RH in the same scenario increased (3.74 percentage points).

An explanation to this phenomenon might be that in the T-house, any diffusion open material added to the indoor side of the wall offers additional moisture adsorption and/or absorption. Therefore, RH is reduced by the addition of plastered MgO boards regardless of the higher vapour resistance of the plaster because the acryl primer is still diffusion open. In the C-house, the increase of RH in the same scenario indicates that in buildings without an airtightness layer, the vapour resistance of indoor materials influences significantly the accessibility of the in-wall materials for water vapour. The deeper layers are therefore not freely available for sorption and the overall RH increases. This finding adds to the general knowledge of hygrothermal performance. The results might be used as an indication of the possible disadvantages of acrylic paints widely used in NZ housing.

The discussion about the influence of diverse materials on indoor RH leads to the question about the requirements for undertaking an effective hygrothermal assessment of houses during the early design stage. Apart from the technical requirements, which are discussed further, the criteria of the comfort zone are vital to the assessment. Therefore, the following part takes into account different ideas about human exposure to humidity.

7.1.3 Comfort Zone Criteria

As already mentioned earlier in the text, for an understanding of this research, it is important to emphasize that indoor RH represents the characteristic of the interest.

Since the Sterling et al. (1985) study of *"Criteria for Human Exposure to Humidity in Occupied Buildings"* new significant studies related to indoor RH have been undertaken (Costanzo et al., 2018; Mijakowski & Sowa, 2017; Tsutsumi et al., 2007). Sterling et al. (1985) have recommended comfortable levels of RH between 40% and 60% by normal room temperature. However, these levels have been intuitively set and there is still a lack of scientific research, especially in the analysis of the effects of low RH on health and comfort (Derby & Pasch, 2017).

Nevertheless, NZ has outdoor ambient RH, usually between 60-80%, depending on the geographical area (Level, 2017). The annual average RH reaches in some places between 80-90%, such as in Auckland, Wellington, Hamilton, and Christchurch (National Institute of Water and Atmospheric Research, n.d.). Therefore, the researcher finds the recommended upper limit of 60% RH not feasible, especially for coastal areas in summer. The limits should be set in conjunction with the type of ventilation, indoor temperature, outdoor temperature, and RH. Consequently, by sufficient air exchange rate and heated indoor, the moisture is not trapped in the building and any short-term excessive water might quickly dry out.

Human beings' comfort zone, according to ASHRAE, might be located in a specific range of RH and temperature depending on metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity (ASHRAE, 2017b). These factors are variable as they depend on occupants, the environment, and duration of exposure. Therefore, the researcher agrees that the rigorous determination of a comfortable indoor environment is not possible (Derby et al., 2017). However, from the peer reviewed articles and other documents, it is possible to derive a statement that people do not feel very well in the environment with extremely high or low RH. Despite the facts that ASHRAE Standard 55:2017 (ASHRAE, 2017b) does not specify a minimum humidity levels, BS EN 16798-1:2019 recommends for category II (normal level of occupancy expectation) 25-60% RH. However, these design criteria are only valid for the humidity in occupied spaces if humidification or dehumidification systems are installed (British Standards, 2019a).

The researcher notes that this standard has limits set for spaces equipped with dehumidification systems. Similarly, ASHRAE Standard 62.1-2016 requires that designed RH levels be limited up to 65% RH for mechanical systems with dehumidification capability (ASHRAE, 2019b). The current NZS 4303:1990 Ventilation for acceptable indoor air quality is based on the outdated ASHRAE Standard 62-1989. In spite of the fact that the ASHRAE has no humidity limitations for other mechanical system types or where spaces are not served by mechanical systems, NZS 4303:1990 does. NZS 4303:1990 recommends RH no greater than 60% inside of habitable spaces without any conditions on the type of ventilation system. The researcher points to the fact that firstly, the standard is nearly thirty years old and secondly, it gives an unrealistic recommendation to maintain RH in NZ houses between 30-60%. Given the fact that the latter is not possible to achieve in NZ with natural ventilation, the standard solves this controversy with a note: “In certain areas on New Zealand the 30% to 60% relative humidity recommendation is not within the operating capabilities of the ventilation system” (Standards New Zealand, 1990, p. 6).

Therefore, additional means for regulation of indoor RH are necessary in NZ homes in order to minimize the levels of allergenic or pathogenic organisms, such as fungi and dust mites, and to improve IAQ and comfort. Given the results of the quasi-experiment, a statement might be drawn that the data analysis confirmed the hypothesis: “If materials used in the building envelope have a significant influence on the hygrothermal performance of the building, then the design of sustainable buildings cannot be done without hygrothermal modelling.” Therefore, the research recommends hygrothermal simulation as a vital part of the design process, which is discussed in the following paragraph.

7.2 Hygrothermal Simulation – Challenges in Hygrothermal Assessment

Hygrothermal simulation of the quasi-experiment, as described above, delivers data for comparison with measurements. Despite the fact that the simulation confirmed the results of the experiment, the calculated RH in the tested compartment shows some discrepancies with the measured results. Although the ranking of scenarios in the numerical model results is identical to measured results, the mean, minimum, maximum, and the range of calculated and measured data are not the same (see Table 29). The differences in the standard deviation and mean values found between quasi-experiment and simulation are higher in the C-house. Nevertheless, all differences in the standard deviation and mean values are within the range of 5% error from the measured values. The research experiences the highest differences in scenario number four, where the error from the measured mean is 3.9% in the T-house and 4.5% in the C-house. Therefore, the following paragraph discusses the possible causes of the differences between calculated and measured results.

7.2.1 Discussion About Differences Between Simulated and Measured Results

WUFI Plus has been developed to simulate the HAM transport in the whole building or separate zones in the building, as described in section 5.1.1. In spite of the fact that WUFI Plus is user friendly software, it requires input parameters containing temperature- and moisture-dependent hygrothermal properties. Therefore, the partly unknown material properties, interzone ventilation rate, weather data, and their estimated values might influence the results.

The detailed description of the limitations and challenges of the simulation might be found in Chapter 5, section 5.3. The research uses hygrothermal properties data of the MgO boards supplied by the manufacturer (Appendix B). Although the laboratory test was done in 2011 when the ASTM E96 / E96M-10 have been active, the MgO boards have been tested to ASTM E96 / E96M-05 (ASTM, 2005). Since then, this standard was superseded multiple times and the current standard is ASTM E96 / E96M-16 (ASTM, 2016). During the test, two procedures, such as A-desiccant method and B-water method, were conducted at 73.4±3.6 °F and 50±2% RH. This means that the laboratory tested the sorption capacity of the material by these stable conditions only and have not reflected the moisture dependent permeability values nor accounted for hysteresis effects. However, the hysteresis phenomenon, as described by J. Berger et al. (2018), has a significant effect on the sorption capacity of the material over a longer time, particularly by multiple steps of RH. In the case when RH and temperature are fluctuating, such as the case of the quasi-experiment, cycles of desorption-adsorption processes take place.

Valuable knowledge about the relationship between temperature and mixing ratio might be found in the field of food packaging. The water vapour transmission rate (WVTR) is one of the key factors defining the shelf life of the packaging product (Gaona-Forero et al., 2018; Kuusipalo & Lahtinen, 2005; Sängerlaub et al., 2018).

Consequently, the WVTR by many materials depends on RH and temperature (Chen et al., 2014; Chennouf et al., 2018; Feng & Janssen, 2016; Galbraith et al., 2000). WUFI can in these cases, employ a table resulting from dry cup tests with three chamber-RH levels at 50%, 70% and 90% RH (Fraunhofer Institute for Building Physics, n.d.-c). Despite the fact that the dependency of the diffusion resistance factor on RH can be determined by a combination of test methods described in ASTM E96 / E96M-16 (ASTM, 2016), this testing of MgO boards was not provided. However, as the determination of the moisture dependent hygrothermal qualities is a time-consuming procedure, the data are not available for most building products.

Generally, depending on the material, the determination of sorption isotherm might be a very long process as reaching equilibrium moisture content by hygroscopic materials takes up to 60 days for each measured RH (ASTM, 2016). Therefore, the analysis of the laboratory results for the MgO boards (Appendix B) shows that the testing was done for insufficient time. The laboratory conducted the test procedure for each method between 10 and 14 days, while equilibrium has not been reached yet. Additionally, the laboratory has not used a dummy that is recommended for highly hygroscopic materials. Therefore, the test results are unreliable. This fact revealed itself by the conversion of permeance into water vapour resistance factor μ-value. In spite of the fact that μ-value is a bulk material property independent of its thickness, the converted values from permeance of different material thicknesses are not identical. Therefore, the researcher has to estimate the μ-value for the 10 mm MgO boards.

Despite the fact that in this study, the exact hygrothermal properties of the materials are unknown, model prediction of RH development by using a classic diffusive model may be devoid of accuracy. The common discrepancies between measurements and calculations are due to the underestimation of the adsorption process and/or overestimation of the desorption process in the numerical equations by diverse moisture levels (J. Berger et al., 2018). This means that the simulation predicts slower moisture transport than measured during the in-field experiment. Therefore, some phenomena, such as nonequilibrium behaviour between water vapour and bound water, or transport by air convection are in the simulation neglected (Busser et al., 2019). The research results demonstrate this limitation, primarily due to the use of hygroscopic fibrous materials, such as the MgO board and wood-based products. Several studies have addressed the problem that hygrothermal models do not precisely reproduce the measured RH levels under dynamic load, especially by the presence of hygroscopic materials (Colinart et al., 2016; Kreiger & Srubar, 2019; Labat et al., 2015). This might, to the opinion of the researcher, have its origin in the unknown structure of porous materials and the complexity of physical processes in moisture transport. In spite of the fact that many researchers investigated the water vapour transmission in porous materials (Feng & Janssen, 2019; Hens, 2016), the relationship between the structure of the porous material and the processes of moisture transport remains open (Orlik-Kożdoń & Steidl, 2018). Nevertheless, the simulation results demonstrate the influence of hygroscopic qualities of building materials on the hygrothermal performance of the construction.

Due to this fact, the effective hygrothermal simulation used as a tool for assessment and optimization of a proposed building can improve building sustainability. A comprehensive literature review showed that good performing buildings have lower operational costs, last longer, and provide healthy indoor air. Therefore, such buildings have lower life cycle costs and less negative impact on the environment. The building performance is improved by lower energy demand, more stable RH, the lower probability for interstitial condensation, mould, and fungi development. Therefore, BIM-integrated hygrothermal simulation can enable continuous assessment and improvement of the building design. Consequently, alternative and sustainable materials or solutions are easier to implement. Thus, the following section discusses the requirements for the integration of hygrothermal simulation into BIM.

7.3 Requirements for the Integration of Hygrothermal Simulation Into BIM

This chapter evaluates various possibilities for the interfacing of BIM and hygrothermal modelling on an example of two common software – Revit and WUFI Plus. WUFI Plus enables, according to the WUFI Plus Manual, a direct import of geometry data only (Antretter et al., 2017) but not material properties nor assembly settings. Therefore, the current situation requires manual entry of these data. Generally, the direct import of CAD-data is not flawless and often requires human interventions (Dimitrov & Valchova, 2011).

Interoperability improvements and the integration of hygrothermal simulation into BIM are explored in Chapter 6, section 6.1. The suggested solutions are ranging from an integration of the hygrothermal model into BIM to the improvements to the interoperability of separate programs. However, due to the fact that Revit and WUFI Plus are proprietary programs, the proposed implementations/changes need cooperation between the software providers.

The implementation of WUFI Plus in Revit would allow for hygrothermal optimization of the designed building. The proposed hygrothermal settings, as described in Chapter 6, are similar to the existing energy settings in Revit. Due to the fact that Revit offers an extension of material properties, hygrothermal properties might be added besides the existing thermal properties. The proposed hygrothermal optimization provides an opportunity for improvements in the hygrothermal performance of new and existing buildings from concept to detail. The automatic creation of a hygrothermal analytical model based on an architectural model would allow for a fast export of project data into WUFI Plus. Before using this method of direct data transfer, the definition of hygrothermal settings, and the creation of a hygrothermal analytical model in gbXML will be necessary. The hygrothermal analytical model would be created by Revit and composed of parameters required by WUFI Plus. The analytical spaces and analytical surfaces for this model will be created from parameters defined in the proposed Hygrothermal Settings dialog. This way, all data in the form of a hygrothermal analytical model might be automatically exported to WUFI Plus for hygrothermal simulation. Consequently, WUFI Plus improvements might enable direct import of the Revit hygrothermal analytical model without the need for any personal intervention. Therefore, WUFI Plus would be able to read the model data inclusive assemblies, physical material properties, and orientation of the building and calculate the hygrothermal performance of the building or its zones.

Another opportunity for interfacing BIM with hygrothermal modelling represents the API platform, which offers an integration of other applications (including analysis applications) into Autodesk Revit products. WUFI Plus as an optional Add-In would be an option. This means that WUFI Plus will be able to directly communicate with Revit. The user/designer will have multiple opportunities for changing materials in assemblies related to the whole building or to a particular zone(s). The variants will be treated as separate cases. The simulation results will allow for an optimized design. Due to the fact that Revit calculates materials quantity, evaluation of cost difference for diverse cases would be possible.

Despite the fact that it is 45 years since the BIM concept has been introduced by Eastman (1975), the architecture, engineering and construction (AEC) industry is still not able to fully adopt the fourth industrial revolution (Industry 4.0) (Daniotti et al., 2020b). According to Daniotti et al. (2020b), data management and the interlink between machines—objects—people and processes represent essential attributes of the Industry 4.0. This research findings are showing that especially data management and digital cooperation depict the most important requirements for integration of hygrothermal performance assessment into BIM.

Firstly, for further analysis of an architectural project, the availability of relevant, coherent, complete, and open data libraries is vital. In this sense, the researcher does not agree with Xun (2009), who writes that metadata (non-graphic data) are more important in the later stages of the life cycle of the product. On the contrary, for the design of sustainable and zero-energy buildings, the physical characteristics of materials are vital for the thermal and hygrothermal performance analyses. Therefore, the transfer of data between various software should embrace the prospect of selective object/material characteristics. For example, in order to provide hygrothermal simulation, the designer needs to select the physical material properties (listed in section 6.2.3) required by WUFI for calculation. This process has to be supported by coherent and interoperable product data libraries in an OpenBIM, such as libraries based on standardized IFC compatible product data management (Palos et al., 2014). However, contemporary libraries are often proprietary and do not contain hygrothermal data. In spite of the fact that WUFI offers a material library, many of the building materials are missing and the library is not available for architectural software, such as Revit. Therefore, the product data in the interoperable BIM libraries have to be coherent, containing information for the entire process, systematically organized, and based on standardized terminology. Additionally, this research recommends that data about every material/object should consist of relevant, high quality, and complete information about physical data necessary for thermal and hygrothermal modelling. These recommendations are in alignment with the general requirements for the libraries of BIM objects, as described by Daniotti et al. (2020c).

Although IFC is accepted as standard data exchange format in the construction and facility management industries (Sacks et al., 2018), and standardized in ISO 16739-1:2018 (ISO, 2018b), it is a very complex and highly redundant product model schema (Belsky et al., 2016). Recent research has shown that interoperability issues consist mainly of the inability of diverse software to interpret objects and inconsistency of model data due to distinct representations of the same geometry, properties and relations (Lai & Deng, 2018). Therefore, Model View Definitions (MVD), introduced by buildingSMART, aim to provide semantic clarity to IFC exchange files (buildingSMART International, n.d.-b). MVD are supplements to the overall IFC schema, which enable a description of the IFC data model for the concrete data exchange (Borrmann, Beetz, et al., 2018).

Consequently, a precise semantic definition of data exchange between Revit and WUFI Plus depicts the most important requirement for the successful integration of hygrothermal modelling into BIM. However, to the knowledge of the researcher, any definitions nor MVD for the data transfer for hygrothermal modelling exist. All necessary information, such as geometry, orientation, the structure of building envelope, materials, etc. should be defined clearly because the representation for semantic concepts might differ by separate software providers (Sacks et al., 2017). Despite the importance of IFC export and import specifications tailored for each MVD, it is true that the development of such subroutines is demanding on vendors' human and financial resources (Borrmann, Beetz, et al., 2018). Therefore, several researchers are developing semantic enrichment engines for BIM which intend to add application-specific information to a digital building model (Belsky et al., 2016; Sacks et al., 2017). Another solution to the integration of hygrothermal modelling into BIM might be the development of semantic web technology and semantically defined building information as suggested by Niknam and Karshenas (2015) for sustainable building design.

Next, due to the fact that digital cooperation represents a crucial attribute of the Industry 4.0, diverse software should be interoperable. “Proprietary languages, rules and guidelines, as well as proprietary libraries, are the death of BIM if not united by a common “dictionary”…” (Daniotti et al., 2020a, p. viii). However, the reality is that the most of the available programs and libraries are not fully interoperable. Therefore, stakeholders should consider interoperability along the whole supply chain before BIM tools implementation (Oti & Abanda, 2020). Ideally, digital cooperation beyond the common structural and technological approaches would be the norm of BIM-based collaboration (Papadonikolaki et al., 2019). In this context, the researcher agrees with Oti and Abanda (2020) that the creation of built environment involves a combination of disciplines, such as engineering, architecture, urban planning, real estates, environmental studies, geography, industrial design, interior design, visual arts, history, law, and sociology.

Additionally, the design and construction of sustainable buildings require the implementation of building physics/building science and the dynamic needs of people. These aspects are entirely missed in the cited article. Despite the fact that the energy assessment of buildings is in many countries obligatory (European Commission, 2018; Loncour & Heijmans, 2018; Zakula et al., 2019), Oti and Abanda (2020) have not included any energy modelling nor analytical tools into the overview of the BIM systems.

However, building performance analytical tools are vital for the future built environment. This research argues that a BIM-integrated hygrothermal simulation tool can reduce errors affecting the hygrothermal performance of buildings and increase hygrothermal efficiency. The hygrothermal modelling allows for calculations of multiple design options, and therefore, supports the decision process in the design phase. Simulation results reveal hygrothermal consequences of design choices, such as chosen building envelope, orientation, structure, used materials, ventilation, fenestration and shading. Due to the fact that the simulation is specific to the climate and future use of the building, these results might be utilized by building performance optimization (Torres-Rivas et al., 2018). Therefore, the integration of hygrothermal simulation into BIM leads to improvements in building sustainability.

Acknowledging the complexity of buildings' hygrothermal performance, it is crucial to note that this research covers only a segment of the whole. The study evaluates the assessment of the first layer from the inside as an essential part of the design decision process. Other parts leading to an integrated solution of HAM flow include, but are not limited to, suitable ventilation, airtightness, the orientation of the house, use of passive solar energy, shading, passive cooling, or thermal insulation. Therefore, the research emphasizes the need for a thorough hygrothermal assessment of the construction, especially of the first layer from inside. Due to the infiltration, air open structures need more energy for heating and cooling the indoor and are prone to interstitial condensation and mould (Shrestha et al., 2019). This is not viable because of the energy saving needs (Bhandari et al., 2018; Loncour & Heijmans, 2018). The solution would be a holistic and integral approach to the combined HAM flow in the design process, as described in the following Chapter 8.

7.4 Conclusions

The results of this research indicate that sustainable design requires an integral approach with dynamic models assessing multidisciplinary factors. Therefore, the proposed framework, as described in the following chapter, is beyond static models of the literature discussions. Hygrothermal modelling forms a part of the framework. The fourth industrial revolution (Industry 4.0) fundamentally changes the way how buildings will be constructed (Lojanica et al., 2018), and the whole architectural design process (Abdelhameed, 2019). These research findings are showing that especially data management and digital cooperation constitute the most essential requirements for integration of hygrothermal performance assessment into BIM.

7.5 Summary

This chapter presented the discussion of the overall findings of the study delineated in Chapter 4, 5, and 6. The discussion consisted of the implications of the research for existing knowledge and addressing research questions related to the research objectives (1. – 3.), as stated in section 1.4. This research makes a significant contribution to the knowledge because none of the existing studies tested and simulated the influence of used materials on the development of indoor RH by controlled humidification.

Chapter 8 System Approach

Motto: "We, along with the rest of the natural world, are all interconnected within the larger web of life" (The United Nations, n.d.).

During the last two decades, it has become evident that the human race has entered a global age where diverse worldviews, cultures, religions, and science branches are in the midst of a deep transformation (Gangadean, 2010; Newey, 2019). Increasing incidences of loss/loss business outcomes due to dysfunctional multi-stakeholder relations pinpoint the ramifications of the problematic business thinking and practice in many business activities (Fish & Wood, 2017). Simultaneously, a new evolutionary stage of consciousness, called "integral" is emerging (Wilber, 2007). Annals in Social Responsibility described integral business as follows ("How stages of consciousness," 2019):

> A future vision is of integral business where a currency of well-being is the main focus. Work would be undertaken in a mindful culture directed at encouraging an achievement of harmony across all eight well-being components. The value thrown off by such companies would be in the form of well-being creation for society. (p.21)

Therefore, a new system approach to radically improve the architecture, engineering, and construction (AEC) industry is emerging (Fewings & Henjewele, 2019; Owen et al., 2010). Despite the development of integral architecture (Zeiler, 2011, 2015), a gap in the literature exists because a description of the complex integral system in the AEC industry is missing.

This chapter forms the second part of the thesis and offers a futuristic examination of existing issues in the NZ housing design process. Part one (of this thesis) explained why BIM, as a tool for collection and management of information about a building, should include energy, hygrothermal, and airflow models to support the optimization process of sustainable buildings. Therefore, the subject of the first part obtained incorporation of hygrothermal modelling into BIM to address moisture related problems and the building materials' influence on indoor relative humidity (RH). The requirements for interoperability between the hygrothermal model WUFI Plus and the architectural design tool Revit are examples of the growing field of integration. However, the problem of energy-inefficient, unhealthy, cold, mouldy, and damp houses in New Zealand (NZ) is complex, and therefore, couldn't be solved with the same attitude as it was created. Improvements in tools have to be a part of an innovative approach. A radical change in thinking is necessary, as Albert Einstein already said: "Problems cannot be solved by the same level of thinking that created them" (as cited in German in Stahlbaum, 2020).

Therefore, the second part of the thesis focuses on the paradigm shift in the architectural design process. Taking a system approach means thinking about the relationship between design process management and the social, environmental, and economic systems or structures that encompass the built environment. The first two paragraphs of this chapter consist of defining the integrative and holistic system approach — named Complex Integral Design New Zealand (CIDNZ) and discussing the transformation phase of the paradigm shift. The proposed framework introduces alternative perspectives on how to design warmer, drier, and healthier houses for the NZ context. Consequently, the researcher suggests tools for the evaluation of CIDNZ and discusses the integration of diverse perspectives in the system approach. In the concluding paragraph, the vital contributions of this chapter are summarized.

8.1 Complex Integral Design New Zealand (CIDNZ)

Since the energy crisis in the 1970s and forthcoming human-induced climate change, energy-related issues are influencing the whole world. The building industry has contributed significantly to this situation (Ürge-Vorsatz et al., 2011). Consequently, changes towards sustainability and resilient building design and construction are necessary to minimize the negative impact of buildings on the environment (Cohen & Snell, 2018). However, the most improvements so far have been targeted to a specific problem-solving without any consideration of the whole. For example, in NZ, the incentive of warming up the existing houses led to insulation retrofits (BRANZ, 2018). The insulation has been typically installed to some elements of the house only, like walls, floors, or ceilings, but rarely to the whole building envelope (Ghose, McLaren, et al., 2017). As a result of these enhancements, the energy balance and the carbon footprint have been improved. However, the retrofits-related shifts in the position of the dew point have ramifications. Interstitial condensation, mould growth, and rotting of construction materials represent possible consequences of partial improvements in the thermal resistance of building envelopes (Shrestha et al., 2019; Vereecken, Van Gelder, et al., 2015).

From the system's definition point of view (ISO/IEC/IEEE International Standard, 2017), every building might be seen as a complex system that interacts with the environment and humans. From the system theory perspective (Rhodes, 2012), a building includes all of the used materials, equipment, location, shape, functions, and relations to the environment and occupants. What makes each building a system are the links and dependencies of one part on another and the environment. Any change of some element, function, behaviour of occupants, or climate has an influence on the whole system — building. This approach represents a piece of new knowledge. In theory, BIM is a dynamic process accompanying the whole life cycle of a building. However, as shown in part one of this thesis, the praxis is still far away from this potential. A necessary transition process, therefore, might enable changes in the AEC industry, leading to the integration of the fourth industrial revolution (Industry 4.0) (Daniotti et al., 2020a).

Additionally, there is undeniable evidence that humans reached a radically new level of consciousness and stepped into an era of globalization (Stein, 2019). Therefore, the minimalization of the negative impact of buildings on the environment and climate is not sufficient. The expanded consciousness recognizes the need for a harmonization of the man-made world with the life on the planet Earth. This corresponds to the United Nations Interactive Dialogue of the General Assembly on Harmony with Nature which invites to promote "… the balanced integration of the economic, social and environmental dimensions of sustainable development through harmony with nature" (The United Nations, 2018, p. 5). Consequently, a definition of a new set of operations is necessary. We need to set a benchmark, in other words, identify the need for certain considerations. From this point of view, the proposed approach of CIDNZ aims to radically improve the performance of NZ houses.

8.1.1 The Definition and Background of CIDNZ

Complex Integral Design New Zealand (CIDNZ) represents a comprehensive and balanced system-based design and delivery process that facilitates and accelerates cross-disciplinary and trans-disciplinary expertise and knowledge to create buildings in balance with nature, environment, and human needs.

With the word "complex" the researcher advocates for complexity science as both a theoretical and practical framework for addressing housing problems in NZ. CIDNZ aims to radically improve the housing by integrating contextual conditions in the search for generalizable findings and recognizing the value in the inter-disciplinary knowledge. "Complex" therefore expresses two meanings. Firstly, as Saurin and Rooke (2020) wrote:

> … construction projects might be framed as complex socio-technical systems (CSS), which are a sub-set of the broader family of complex adaptive systems. Since many complex adaptive systems are not socio-technical (e.g. ecosystems, which may interact with construction projects), this distinction is necessary. (p. 325)

Therefore, from a complexity science point of view, complex systems include many interacting components and diverse forms, such as networks and graphs, cellular automata, fractals, agent-based models, swarms, self-organizing, chaotic, and cybernetic systems (Downey, 2018). Secondly, the word "complex" points to a changing way of thinking. The traditional forms are extended or transformed by emerging holism, mutual causality, and perspectival observation (Dent, 1999).

CIDNZ is based on comprehensive engineering and other disciplines, including but not limited to architecture, engineering, building physics, indoor air quality, environmental science, information technology, computer sciences, building services, building biology, meteorology, human physiology and psychology. The system approach used in CIDNZ represents the ability to look at influencing factors and elements, tasks, goals, and functions from a "distance", which allows for different points of view. CIDNZ implements a new modality of thinking, called integral thinking, which rests upon the holistic consciousness, and goes wider than "integrated" because it contains concepts of inclusivity, pluralism, and reverence (Gidley, 2010).

Every building, inhabitant, stakeholder, or a group of people (for example, a family) are seen in CIDNZ as holons and examined in their whole/part relationships during the life cycle of the building. The theory of holons has been introduced in Chapter 2, section

2.1.5. Holons are organized in hierarchies and heterarchies, called by Wilber holarchy (Gallifa, 2019). Therefore, the analysis of the holarchy and relationships between holons and holarchy allows for the integral examination of multifaceted, cross-disciplinary, human- and nature-centred problems in the CIDNZ process. In this sense, the CIDNZ forms a holon as well.

CIDNZ uses the integral examination, which executes in four dimensions: transcendence, communion, agency, and immanence (Gallifa, 2019). The transcendence demonstrates the ability of the holon to change and evolve. Therefore, it allows for the evolution of the whole system (Gallifa, 2019). For example, the integration of the hygrothermal modelling into the design process enables improvements and the optimization of the hygrothermal performance of the building. The communion allows for relationships with other holons. This sometimes happens through indirect ways, such as government regulations, human priorities and values (Gallifa, 2019). Therefore, CIDNZ will encourage dynamic relations with building authorities and research to improve the design process and in general, the quality of NZ housing. The agency represents the ability of the holon to project the internal structure and transform or influence the environment (Gallifa, 2019). The agency will carry out an essential role in CIDNZ because the AEC industry might benefit from the cooperation and integration of diverse fields of knowledge. The immanence is the holon's tendency to preserve the status quo, repeat the past, and therefore, add to the stability of the system (Gallifa, 2019). In CIDNZ, the immanence means the ability of the system to use reliable, proven, and tested methods, technology, and materials while encouraging for the transcendence and evolution.

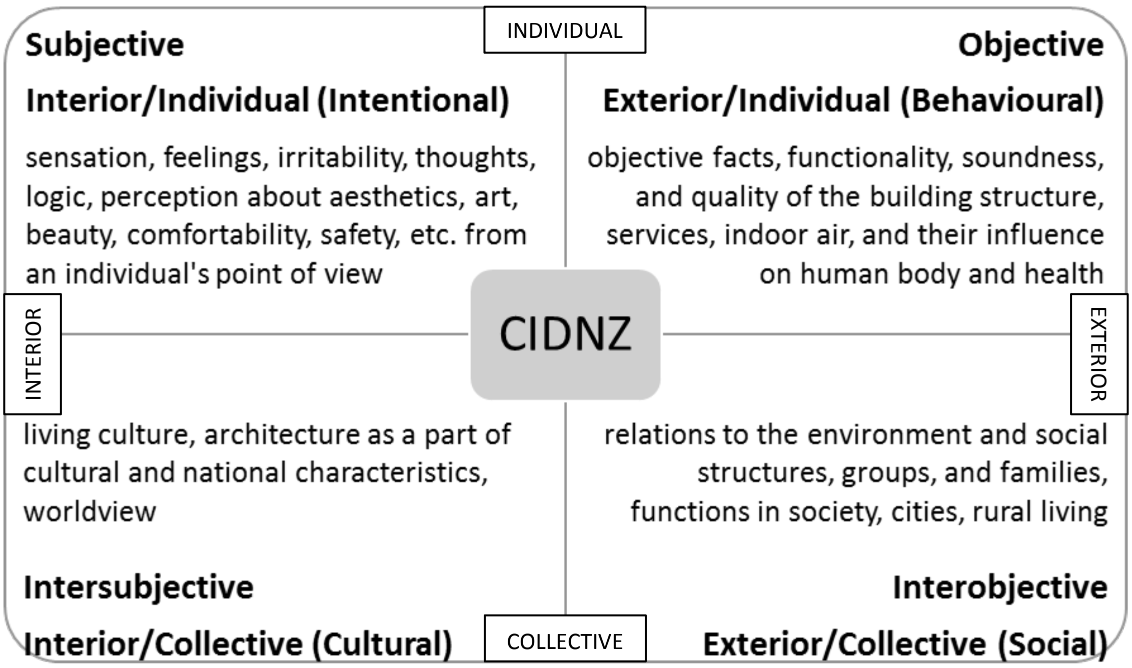
The design and delivery process, and the end-result/building, when seen as systems, offer a paradigm shift in the way how buildings are constructed and used. The system approach in CIDNZ, for example, interpolates questions and examples from natural systems. What does it need to create a zero-energy sustainable building? How can it be done? What are the conditions to eliminate harmful effects on nature and people? How could it be done that the design and construction process go more smoothly, with minimal losses and delays, but not for the costs of the whole? The aim of the CIDNZ approach is the harmonization and optimization of processes, resources (humans and materials), and building performance (thermal, hygrothermal, environmental). For the operations and progression, CIDNZ adopted the integral operating system (IOS) — an integral model that includes four quadrants of growth, development, and evolution (Wilber, 2000b, 2007, 2014a). The description of the four quadrants in CIDNZ forms the content of the following section.

8.1.2 The Four Quadrants in CIDNZ

The CIDNZ system accommodated Wilber's four quadrants (Wilber, 2000a) to form four different views on the entire design process. Therefore, CIDNZ divides the design of sustainable and low-energy houses into four quadrants along two axes, as shown in Figure 36. The horizontal axis, connecting the interior on the left side and the exterior on the right side, depicts a view point related to the subject of evaluation. On the right side of the axis, the subject is objectively examined from "outside", and therefore, it becomes an object. The vertical axis connects the collective perspective on the bottom with the individual perspective on the top.

Figure 36

The Four Quadrants in CIDNZ



Note. Wilber's Quadrants adapted to design and construction from Wilber (2014b).

The subjective quadrant (upper left) describes the influence of the house on the perceptions and sensations of a person. The individual might be the designer or the future inhabitant. Questions in this phase relate to their perceptions and feelings. For example, will the building provide a comfortable and safe environment? Will the design and indoor environment evoke positive feelings and thoughts?

The objective quadrant (upper right) depicts all objective, measurable facts about the building performance, functionality, indoor air quality, etc. and its influence on the human body and health. In this phase, designers ask questions related to the impact of the building on the physical body. For example, what impact will the building have on the health of inhabitants? Will the building provide a healthy living environment? How high is the probability of mould development in the building? How high will be the concentration, if any, of hazardous substances in the indoor environment? Is the building structure durable and safe? In this quadrant, the design team analyses both the individual matter of biological and chemical origins and the synergistic effect of all substances as well.

The intersubjective quadrant (lower left) relates to culture and nation; how the building influences or reflects the existing worldview and cultural values, inclusive corporate culture. Does the building and its design enhance the existing culture? How the building/s will support the global culture? Does the design reflect the characteristics of the nation?

The interobjective quadrant (lower right) reflects the relations to the environment, ecology, economics, and social systems and structures (groups in which people live or work). Due to the world's major problems, such as climate change, pollution of earth, water and air, and depletion of resources, the thinking in this quadrant and acting sustainably gained on importance. Sustainability is a principle of action by which the resources utilized to the needs satisfaction are exploited in such a way that enables natural regeneration of involved ecological systems (Oxford University Press, n.d.).

"Our problems are by-products of our successes" (Maxwell, 2018, p. 349). However, although the solution of environmental issues is crucial for the survival of humanity, the balance between all quadrants is decisive for future well-being (Marshall, 2016). The quadrants in CIDNZ offer four different views on the design process and help in a practical way to formulate questions leading to integrally balanced solution concepts.

Some examples of these questions are as follows. What objectives and criteria we have to set for retrofitting of existing buildings? What are the factors in building performance to support and positively influence the human's well-being and health? How might these factors be satisfied in harmony with the environment? How will the future inhabitants feel in this concrete, nearly zero energy house? What could be done to enhance the cultural, esthetical, and social value of the designed building?

From this point of view, CIDNZ includes and simultaneously expands already existing integral theory's applications in the field of architecture, design, engineering, and construction. The Integral Sustainable Design (ISD) (DeKay & Bennett, 2011) and the integral ecology (Esbjörn-Hargens, 2005) are two examples of these applications. ISD, although representing a more integral view on sustainable design, is mainly oriented towards ecology and the impact of buildings on the environment, energy, and use of materials. ISD examines the sustainability of the design from behavioural, systems, experiences, and cultural perspectives (DeKay & Guzowski, 2006). The quadrants in ISD are seen as follows. On the subjective/individual level, the ISD's perspective contains environmental phenomenology, experiences of natural cycles, and green design aesthetics. On the objective/individual level, ISD is concerned with the efficiency of energy, water, and materials; on the subjective/collective level, relationships to nature, green buildings' ethics and cultures; on the objective/collective level, eco-effective functionalism and buildings as an ecosystem (DeKay & Bennett, 2011, p. 18). Therefore, the subjective levels are only observer-oriented, specifically how the architectural designer experiences and understands the place (the arts), and what others perceive, what is measurable about the place (efficiency) (DeKay & Bennett, 2011). However, ISD does not include any influence of the building on the health and well-being of people/inhabitants.

In this sense, CIDNZ brings new knowledge because it contains all holons related to the building, such as environmental, individual (creator and user), collective, sociological, and ecological. Consequently, the application of the proposed innovative system approach requires a necessary transformation process.

8.2 A Process of Transformation

The development and implementation of CIDNZ involve a process of transformation. The core of the transformation is located in the values which every stakeholder holds. Therefore, a question emerges regarding how to shift the values towards higher stages of individual and collective development; from personal to trans-personal, from rational to pluralistic and integral.

The housing and the associated design and construction remain not a set of static things, rather an open system in which evolution depends on the human values and market conditions (Aksamija, 2017). Therefore, the state of knowledge and value system determine the places where people live and work. For example, the materialistic self-centred values of the modern age, "… the values of accomplishing and getting, having and possessing" (Graves, 1970, p. 150) brought besides wealth, innovations, and comfort exploitation of natural resources and massive pollution of the environment (Beddoe et al., 2009).

For a framework, which the following section 8.3 shall present, the design process in its complexity and the rapidly changing human's values convey radically different ways of thinking. A new set of values based on humanistic, systems, holistic, and integral views develops (Schwartz & Esbjörn-Hargens, 2019). The CIDNZ transformation process, therefore, values the undistorted acceptance of human nature as it is, and problem-solving process, which leads to a balance between individuals, groups, society, and the existing ecosystems. This is a novel way of understanding sustainability in the housing and construction industry in general.

Consequently, the shift in value system is visible in recognition of concepts of consciousness and attention in cognitive psychology and other scientific fields (Galotti, 2017), and the birth of global culture and consciousness (Stein, 2019). According to Beddoe et al. (2009), "A culture can be viewed as an interdependent set of world views, institutions, and technologies" (p. 2484). In this context, the researcher notes that the global culture forms while each nation is developing its own unique culture. "As seen in an organic body, for the whole to become one, each part must develop itself. For each part to develop itself, the whole must become one" (Nishida, 2019, p. 308).

The stages of the individual and collective development might be followed in the spiral dynamic, which represents a human development theory, based on Graves (1970) and first introduced by Beck and Cowan (2014). The spiral dynamic proposed eight levels of development to which Wilber later added the rainbow colours (Butters, 2015). Consequently, the human development system depicts a map of evolving personality and world views. A worldview might be defined "… as a combination of a person's value orientation and his or her view on how to understand the world and the capabilities it offers, the lens through which the world is seen" (van Egmond & de Vries, 2011, p. 855). The historical process of frequently repeated destabilization of worldviews together with the present domination of the extreme postmodernist worldview led to the sustainability problem and ecological crisis (van Egmond & de Vries, 2011). Nevertheless, the emerging climate change and the need for sustainability transformations are bringing radical shifts in worldviews, innovative strategies, and the role of sustainability assessments (Rigolot, 2018).

Consequently, the CIDNZ transformation process involves a movement of values toward the integral worldview domain. The integral worldview constitutes of transformed relationships to the environment, eco-social evolution, and unity and flourishing of all beings (Ferreira, 2018). Simultaneously, it accepts and understands all major typologies of worldviews, such as premodern, modern, and post-modern. The integral worldview, therefore, offers an ethical framework that operates within a circle consisting of the four quadrants, eliminating one-sided identifications and defining "human dignity" (van Egmond & de Vries, 2011). Integral thinking is particularly useful in complex fields that require comprehensive approaches, such as housing design and construction. Integral thinking includes traits of advanced ways of thinking, such as ecological, systems, holistic, post-formal[1], and metaphysical (Gallifa, 2019).

Therefore, CIDNZ implements integral thinking which is an inclusive thinking in systems. Inclusive thinking is based on a notion of cross-sector and multi-disciplinary collaboration and shared values (Lu, 2013). The transformation process to integral thinking happens not as DeKay and Bennett (2011) write as "… a shift from behaviors to system" (p. 256), but as a complex system that includes all quadrants and all levels

[1] Features and characteristics of Post-formal thinking are described in Appendix C.

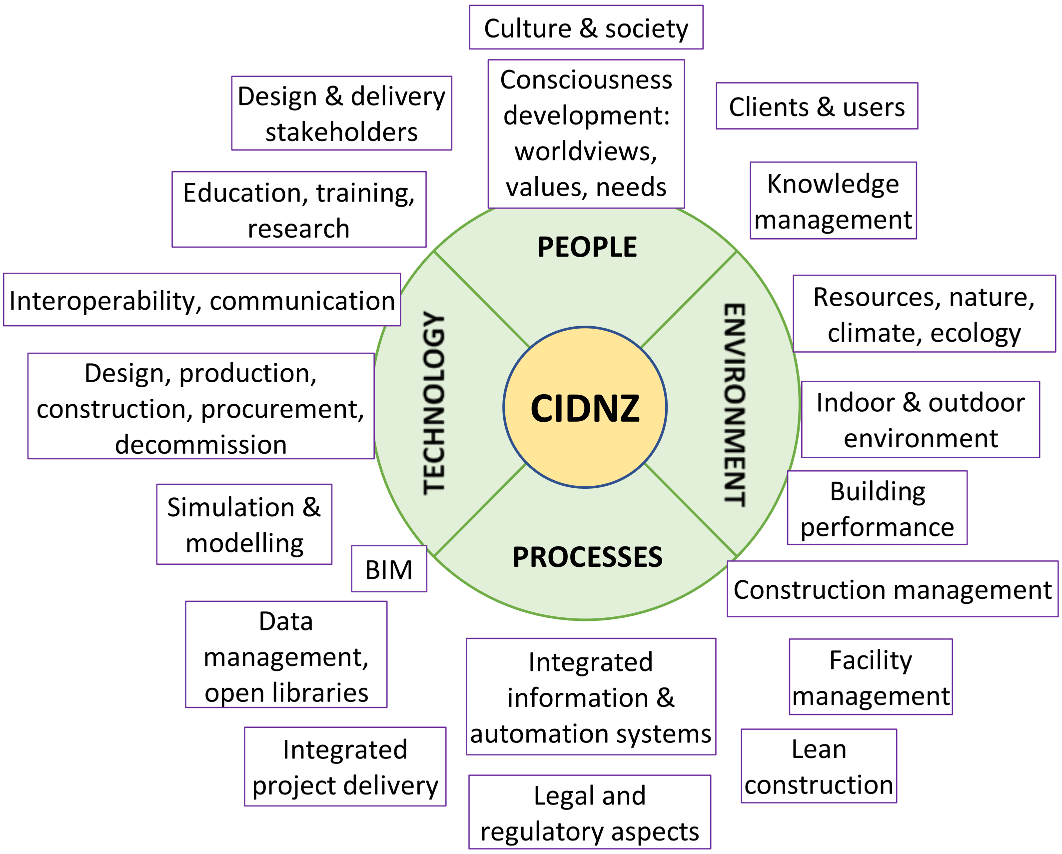
(Landrum & Gardner, 2005). Particularly, the CIDNZ ecological thinking aims to achieve a balance between the upper right and the lower right quadrant; in other words, a balance between behaviours/functions and environmental, societal, and ecological systems. Therefore, the transformation process represents an ever-expanding perception that reflects "… the need to change the legal anthropocentric paradigm and replace it with biocentric thinking which recognizes Nature's intrinsic value and advances the interconnectedness between human beings and Nature" (The United Nations, 2019, p. 4).

The transformation process depicts an entirely new quality of perceptions that are based on the second tier of human consciousness development. This is because this level of consciousness is profoundly different from all previous levels. It is the first time in the known human history when the shift happens, not by fighting and denying the previous levels (Wilber, 2019). In this level, the world view is based on recognition and acceptance of all the progress done in the past, learning from mistakes, and integration of the knowledge for the well-being of all (Schwartz & Esbjörn-Hargens, 2019). Through this process, holistic views of construction are developing. The holistic views include "… integrated, collaborative processes, enhanced technical and social skills, and interoperable technologies to support integrated information and automation systems and knowledge management" (Prins & Owen, 2010, p. 227).

CIDNZ comprises all stages in the life cycle of buildings. Therefore, the transformation addresses relations to the environment, stakeholders, technologies, and processes involved in the design, delivery, usage, and decommissioning of buildings. Simultaneously, the process of transformation needs support from research and education. CIDNZ recognizes four significant aspects in the AEC industry: people, processes, technology, and environment. Figure 37 schematically visualizes the four fundamental aspects of CIDNZ and the conceptual framework for transformation.

Figure 37

Fundamental Aspects of CIDNZ and the Conceptual Framework for Transformation



The conceptual framework for transformation contains collaborative processes across all project phases, enhanced skills, integrated information and automation systems, and knowledge management. These are the four elements of the Integrated Design and Delivery Solutions (IDDS)[2] (Owen, 2009). IDDS is the CIB[3] vision for a more holistic future transformation of the construction sector. Additionally, CIDNZ recognizes two crucial elements, such as human needs and environmental systems. Any change/improvement in one of the industry elements has a direct or indirect influence on the industry foundations (Owen et al., 2013). Differences between IDDS and the complex integral design might be recognized in the fact that the former aims to enhance the efficiency and value of projects. The later goes a step further. CIDNZ as a

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[2] "Integrated design and delivery solutions use collaborative work processes and enhanced skills, with integrated data, information, and knowledge management to minimize structural and process inefficiencies and to enhance the value delivered during design, build, and operation, and across projects." (p.3) Owen, R. (Ed.). (2009). *CIB white paper on IDDS integrated design & delivery solutions* (Vol. 328). CIB. http://www.irbnet.de/daten/iconda/CIB18413.pdf.
[3] International Council for Research and Innovation in Building and Construction.

process includes all previous stages of integrated, collaborative processes in personal and objective levels by a new integral cross-paradigmatic approach. Therefore, CIDNZ transformation process influences all fundamental aspects as described in the following sections.

8.2.1 People

The people involved in CIDNZ consist of two major groups: the users/inhabitants, and the design and delivery stakeholders. Both of these groups will undergo a process of changes and transformation. As Dent (1999) wrote more than 20 years ago: "Our reality changes as our ability to detect phenomena changes" (p. 16). The human needs and values, and individual's worldviews, therefore, form a crucial element of the transformation process. Consequently, CIDNZ includes the identification of contemporary and future physical, psychological, and sociological needs and values, as well as aesthetics, health, safety, and functionality. The recognition of the human needs and values in CIDNZ proceeds across four directions: individual, collective, interior, and exterior.

On the side of design and delivery, the enhancement of skills and knowledge management throughout the industry foundations are decisive for the successful transformation. CIDNZ team members work in cooperation through the whole supply chain, and continuously improve the level of knowledge. The involved processes require new/advanced skills in technology applications, multitasking, and the ability to think integrally in a cross-disciplinary way (Daniotti et al., 2020a). Therefore, people with joint degrees, such as the architect/engineering, will be in demand (Owen et al., 2013). Some professions, such as construction or architectural managers and mediators, might gain importance (Ali, 2019). The collaboration and shared knowledge about past projects will improve the skills of tradespeople who will participate in integrated work processes (Owen et al., 2010). Consequently, the educational system will require changes towards integral thinking and inter-disciplinary approach (Gallifa, 2019), especially in combination with environmental and human sciences. It will not be enough to build technically advanced low or zero energy buildings but to harmonize the built environment with nature, health, and wellbeing of people.

8.2.2 Processes Across All Project Phases

The AEC industry is already undergoing a transformation process due to the new technologies and collaboration with BIM (Papadonikolaki et al., 2019), Integrated Project Delivery (Piroozfar et al., 2019), and Lean Construction and Procurement (Tzortzopoulos et al., 2020). However, the reality of the processes across all project phases is that very few firms are able to collaborate effectively (Daniotti et al., 2020b; Owen et al., 2010). Interoperability issues between diverse BIM tools and design systems still exist, as described in detail in Chapter 3 (p. 102) and Chapter 6 (p. 179). A prerequisite to the successful development of collaborative processes across all project phases is, however, the interoperability of diverse software. Therefore, stakeholders in a supply chain would benefit from interoperability considerations by the acquisition of new technology (Oti & Abanda, 2020).

The process of transformation to achieve CIDNZ will require a thorough analysis of supply chain and team members for each project to ensure the optimal transition. The analysis will serve in setting up a new organizational structure based on co-operation, collaboration, acceptance, and respect. The professions of the team members should correspond to the overall aim of the project, enabling for cross-disciplinary approach in all of the four quadrants. The team members might belong to scientific fields of architecture, building physics/science, engineering, design, psychology, environmental sciences, project management, sociology, information technology, etc. Besides the importance of technical equipment and organizational structure, communication, conflict management, negotiation, and teamwork represent the essential factors of successful collaboration (Papadonikolaki et al., 2019). Consequently, CIDNZ as a system should improve the value of housing, not only in economic terms of delivering better value in a shorter time and lower costs but relating to human needs and environment. The latter two attributes also include architectural and aesthetical values, supporting the well-being of occupants and the integration of buildings into the environment in a sustainable manner. CIDNZ, therefore, requires a paradigm shift in values of all involved stakeholders, inclusive users, developers, designers, and members of the supply chain.

The CIDNZ processes include principles of Integrated Project Delivery (IPD) and Lean design and construction. IPD is based on a contractual agreement between main project parties (client, designer, and contractor) about collaboration, use of BIM, and improvement of value for money by minimizing waste, inefficiency, and conflictual relationships (Piroozfar et al., 2019). However, despite a growing interest in IPD, the reality is that "… only few institutions are able to adapt their programs to meet this need" (Ali, 2019, p. 2041). In the 1990s, Koskela applied a new production philosophy, which started in Japan in the 1950s, to construction (Koskela, 1992). Since then, a continual evolution of reconceptualization of construction as a production process and the Lean design and construction movement are changing the AEC sector (Tzortzopoulos et al., 2020). Lean represents improvements in the management and production and is associated with just-in-time and implementation of information technology to minimize excess labour or stock of goods (Koskela, 2020). Consequently, the transformation in the AEC industry requires full integration of information and automation systems. The necessary free flow of information is discussed in the following section.

8.2.3 Interoperable Technologies

To successfully transform complex systems, such as the AEC sector in the 21st century, implemented technologies in all stages have to be interoperable. Therefore, one of the imperatives of the process of transformation to CIDNZ consists of the interoperability analysis of the construction technology to achieve optimized solutions and higher value levels in the AEC sector. The status quo and the problematic of interoperability are assessed in Chapter 3, section 3.4.4.

Shirowzhan et al. (2020) describe construction technology as "… tools, systems, mechanisms, computers, electronic boards and components, equipment and any combination of resources used for carrying out physical construction activities in the process of construction from design to demolition" (p. 2). Consequently, the compatibility measures influence the building performance and the impact of the construction process on the environment and economics. Improvements of compatibility measures require changes in the information systems (BIM), business processes, and management of business relationships to move "… from traditional red ocean strategies, i.e., efficiency and differentiation, and aim at blue ocean strategies, i.e. value innovation" (Grilo & Jardim-Goncalves, 2010, p. 530).

However, the current information management is still limited (with some exceptions) to a complete model exchange, which leads to poor semantic integrity and loss of information (Owen, 2009). Although many studies acknowledge the compatibility and interoperability issues in software architecture (Haoues et al., 2017), they "… have not been directly discussed in recent BIM standard investigations" (Shirowzhan et al., 2020, p. 13). According to some researchers, the future of interoperable technologies lies in semantic BIM and Semantic Web Services (Niknam & Karshenas, 2015). Other examples of semantic systems are intelligent management of energy and security in buildings (Santos et al., 2020), or real-world semantics for acquisition, processing, and analysis of large volumes of data (Davies et al., 2020). From the practical point of view, CIDNZ recommends including in the team an information manager, an interoperability specialist responsible for determination of the optimal software and information flow which suit the project the best. Additionally, free information exchange between all stakeholders in all directions is crucial for CIDNZ for several reasons. Communication of values, balance between built environment and nature, optimization of a design in all quadrants, energy efficiency, and performance are some examples.

To achieve this, further development of semantic interoperability and information science but the transformation of professionals' education in the construction industry are necessary. As already discussed in detail in section 7.3, data management and the interlink between machines—objects—people and processes represent essential attributes of the fourth industry revolution (Daniotti et al., 2020b). Therefore, to enable the optimization and further analysis of an architectural project relevant, coherent, complete, interoperable, and open data libraries should be available (Daniotti et al., 2020c; Palos et al., 2014). Additionally, a precise semantic definition of data exchange between implemented software will enable conflict-free data transfer and minimize errors (Belsky et al., 2016). A significant transformation will happen in information management by using sophisticated models, view- and rule-based approaches (Santos et al., 2020). Simultaneously, companies will need to solve problems related to software innovations and accommodation of new technology together with the existing (Oti & Abanda, 2020). Therefore, CIDNZ suggests an independent examination of compatibility and interoperability in the construction technology context as a part of the transformation process.

8.2.4 Environmental Systems

The CIDNZ approach is of transformation with a transition towards the balance of environmental systems. The explanation of interactions and processes in environmental systems is, therefore, vital to the understanding of this transition. From the integral view, the holarchy of environmental systems includes interconnected natural and man-made holarchies with complex relations, processes, and impacts. Natural systems are open and dependent on other systems, which are often of anthropogenic origin (Eichhorn, 2016).

Therefore, CIDNZ comprehends the term “environmental systems” as an integration of indoor and outdoor environments, ecology, resources, transport, climate, weather, humans, and natural systems. Ferguson (2003) described an environmental system (ecosystem) in the NZ Ministry of environment document *Sustainable Wastewater Management: A handbook for Smaller Communities* as follows:

> An ecosystem is a community of interacting organisms and the physical environment in which they live. Humans and their buildings and settlements are part of this community, which can include birds, plants and insects, as well as inorganic matter (such as rock and metals) and natural forces (such as the flow of water, fire, or the chemistry of photosynthesis[4]). All of these link together and interact as a complex web of life. (p. 11)

This holistic approach to the environment has deep roots in many indigenous traditions. For example, Māori worldview, mātauranga Māori, is based on a belief in the deep spiritual connection between people and the environment (all living and non-living things) (Kahui & Cullinane, 2019). This means that the relationships between humans and environmental systems determine decisions, rather than their effects. In this sense, CIDNZ might learn about the interconnectedness of all things from the Māori theory of the origin of the universe. Māori people believe that “… any actions that change or degrade the mauri[5] of one thing will have a corresponding impact on

[4] „Photosynthesis occurs in all green plants. It is the process by which sunlight is used to turn carbon dioxide and water into sugar and oxygen” (Ferguson, 2003, p.11).

[5] Mauri represents „… life principle, life force, vital essence, special nature, a material symbol of a life principle, source of emotions - the essential quality and vitality of a being or entity. Also used for a

the form or integrity of another” (Ferguson, 2003, p. 15). Therefore, for many Māori, the respect for the physical environment coincides with the obligatory protection and safeguarding of mauri as an essence located inside of each entity. Māori people see humans “… as an integral part of the ecosystem” (Kahui & Cullinane, 2019, p. 2). On the contrary, the prevailing worldview sees nature (ecosystem) and humans (human activities) as separated. However, the indigenous collective leadership principles might be beneficial to all complex adaptive systems that are resilient, non-linear, and interdependent, such as shared leadership in teams engaged in a creative task (Cullen-Lester & Yammarino, 2016). The core of the Māori collective leadership as a multi-dimensional paradigm forms the knowledge code, which is “… a way of tapping into and releasing collective intelligence that is transmitted from one generation to the next” (Spiller et al., 2020, p. 531). Therefore, a leader, a rangatira[6] represents the ability to being a paradigm warrior, working on its potential, supporting and leading people toward a state of belonging and flourishment (Māori Dictionary, n.d.). However, these principles are not about any individual leader but a complex of roles and responsibilities (Spiller et al., 2020).

Therefore, understanding what the environmental systems represent and how they are formed, interconnected, and interdependent is vital to the CIDNZ transformation process. The buildings and built environment configure a subset of environmental systems, which include natural systems and people. Consequently, the researcher believes that the built environment has to fit into the environmental systems if humanity is to survive in the long term. The system approach requires a more sophisticated way of thinking about environmental systems. Simultaneously, a question arises about the flexibility and balance of these systems. Therefore, the strong transition involves the integration of science in diverse fields, identification of problems, adaptation and redesign of critical systems in the AEC industry, and management of the transformation process.

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physical object, individual, ecosystem or social group in which this essence is located” (Māori Dictionary, n.d.).

[6] Rangatira means „… chief (male or female), chieftain, chieftainess, master, mistress, boss, supervisor, employer, landlord, owner, proprietor - qualities of a leader is a concern for the integrity and prosperity of the people, the land, the language and other cultural treasures (e.g. oratory and song poetry), and an aggressive and sustained response to outside forces that may threaten these” (Māori Dictionary, n.d.).

8.3 Framework for Designers

This study is concerned with improvements in housing quality, especially with the hygrothermal performance of buildings. However, as delineated in the previous chapters, the problematic of built environment sustainability is of such complexity and interconnectedness that the real and long-lasting improvements require a system approach.

The complexity of the built environment might be demonstrated in hygrothermal relations in buildings. Although buildings without a vapour barrier can have satisfying moisture performance by fluctuations of RH (Salonvaara et al., 2004), the probability of uncontrolled in-wall condensation, mould growth, or rotting is very high (Domhagen & Wahlgren, 2017). Therefore, several researchers suggest an airtight but vapour permeable building envelope (Simonson et al., 2005; Yarbrough et al., 2019). Nevertheless, as already mentioned, the design and construction of sustainable and energy efficient buildings require consideration of multiple factors, including hygrothermal relations. During the process, designers of sustainable buildings need to answer many questions. For example, how high are the moisture loads into the wall? Is the drying process possible? How long would the drying out take? Is the wall construction diffusion open? If yes, how does such construction perform in the long term? Is there any risk of additional wetting of the building envelope from driving rain, melting of frozen water, or excessive indoor RH? How could the building adjust to future usage needs?

The design process that follows an integral approach might eliminate most of the problems described in this research. Therefore, this research proposes a new framework for designers to improve the sustainability of housing. The elements of the framework are not new, but the concept of the design process is. The basic idea behind this concept is to create habitable spaces for people in harmony with nature and natural forces, not against it. The holistic architecture is copying nature in its function, as several researchers emphasize (Esbjörn-Hargens, 2005; Yarbrough et al., 2019). The integral sustainable design takes natural systems as a model for design and develops an ecological literacy that understands and applies the principles of ecosystem structure, process, and organization (DeKay & Bennett, 2011). For example, the concept of integrated environmental approach stresses the necessity of simultaneous consideration of the building structure, energy efficiency, indoor environmental quality, and moisture management during the whole design process (Bomberg, Gibson, et al., 2015; Bomberg et al., 2016). This does not mean that the design has to be simple or boring. This means that the design process implements a system approach to buildings as a vital part of the environmental systems, goes from the environment to humans, and offers unlimited possibilities.

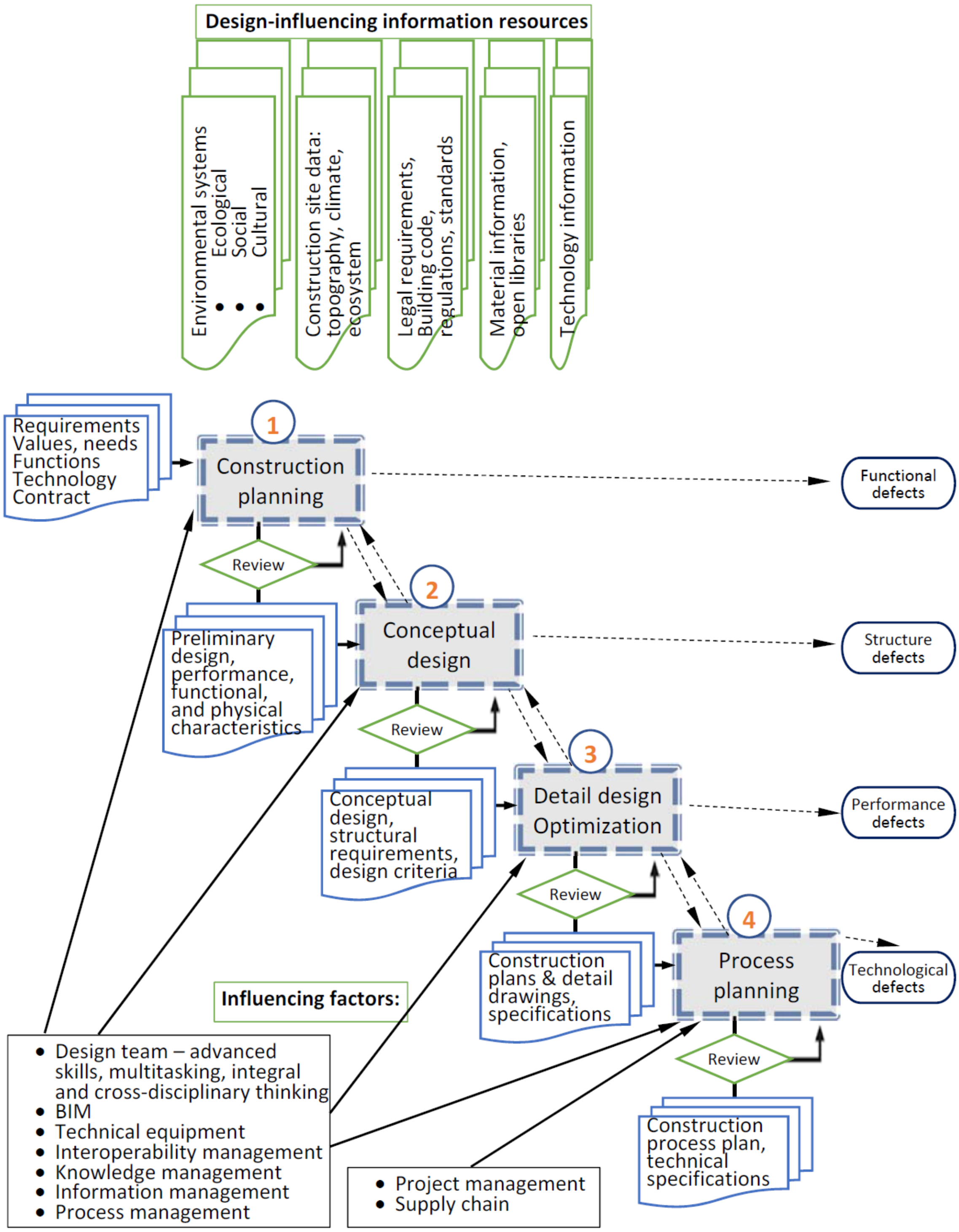
“Nature is no longer just a thing” (p.3), as Justice Antonio Herman Benjamin of the High Court of Brazil stated:

> Granting rights to Nature reflects a profound change from the traditional legal wisdom which once considered Nature just a collection of elements and now sees Nature as the meaning and foundation of all life. This shift in paradigm, once the topic of philosophical and ethical circles, now reveals itself as a legal paradigm. (The United Nations, 2019, p. 3)

Therefore, future housing and the related design and construction process need radical changes. The concerns are not limited to energy efficiency, CO_2 reduction, or moisture, but include issues related to environmental systems, humans, and Nature. To radically improve the quality of housing in NZ the AEC industry has to consider customer requirements and needs at early construction planning stages. Simultaneously, the designer team needs to manage the increased complexity of buildings and their construction. This research introduces a complex integral framework that integrates construction planning and design, optimization, and control tools at strategic, tactical, and operational levels. The framework offers stakeholders the possibility to actively engage in the design process, influence the impact of the building on the environment, and be informed about concurrent design variants. Figure 38 depicts the structural relationship model of the framework with the influencing factors and design defects. With the paradigm shift in mind, the following sections briefly describe four steps in the CIDNZ framework for designers.

Figure 38

The Structural Relationship Model of the CIDNZ Framework, Influencing Factors, and Design Defects



8.3.1 Step 1 – Construction Planning

Construction planning is in its role similar to product planning which is considered to be the crucial stage in the decision-making process in the design (Hochdörffer et al., 2018). This step in CIDNZ involves the identification of values and functions, customer/user needs, resources, and analysis of construction site, climate, ecological, social and cultural environment. The outcome of construction planning encompasses preliminary design decisions, building performance objectives, time schedule, design resources, knowledge, and technology. At this stage, designers aim to eliminate functional defects in the design (Zheng et al., 2018). The preliminary design contains fundamental decisions about solar gains, thermal mass, and ventilation. The designing process in the first step follows the recommendations for the high quality environment buildings (Bomberg et al., 2016). It is based on the principles of climate specific design (Mitterer et al., 2012) and climate-responsive design (Looman, 2017). The origin of the latter two design philosophies might be tracked from the early 1950s when Olgyay first introduced the term bioclimatic design. The original publication of Olgyay's *Design with Climate* book (1963) laid the foundation for an architecture based on outdoor climate (Olgyay et al., 2015).

Different outdoor conditions and the intended use of the building require divergent construction concepts to achieve energy efficiency, healthy indoor environment, and durability of the building. Designers/architects decide in the early design stage about the size, position and orientation of the building, insulation, fenestration, air-tightness, zoning, need for heating and cooling, mechanical or natural ventilation, shading, and thermal mass. Therefore, preliminary design, as a result of this stage, is based on the multidisciplinary holistic approach to the creation of new spatial objects in the existing environment. The successful applications of bioclimatic factors into BIM sustainable architectural design require an extensive knowledge in biology, climatology, and building physics (Bondars, 2013). Therefore, a crucial part of the suggested framework for designers consists of the further education of the team members. The interdisciplinary knowledge might enhance the ability to understand and adequately interpret the relations between the indoor and outdoor climate conditions, and the involved environmental systems.

8.3.2 Step 2 – Conceptual Design

At the conceptual design stage, demands, functions, and values need to be prioritized and identified from the perspective of all four quadrants. Therefore, CIDNZ ads to the technical system and human use perspectives (Ai et al., 2020), which represent the behavioural view (the upper right quadrant), intentional, social, and cultural perspectives.

At this stage, decisions are made which have an influence on the final carbon emissions (Ai et al., 2020), thermal and hygrothermal performance, indoor air quality, and the impact on the environment and human well-being. Designers aim to eliminate structure defects in the design (Zheng et al., 2018). The second step in the proposed design framework comprises, therefore, of the determination of building structure, materials, assemblies, and technical systems. The objective of this stage is to optimize the thermal and hygrothermal performance of the building, and minimize negative impacts on the environment and humans. The designer considers diverse factors, such as the energy demand of the building (in-build and operational), durability and quality of materials, risk of surface and interstitial condensation, and permanent wetting of the construction (wind-driven rain). Therefore, the composition of the roof and exterior walls should respect the outdoor and indoor situation to achieve a high energy efficiency and good hygrothermal performance of the building envelope.

Additionally, internal walls and ceilings provide a valuable area for moisture and thermal buffering. This research suggests distinguishing between the hygrothermal functions of internal elements and building envelope. This is new knowledge of this research, which allows for enhanced moisture management in buildings without affecting the primary functions of the building envelope. Practical moisture buffering (sorption and desorption of water) on a regular basis is according to the effective moisture penetration depth (EMPD) model only possible in a thin surface layer of indoor material (Cunningham, 1992; Wan et al., 2019; Woods & Winkler, 2018). Accordingly, for every hygroscopic material might be set an optimal moisture buffering thickness (Maskell et al., 2018). Therefore, the proposed hypothesis takes into account the first 10-20 mm of the top inside layer of indoor surfaces. By some materials, such as the earth is only a thin layer (4 mm) sufficient to effectively manage the indoor RH amplitude (Labat et al., 2016). Therefore, the selection of building materials and their purposeful placement represent an active approach to passive regulation of indoor RH (Brauner et al., 2016).

8.3.3 Step 3 – Detail Design and Optimization

The third step in the proposed framework by using BIM contains the incorporation of whole building energy simulation tools, such as DOE-2 or EnergyPlus (Gao et al., 2019; Maile et al., 2007; Pezeshki et al., 2019), and whole building hygrothermal simulation tools, such as WUFI Plus into the design process (Pazold et al., 2014; Winkler et al., 2014; Yu et al., 2019). The choice of building simulation programs depends on the personal experience of the designer, available hardware, and the frequency of usage (Harish & Kumar, 2016). Due to the fact that the sophisticated hygrothermal analysis by numerical simulation assesses building hygrothermal performance under real climatic conditions, diverse design options might be tested. The computer modelling WUFI Plus, which is fully compatible with BS EN 15026 (British Standards, 2007a), simulates the interactions between the building envelope, building services, outdoor conditions, and the proposed use of the building. The hygrothermal modelling is described more in detail in Chapter 5 (p. 156).

At this stage, designers aim to eliminate performance defects in the design (Zheng et al., 2018). Therefore, during the third stage of the design process, designers should consider the physical properties of the construction, humidity generated by occupancy, and external climate. The considerations include thoughts about the shape and orientation of the building in relation to the site topography, prevailing winds, sunlight, shade from the surroundings, and possible water intrusions (driving rain). The tasks in this design stage are in accordance with the recommendations of BS 5250:2011+A1:2016 *Code of Practice for Control of Condensation in Buildings* (British Standards, 2016). The assessment of the risk of surface and interstitial condensation and mould growth should follow the methods described in BS EN ISO 13788 (British Standards, 2012b). Consequently, the incorporating of moisture transport mechanisms into the decision process might prevent the underestimation of heating and cooling energy (Yu et al., 2019). Research shows that energy consumption by consideration of moisture effects might be significantly higher than by thermal simulation only (Kreiger & Srubar, 2019; Moon et al., 2014). Consequently, the employment of both thermal and hygrothermal simulation enables the evaluation of proposed construction and building materials. It supports decisions during the early stages of the design process when the costs for changes are the lowest (Gao et al., 2019).

Since the design defects are the prevalent causes of future costs during the construction process and building usage (Al-Hammad, 1997; Ali, 2013), it is vital to incorporate simulation as a means of design check and optimization. The causes of the design defects are multiple, such as a lack of knowledge, time and costs pressure, or lack of motivation (Josephson & Hammarlund, 1999; Othman et al., 2015). However, design defects are rarely mentioned in NZ, where most studies are concentrating on the defects caused by substandard workmanship or low quality of building materials (Page, 2015; Rotimi et al., 2015). Nevertheless, CIDNZ recognizes the value of defect-free housing design, and therefore, introduces the concept of concurrent engineering into the construction industry in NZ. Concurrent engineering is based on the integration and concurrency as two fundamental design principles (Zidane et al., 2015). Integrated concurrent design considers information from all lifecycle issues and uses a multidisciplinary approach to the optimization of the end-product/building. Therefore, designers concentrate on functionality and performance design in the process of construction modelling (Zheng et al., 2018). Stakeholders, particularly supply chain members and users, are integrated into the design process in the early phases, which potentially benefit the project.

The steps described in the proposed framework might need to be repeated during the design process to achieve optimal thermal and hygrothermal performance of the building. For example, simulation results reveal that the decisions about fenestration in the preliminary design (first step) might cause overheating in summer. Therefore, the design needs changes to reduce solar radiation into the building. However, every decision requires thoughts about the impact of such changes on the whole system, particularly future users. In this example, thoughts need to be given concerning daylight, shading, energy balance during winter and summer, etc. Therefore, designers should include building performance analysis into the design process. Building performance analysis enables ensuring that buildings meet the minimum performance thresholds as required by law, besides that the quality of indoor environment, sustainability and energy savings might be optimized. This requires the incorporation of other building performance domains, such as lighting, sound, ventilation, indoor air quality, and others (de Wilde, 2019).

8.3.4 Step 4 – Process Planning

The fourth step in the proposed framework is the final stage of the design process, which simultaneously constitutes the first part of the construction process. Process planning connects (in any manufacturing system) product design to manufacturing (Barzanji et al., 2020). The construction process is a manufacturing process with several specific characteristics (Dallasega et al., 2020). Therefore, the integration of process planning into CIDNZ might enhance the efficiency of the construction process, save time and costs. During this stage, the designer team finalizes the building design and specifications as the result of the optimization process of the previous three stages. Designers aim at this stage to eliminate technological defects in the design (Zheng et al., 2018). The outcome of process planning includes construction process plan and the technical documentation, such as drawings for construction, design specifications, and other necessary documentation.

Construction process planning and control in CIDNZ might implement diverse activity, location, or objects-based methodologies, such as critical path method (CPM), earned value analysis (EVA), last planner system (LPS), line of balance (LOB), Flowline, location based management system (LBMS), and building information modelling (BIM) (Dallasega et al., 2020). The choice of the project-specific and suitable methodology or their combination depends on the project planning, scheduling, and monitoring perspective of the project execution team.

8.4 Integration of the System Approach

CIDNZ seeks to complement the construction process with a complex integral system through integration spanning from design intent to successful commissioning, operation and maintenance in balance with nature and well-being of humans. Civilization resilience, expressed as the relationship between environmental systems (inclusive social, political, economic, and ecological structure) and well-being, relies on knowledge, institutions, and infrastructure (Cousins, 2016).

ISO/IEC/IEEE International Standard (2017) defines system integration as "… progressive assembling of system components into the whole system" (p. 454). The integration process of the system approach, therefore, depicts three significant features: knowing, doing, and inhabiting. CIDNZ is an interdisciplinary, multi-level, and evolving knowledge system that integrates building physics, systems and integral thinking, modelling, energy calculations, design and architecture, comfort analysis, building services design, management, and other academic fields. However, some knowledge is only possible by learning-by-doing (Ikeda, 2020). Therefore, CIDNZ encourages creativity, curiosity, innovative thinking and testing results. Especially, finding new ways to look at things and new collaborations which might bring diversity and improve solutions to existing problems. As DeKay and Bennett (2011) wrote: "… An Integral Design Theory has to be not only explanatory but also analytic, generative and evaluative" (p. 433). Equally crucial to innovative thinking is to share knowledge. Therefore, life-long education and communication of what we know supports the integration process.

CIDNZ is contemporaneously an action system. By "doing", CIDNZ integration provides a platform for change. The goal is to raise standards by framing the cross-disciplinary problem in zero-energy sustainable housing. As already mentioned earlier (in section 3.1.3), all homes in NZ have to be built to the minimum legal standards. However, the NZ Building Code is behind the international standards for comparable climate (International Energy Agency, 2017; OECD, 2017). Consequently, the costs over the whole life cycle of the houses built to the minimum legal standards are much higher than by houses built to a higher standard (Ade & Rehm, 2019). Therefore, CIDNZ advocates for code changes to promote better results.

The inhabiting of the evolving knowledge and action brings clear communication about the integral meaning of sustainability and leadership in times of change. Therefore, CIDNZ might improve on our understanding of housing design, mobilize and activate creativity, and bring innovations. The complex integral approach to design is a new way of how to adapt the built environment to the changing world. The integration of the system approach might follow a spiral development of thinking which Hokoi (2019) employed by his hygrothermal research and described as:

> Understand an issue through simplification, complicate the issue by looking at it in a complicated manner or extending the issue, and simplify the complicated issue again by looking at it with a more advanced and clearer understanding. (p. 5)

Consequently, with the look of an advanced and more precise understanding, the following section evaluates the process of transformation and integration of the system approach.

8.4.1 Evaluation of CIDNZ

Radical changes are necessary to achieve cost-effectiveness, waste and energy reduction, health enhancement of people, and harmonization of the built environment with the natural system on Earth. CIDNZ expresses a proposal on how to achieve these changes. This section addresses thoughts and questions about the evaluation of the integration process. How to evaluate a complex process which embodies not quantifiable measures? Another question accrues when we consider the value of the well-being of people. How might we measure the success of a project in these dimensions? The researcher suggests the evaluation of CIDNZ as a system that can be measured, refined, and optimized.

CIDNZ evaluation is not based on a points system because values of a multilevel and complex system may not be interchangeable or attainable due to their diverse qualitative and quantitative measures (Moore et al., 2019). Additionally, composite finite sums are markedly different from simple finite sums. The defining properties of simple finite sums and their fundamental recurrence identity are no longer valid (Alabdulmohsin, 2018). The assessment of complex system changes needs to account for time, as effects of feedback loops emerge over time (Moore et al., 2019). Therefore, the CIDNZ system inhabits a feedback loop, which leads inescapably to improvements. The feedback is supported by a sense of internal conviction that the design team is willing to find the optimal design solution. The system is based on the integral and critical thinking which seeks adversity and willingness to change not only the opinion but the rules as well. This system is supporting the belief that it exists in multiple ways to reach the goal. Therefore, the evaluation of this system forms holistic and perspectival answers to the question of how good the system serves the goal towards the well-being of people and balance with nature.

System Definition and Structure

Systems and Software Engineering Vocabulary defines a system as:

1. combination of interacting elements organized to achieve one or more stated purposes
2. product of an acquisition process that is delivered to the user
3. something of interest as a whole or as comprised of parts
4. interacting combination of elements to accomplish a defined objective
5. set of interrelated or interacting elements. (ISO/IEC/IEEE International Standard, 2017, p. 453).

The integration of the system approach will, therefore, require more research and detailed system description and analysis to determine the organization, information, hardware and software requirements, and processes of the CIDNZ system. Simultaneously, to identify relations inside of the system and to other systems. Therefore, the following section delineates the evaluation characteristics of the CIDNZ elements, which will need further development.

System Elements

This research proposes an evaluation of the system based on the four elements described in section 8.2: people, processes across all project phases, interoperable technologies, and environmental systems. The system elements are evaluated by using the integral approach with an application of perspectival mindsets. This means that the evaluation aims a multi-perspectival and holistic characteristic. This section suggests the broad characteristics of the evaluation process, which will need further development and specification in detail.

The evaluation of the people-element involves the identification and evaluation of values related to individuals, such as team members and stakeholders (inclusive users/inhabitants and supply chain members), and collectives, such as cultures and societies. Table 31 depicts some of the suggested values.

Table 31

Evaluation Characteristics of the People-Element

Individual Values	Collective Values
Qualification of team members, multi-tasking, integral and holistic thinking, life-long learning	Sharing of knowledge, education programs on all levels, praxis-oriented, management and cross-disciplinary education
Communication, collaboration, acceptance, respect, motivation, conflict management, negotiation	Financial and social benefits of cooperation, learning from past experiences
Willingness to experiment, innovate, change, ability to adapt, listen to others	Peer-review, recognition, learning by doing, new career development
Users/inhabitants values and needs reflected in the project	Cultural, esthetical, societal values and needs reflected in the project
Stakeholders cooperation, free information flow in all directions	Savings in time, costs, and material; realization of whole-life value

The involvement of stakeholders into the CIDNZ process might bring multiple values that are only partly measurable. For example, waste reduction, savings in time, costs, and materials, or improvements in the indoor environment, quality and performance of the building. However, the benefits of the complex integral system approach are often hidden in non-quantifiable values, such as enhanced well-being of inhabitants, company reputation, knowledge of team members, or non-disturbance of the natural habitat. Therefore, a complex evaluation of the processes-element belongs to the delivered values of the CIDNZ integration. Table 32 delineates evaluation characteristics for the processes across all project phases.

Table 32

Evaluation Characteristics of Processes Across all Project Phases

Processes across all project phases	Values
Organizational structure	Level of integration of information and automation systems enabling a free flow of information
Analysis of processes	Holistic, modular, procurement models, identification of best practices, flexible, configurable according to project information and needs
Analysis of supply chain and team members	Co-operation, collaboration, acceptance, respect
Involvement of stakeholders	Improvements in quality and performance of buildings, well-being of inhabitants
Professions of CIDNZ team members	Correspondence to the overall aim of the project; enabling of the cross-disciplinary approach in all of the four quadrants
Knowledge management	Enhancement of structural and process efficiency
BIM and analytical tools, such as hygrothermal modelling	Level of implementation and interoperability
Integrated Project Delivery (IPD)	Level of implementation
Lean design and construction	Improvements in the management and production, just-in-time and implementation of information technology to minimize excess labour or stock of goods
Process efficiency analysis	Influence on ROI, waste, CO_2 emissions, eco-systems, and reduction of design defects. Loop between evaluation – recognition of necessary changes – implementation of measures – evaluation

The evaluation of technologies is mainly oriented on interoperability analysis of the design and construction technology to achieve optimized solutions and higher value levels in the AEC sector. Examples of questions related to the evaluation of technologies and their interoperability are listed in Table 33.

Table 33

Evaluation Characteristics of Technologies and Interoperability

Do the implemented technologies allow for …
Experimentation and simulation of design variants over the full life-cycle?
Flexible processes and modular tools?
Interaction with users, flexible and adaptable to changing needs?
Development of interfaces to standards?
Optimization of thermal and hygrothermal performance, daylight, quality of indoor air, etc.?
Assessment of the impact on environmental systems?
Collaboration between stakeholders, sharing of models and information?
Reduction of functional, structure, performance, and technological defects?
Open BIM across all project phases and actualized as-built?
Open libraries and quality of data?

The evaluation of environmental systems aims to assess the influence of CIDNZ on all involved systems, flexibility, and balance between them. This evaluation is, therefore, complex and requires further research. Some examples of possible evaluation characteristics of environmental systems are listed in Table 34.

Table 34

Evaluation Characteristics of Environmental Systems

Questions in the evaluation of environmental systems
What the involved environmental systems represent?
How are the environmental systems formed, interconnected, and interdependent?
What is the structure of the involved environmental systems?
Is the built-system flexible to allow balance of the whole eco-system?
What are the critical sub-systems and how might be adapted or re-designed not to harm other systems, such as natural systems or people?
What is the quality of the indoor environment?

System Effectiveness

CIDNZ assessments bring together evaluations between material and immaterial, and individualist and collective values. The critical question is if the system brings some balance between these values and if the balance can be maintained during the whole life cycle. The system evaluation starts, therefore, with the system description "… defining the organization, essential characteristics and the hardware and software requirements of the system" (ISO/IEC/IEEE International Standard, 2017, p. 453).

The next step in the evaluation process represents the description of the system breakdown structure (SBS). *ISO/IEC/IEEE 24748-4:2016, Systems and Software Engineering - Life Cycle Management - Part 4: Systems Engineering Planning, 4.12* defines SBS, as cited in ISO/IEC/IEEE International Standard (2017), as:

> 1. system hierarchy, with identified enabling systems, and personnel that is typically used to assign development teams, support technical reviews, and to partition the assigned work and associated resource allocations to each of the tasks necessary to accomplish the technical objectives of the project. (p. 453)

SBS forms the basis for cost tracking and control, and supports system effectiveness analysis to determine the level of the system's performance in the intended environment (ISO/IEC/IEEE International Standard, 2017). In this point, a clear distinction between possible complementary effectiveness analyses should assist the interpretation of the analysis results. The CIDNZ evaluation and transformation include sustainability assessment, which "… always involves social systems that have their own perspectives, with meaning, values, and logics" (Alrøe & Noe, 2016, p. 5).

Therefore, two kinds of complementary assessment tools should be developed. Each of these tools has different perspectives and values. An entire CIDNZ assessment tool, describing in detail and evaluating the implementation of the complex integral system approach to building industry, and a swift CIDNZ assessment tool, allowing for the fast overview, learning, and motivation. The swift CIDNZ assessment tool will constitute a set of criteria (Table 35). The analysis of these criteria will lead to an evaluation of multiple integration aspects but no quantification nor ranking. The purpose of this tool is to support the integration process and help to identify areas that need attention or more development. Therefore, coaching for appropriate tool use should accompany the integration process of the system approach and its evaluation.

Table 35

Swift CIDNZ Assessment Tool Criteria

Stage/Step	Indicator
Construction planning	Selection of design team – cross-disciplinary and multi-tasking, collaborative
	Environmental systems analysis – nature, bio-diversity and the impact of the planned construction on these systems
	Construction site analysis, position and orientation of the building
	Knowledge and information management
	BIM
	Principles of IPD and Lean design and construction
	Process and interoperability management
	Functions, requirements, values, needs – based on all four quadrants
	A contract between major stakeholders (minimum between designer, owner/investor, and construction company)
Conceptual design	Performance requirements
	Materials information and selection, life cycle assessment (embodied CO_2 combined with durability assessment)
	Functional and physical characteristics specified
Detail design and optimization	Thermal and hygrothermal performance optimization (energy demand in kWh/m^2, ventilation, heating, thermal mass, shading, passive solar, moisture buffering, mould prevention, etc.)
	Airtightness – diffusion open materials
	Building energy, HVAC, lighting, and data management
	Daylight and quality of lighting
	Acoustics – noise reduction
	Quality of indoor air – pollutants, temperature, humidity, ventilation – well-being aspects
	Design for durability and resilience – the quality of materials, evaluation of hygrothermal relations, emissivity
	Water saving measures – use of rain water, dual waste water system allowing for recycling of water from sinks, washing machines, showers, and baths for watering the garden or flushing toilets after local treatment
	Energy sources – passive measures, renewable energy

Stage/Step	Indicator
Process planning	Project management – inter-disciplinary knowledge
	Supply chain optimization, just-in-time
	Waste management – reducing and recycling waste
	Testing of airtightness, energy performance, quality of indoor air, water and light, thermal and humidity comfort, acoustics, visual and esthetic comfort
	BIM – as-built data actualization

The CIDNZ assessment tools include some aspects which are not used by Green Public Procurement[7], such as nature and bio-diversity, and passive building design strategies (Braulio-Gonzalo & Bovea, 2020). Examples of passive building design strategies include the use of solar energy, thermal mass, and natural ventilation to limit energy demand, and use of roof overhang or vegetation for shading (DeKay & Brown, 2014). The passive measures for hygric indoor climate regulation, such as moisture buffering by hygroscopic materials, are addressed in section 3.2. These measures can help to minimize or eliminate energy use for air conditioning technology while maintaining indoor comfort (Stopp et al., 2016).

The CIDNZ focusses on improving the housing quality in NZ. This research understands buildings as man-made environmental systems, and therefore, the changes go beyond technical and organizational issues. By viewing CIDNZ as a four-quadrant holon, the assessment of system effectiveness includes all aspects of the system phenomenon. Since the people aspect is primary, change should be built on the willingness, enthusiasm, and knowledge of stakeholders and end users. Therefore, CIDNZ system effectiveness depends on the ability to learn from existing theories and approaches, past experiences, scientific research, and nature.

[7] Green Public Procurement was developed by EU and is defined as “a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life-cycle when compared to goods, services and works with the same primary function that would otherwise be procured” (COM 400. Public procurement for a better environment, 2008, as cited in Braulio-Gonzalo et al., 2020, p. 1).

8.5 Conclusions

The CIDNZ approach is of transformation, in which the first phase is of strong transition. The strong transition involves the integration of science in diverse fields, identification of problems, adaptation and redesign of critical systems in the AEC industry, and management of the transformation process.

The suggested integration of scientific achievements, available tools, and partial knowledge into the design process of houses in a holistic and integral way - named Complex Integral Design New Zealand (CIDNZ) - is designed to change the quality of houses. The proposed framework is introducing a new perspective on how to design warmer, drier, and healthier houses for the NZ context. CIDNZ encourages architectural and engineering design to adopt a new way of thinking, which is based on integrative and interdisciplinary principles. The perspective of the design process transforms from originally cost-oriented view (cheap and fast built) to a complex system to create healthy, energy-efficient, zero-energy buildings without a negative influence on the environment and in harmony with life and nature.

The end-users might apply the presented CIDNZ system in stages or, alternatively, start with an encouragement of complex integral thinking. This way, the principles might be easily adapted to the existing business structure and develop with time on the basis of “learning by doing”. However, the application of the CIDNZ principles requires a guided and encouraged transformation process. The core of the transformation lies in the values and worldview which each stakeholder holds. Consequently, CIDNZ introduces a novel understanding of sustainability in housing. Sustainable system succours to establish and maintain a balance between individuals, groups, society, and existing ecosystems. Therefore, the future housing (created by the CIDNZ principles) will be durable, less disturbing to the natural habitat, less polluting the environment, constructed from high quality, recyclable or reusable materials, have a healthy indoor environment, and enhancing the quality of life. The proposed CIDNZ framework is flexible, allowing the addition of new perspectives. It focuses on people by respecting a broad spectrum of human needs, inclusive physical, psychological, social, and spiritual. Therefore, the housing will enhance humans’ individual and social lives, harmonize with larger environmental systems, and be adaptive to changing needs.

Chapter 9 Conclusions

Motto: “Building art is a synthesis of life in materialized form. We should try to bring in under the same hat not a splintered way of thinking, but all in harmony together” (Alvar Aalto, as cited in Demakis, 2012, p. 11).

The aim of this thesis has been to understand the relationship between BIM and sustainability and to approach the design process from systems engineering methodologies. This thesis evaluated the risks of underestimating hygrothermal relations in buildings and suggested possible solutions to design energy efficient, healthy, and durable buildings. This research focused on possible ways how to improve the quality of houses in NZ, particularly hygrothermal performance. Suggested BIM innovations and the proposed implementation strategy are aiming to find answers to the questions in the time when they are needed, and prevent the building performance design defects. Research questions have been answered in two distinctive parts. In Chapters 3 – 7, the researcher analysed moisture related issues in NZ housing and requirements for hygrothermal simulation. The identified challenges associated with undertaking effective hygrothermal assessment led to the suggestion of the incorporation of a hygrothermal model into BIM. In Chapter 8, the researcher applied a system approach to the design process and proposed a framework to design warmer, drier, and healthier houses for the NZ context. The introduced Complex Integral Design New Zealand (CIDNZ) delineated a new way of the design process based on integral, complex, and systems thinking.

9.1 Rationale and Significance of the Study

This thesis theme was born from the life-long researcher’s passion for healthy living. The aim to provide warmer, drier, and healthier houses for New Zealanders without a negative impact on nature pertained as the motivation to search for new ways. Therefore, this thesis examined the moisture related issues in NZ, conditions, and requirements for BIM enabling assessment of construction projects regarding hygrothermal relations, calculations and optimization. This theoretical knowledge has been transferred into the second part of the thesis, which suggested a new system-based design process promoting interdisciplinary, holistic, and integral approach.

Although these parts form the whole, they differ in the chosen epistemology and ontology. The in Chapter 8 implemented integral theory is all-inclusive. This research has been rooted in objectivism and used quantitative methods and fundamentally qualitative causal reasoning. For the data analysis and the evaluation of relations between variables, this study used a combination of statistical methods and deductive reasoning.

The first part of the thesis demonstrated with the in-field and virtual experiments that materials used in the building envelope have a significant influence on the hygrothermal performance of the building. Consequently, the design of sustainable buildings cannot be achieved without hygrothermal modelling. Therefore, the BIM expansion in terms of the hygrothermal assessment of materials and whole buildings might prevent moisture related problems. The second part of the thesis presented an alternative perspective from which we look at the task of how to build better, healthier, warmer, and safer houses. From this perspective, the design and construction process and its end-product, buildings, form open systems because they interact with their environment and other systems. Therefore, the holistic approach to the sustainability of the construction process pertained the whole project.

The inspection of theoretical and practical understanding of the objective revealed several gaps in the literature. Apart from energy modelling, sustainability assessment has a minimal presence in the used BIM tools (Gao et al., 2019; Romanska-Zapala et al., 2019). A gap in knowledge exists of how to enable BIM to participate in a design process that pursues a holistic approach, particularly in an optimal design with hygroscopic materials (Wan et al., 2019). Additionally, the research on the practical incorporation of hygrothermal modelling and mould growth risk into BIM is limited (Fedorik et al., 2017). In the praxis, a gap exists between the calculated and the real as-built energy performance (Kubilay et al., 2019; Zou et al., 2019). Another knowledge gap persists on the parameters and specifications that are needed for standardized data libraries, practical solutions for BIM, and simulation models (Daniotti et al., 2020a). Therefore, the use of these viable tools for effective decision-making process regarding sustainability and energy performance of the building is limited. Besides of integral architecture (DeKay & Bennett, 2011; Zeiler, 2015), the literature about a complex integral system in the design and construction process is missing.

This thesis addressed the mentioned gaps in knowledge by going from the analysis of theory to facts (results of experiments) and finally, practical implications. The practical implications, such as proposed BIM extension and framework for designers, enhanced the existing knowledge. The integration of hygrothermal modelling into BIM and the implementation of the CIDNZ system might bring improvements to the design in the phase of the project when, as Gao et al. (2019) sad, the costs for changes are the lowest. The introduction of integral thinking to the design process has the potential to revolutionize the way how the housing needs will be satisfied. The researcher inevitably sees nature and humans as one ever-changing and adjusting system. If people construct their houses with respect to nature and themselves, the built environment would be in harmony with the life on the Earth.

The findings of this study are of value for practitioners and policy makers. Practitioners, especially architectural designers and engineers, construction consulting companies and developers, are likely to get vital information concerning how to improve the quality and durability of buildings radically. The information is of the possible implementation of hygrothermal modelling into the design process (BIM) and the paradigm shift in the AEC industry. The companies involved in architectural design and construction might benefit from the application of the CIDNZ principles in all stages of the construction process. The consequent practical application of these principles and integral thinking might eliminate or reduce the design defects and lead consequently to the reduction of costs involved in their rectification. There are several feasible advantages in the practical application of the proposed CIDNZ methodology and holistic principles. Therefore, policy makers might gain different insights on how to change the regulations in the assessing field of building performance. The mutual comprehension of moisture, air, energy, health, and environmental issues in the complex integral way would open a new possibility in the necessary improvement of housing in NZ.

9.2 Research Scope

The writing process of this thesis merely enhanced the researcher's knowledge and gradually awoke a novel way of thinking. Before the researcher read the literature or collected and analysed the empirical data, she believed that dynamic simulations would solve the moisture problems in NZ. This fundamental conviction was based merely on her theoretical and practical knowledge about sustainable buildings and building physics. However, the critical study of the academic literature revealed that the problematic of low-quality housing is complex and affected by several factors from which the physical laws typically represent a significant part. Therefore, the research scope encompassed integral thinking about sustainability in the AEC industry.

This thesis explored the determined research area from an individual and collective level which formed the whole. The test houses provided a suitable environment for the in-field testing on a praxis-oriented individual level. The testing in real houses revealed the levels of RH reached in occupied NZ houses by different internal envelope materials. Simultaneously, the data demonstrated the impact of different building materials used on the indoor side of walls and the presence/absence of airtightness membrane on the hygrothermal performance of buildings. The simulation experiment, based on the identical parameters, moved the empirical investigation to the virtual modelling. This enabled the analytical study to compare the results of two different experiments and draw conclusions. The requirements for undertaking an effective hygrothermal assessment of houses during the early design stages have been characterized. Consequently, the study named the physical qualities of building materials which influence hygrothermal performance most significantly.

The collective level of the research contained a rational and integral stage. The study in the rational phase investigated interoperability requirements and the possible ways how to incorporate hygrothermal modelling into BIM adequately. Beside the specification of requirements for integration of hygrothermal modelling into BIM, the study showed possible ways how to improve building sustainability based on effective hygrothermal simulation. The rational stage led to the description of how the BIM-integrated hygrothermal simulation tool might improve the building performance and reduce errors affecting the hygrothermal performance. For the integral stage, this research applied the system approach based on the holistic and integral view. Buildings, as whole systems, can best be understood as holons interacting with people and the local environment. The integral phase of the research, therefore, was not exclusive. This thesis built on all the previous stages in the development of knowledge and considered multiple system elements and their complex interrelationships in the context of the whole. From this essential point, the system changes in the design process of housing were proposed.

9.3 Summary of Findings and Limitations

This research experienced limitations on the individual and collective level of the research scope. The individual level limitations related to the accuracy of any data. The collective level limitations related to the research problem and purpose – to specify the requirements for integration of hygrothermal simulation into BIM and propose a framework for designers. This research experienced challenges due to the available technical equipment and the nature of the quasi-experiment. The experiment has been influenced by the uncontrollable independent variables, such as weather, initial RH and temperature. The significant challenge of the experiment has been malfunctions of the technical equipment that occurred during the validation process of the testing. Therefore, the researcher merely changed the original quasi-experiment design from simultaneous to switching mode. Consequently, different outside conditions have been inevitably attending each setting. However, the actual indoor and weather data have been available. Therefore, this research carried out the analysis of covariance (ANCOVA) to eliminate the influence of different outdoor conditions during the experiment. The quasi-experiment was deliberately chosen to merely demonstrate the influence of used building materials on indoor RH in a real-life situation.

The experienced constraints in the simulation process have been of the quality of input data and diffusive model calculations. High quality and reliable hygrothermal data have not been available for most NZ building materials. The WUFI materials library contains only the typical materials and products used in Germany and the USA. The limited availability of hygrothermal data simultaneously represented a challenge to the successful interoperability between BIM and hygrothermal models. Additionally, the researcher was aware that the issues of BIM extension contain a hidden dilemma between the amount and quality of necessary information and time for its implementation process (CPU time). Another impediment this research was experienced by the comparison of measured and simulated data. This issue is well known. Busser et al. (2019), for example, argued that these limitations might be unwittingly caused by the fact that the classic diffusive models neglect transport by air convection and nonequilibrium behaviour between water vapour and bound water.

Despite all these limitations, the results demonstrated the influence of building materials and construction on indoor RH levels. The employment of hygrothermal modelling in the design process, therefore, might assist the decisions about materials that influence the hygrothermal performance of the building. Therefore, this thesis revealed the reasons for necessary interoperability between hygrothermal modelling and BIM and evaluated the requirements for the simulation. As a result of the interoperability and simulation analysis, the research suggested multiple ways for the incorporation of the hygrothermal model into BIM. The researcher selected for the analysis two examples of software - Revit representing BIM and WUFI Plus a whole building hygrothermal simulation model.

The presented results of quasi and virtual experiments proved the influence of used construction materials on the hygrothermal performance of buildings. Therefore, the incorporation of hygrothermal modelling into BIM is crucial to the design of sustainable buildings. The sustainability understanding in this thesis has been based on humanistic, systems, holistic, and integral values that lead to harmony between individuals, groups, society, and the existing ecosystems. Such novel ways of the sustainability perception in the AEC industry accompanied the developing process of CIDNZ. The healthy housing supports physical, mental and social well-being. Therefore, CIDNZ recommends besides the energy, costs, and environmental aspects, the evaluation of the quality of buildings.

The thesis introduced the systems approach to the comprehension of dwellings in their functions and interrelations with occupants and the environment. Simultaneously, the system approach was applied to the design, construction, usage, and decommissioning of buildings. Therefore, this thesis introduced an alternative perspective from which we look at the task of how to construct healthier, warmer, and safer houses. It illustrated the viable applications of hygroscopic materials respectively and the advantages of moisture buffering in the NZ context. Finally, by introducing CIDNZ systems approach, the thesis proposed a strategic direction to overcome the remaining issues.

9.4 Recommendations for Further Research

For further research, the thesis recommends replicating the in-field experiment with more sophisticated humidifiers in both houses simultaneously for each scenario. Although this testing would eliminate the difference in external conditions, there would be still a diverse weather situation for each testing scenario. However, this would satisfactorily address the role of the airtightness membrane in the hygrothermal performance that was uncovered by this academic study. The AEC industry would equally benefit from knowledge about the long-term hygrothermal performance of the houses inclusive in-wall measurements.

Based on the simulation experience, further modelling of diverse scenarios with various hygroscopic materials would be beneficial. The experimental results presented in the form of a table might provide a valuable tool for building professionals. Consequently, further research of the complex building-scale benefits of hygroscopic materials, especially the energy-saving and cooling potential of moisture buffering might enrich the results of this doctoral thesis. An additional laboratory testing of hygrothermal characteristics of building materials available in NZ will support the more expanded use of hygrothermal modelling in the design praxis and theory. Simultaneously, the compiling of a data bank with accurate moisture related physical data for every material used in construction would enhance the quality of simulation results. Further research on the programming of suggested incorporation of hygrothermal modelling into BIM might undoubtedly support the automation of this process. Simultaneously, it would enable extensive employment of simulation in the design praxis. However, the successful application of hygrothermal modelling is coupled with an adequate education for building professionals. The simulation tool might positively enhance the quality of housing if its use is accompanied by a more in-depth knowledge of building physics and materials. Therefore, the researcher recommends the consistent implementation of building physics into the architectural designers' curriculum of NZ universities.

The implementation of the system approach into the AEC industry will require more research, comprehensive description and analysis to determine the actual processes of CIDNZ. The practical application of this system might benefit from further research on the organization, information management, and hardware and software requirements in the proposed CIDNZ system. The delineated evaluation characteristics of the CIDNZ elements will necessitate further development, particularly to identify relations inside of the system and to other systems in the holarchy. Therefore, additional research on the complex evaluation of environmental systems and the influence of CIDNZ on all involved systems might build on the thesis inferences.

9.5 Contribution of the Research

This thesis contributed to the present knowledge in multiple ways. The findings of the research confirmed the hypothesis: "If materials used in the building envelope have a significant influence on the hygrothermal performance of the building, then the design of sustainable buildings cannot be done without hygrothermal modelling." In an interdisciplinary and systematic approach grounded in integral thinking, this thesis focused on BIM innovation and its implementation strategy. The key contribution of this research is the introduction of a new perspective on how to design energy efficient, healthy, and durable buildings for the NZ context. Suggested solutions require a restructuration of the whole design and construction process. Hygrothermal modelling incorporated in BIM might allow for automated assessment of the hygrothermal performance and facilitate the optimization of the design. The idea is to apply BIM integrated hygrothermal modelling in several design stages. This would allow for competent decisions regarding environmental impact and sustainability of new buildings and retrofits to prevent unintended moisture related problems during construction and usage of the building.

The research findings confirmed the existing theory in moisture buffering and simultaneously challenged the prevalent orientation of official policies on energy performance. The challenging came from the application of systems approach to the construction process and buildings as integral parts of environmental systems. In this sense, hygrothermal modelling merely represents an element of the sustainable design. Holistic view resting upon construction engineering, architecture, building physics, biology, building biology, chemistry, psychology, and environmental studies might reveal the complex interrelations in buildings. This research instigated the holistic and integral thinking into the housing design, therefore, contributed to the existing theory.

This thesis demonstrated the significance and feasibility of purposeful choice and placement of building materials to design and build healthier and sustainable dwellings. With the analysis of the hygrothermal performance of NZ houses, the thesis contributed to the local practical knowledge. The findings of RH development in real houses merely demonstrated the influence of different materials in diverse construction types (existence or non-existence of airtightness membrane). Therefore, hygrothermal modelling and the decisive use of hygroscopic materials might assist the sustainable design in NZ.

CIDNZ arose as a consequence of the unique context of this thesis. It integrates scientific achievements, available tools, and partial knowledge into the design process of houses in a holistic way. CIDNZ proposes a gradual development of the integrative and interdisciplinary approach in architectural and engineering design through a transformation process. The flexibility of the proposed framework might encourage the addition of alternative perspectives. Consequently, the design process might shift the forefront from prevailing cost-oriented aim for cheap and fast built to long-term energy and cost-efficient, durable, and healthy buildings. The discerning characteristic of these buildings will be their relation to the environment based on balance and harmony with nature. The proposed CIDNZ focuses on people by respecting a broad spectrum of human needs, inclusive physical, psychological, social, and spiritual. Therefore, the housing will enhance humans' individual and social lives and be adaptive to changing needs.

The proposed CIDNZ process accommodates the capacity to integrate diverse perspectives into a unified framework. The suggested framework might lead towards a conscious balance between the freedom to decide what people like (equal outcome) and the economic and environmental factors (equal opportunity). Therefore, the CIDNZ framework might allow for sustainable housing in harmony with the environment and shifts in values and perspectives.

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Appendix A Blower Door Test Results for Test House and Control House

BUILDING LEAKAGE TEST

Date of Test: 27/04/2017
Customer:

Test File: control 1 pressur
Technician: Roger Rob
Project Number:

Building Address: Control- pressure

Test Results

1. Airflow at 50 Pascals: (50 Pa = 0.2 w.c.)	1317 CFM50 (+/- 2.9 %) 8.20 ACH50
2. Leakage Area:	72.5 in2 LBL ELA @ 4 Pa
3. Building Leakage Curve:	Flow Coefficient (C) = 102.2 (+/- 20.0 %) Exponent (n) = 0.654 (+/- 0.056) Correlation Coefficient = 0.99639
4. Test Settings:	Test Standard: RESNET Multi-Point Test Test Mode: Pressurization
5. Accuracy Level	Standard Level of Accuracy Test

Infiltration Estimates

1. Estimated Average Annual Infiltration Rate:
2. Estimated Design Infiltration Rate:

Cost Estimates

1. Estimated Cost of Air Leakage for Heating:
2. Estimated Cost of Air Leakage for Cooling:

BUILDING LEAKAGE TEST Page 2 of 4

Date of Test: 27/04/2017 Test File: control 1 pressur

Building Information

Volume	9640
Surface Area	
Floor Area	1227
Height	8
# of Bedrooms	
# of Occupants	
Year of Construction	2011
Wind Shield	M

Location Climate Information

Ventilation Weather Factor	
Energy Climate Factor	
Heating Degree Days	
Cooling Degree Days	
Design Winter Wind Speed	
Design Summer Wind Speed	
Design Winter Temp Diff	
Design Summer Temp Diff	

Heating and Cooling Cost and Efficiency Information

Heating Fuel	Gas
Heating Fuel Cost	
Heating Efficiency %	
Cooling Fuel Cost	
Cooling SEER	

Equipment Information

Type	Manufacturer	Model	Serial Number	Custom Calibration Date
Fan	Energy Conservatory	Model 4 (230V)	CE4125	-
Micromanometer	Energy Conservatory	DG700	35413	28/08/2012

BUILDING LEAKAGE TEST   Page 3 of 4

Date of Test: 27/04/2017 Test File: control 1 pressur

Pressurization Test:

Environmental Data

Indoor Temperature (°F)	Outdoor Temperature (°F)	Altitude (ft)
68.0	65.0	100.0

Data Points - Automated Test (TT 4.0.52.3)

Nominal Building Pressure (Pa)	Baseline Adjusted Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (cfm)	Adjusted Flow (cfm)	% Error	Fan Configuration
-1.2	n/a	n/a				
62.7	63.6	92.6	1514	1519	-1.5	Ring A
53.7	54.6	76.8	1380	1384	-0.7	Ring A
46.2	47.1	63.1	1252	1256	-0.8	Ring A
40.9	41.7	55.6	1176	1180	0.8	Ring A
33.6	34.4	46.0	1071	1075	4.1	Ring A
27.6	28.4	32.0	894	898	-1.5	Ring A
22.5	23.4	27.0	823	826	3.0	Ring A
16.8	17.7	185.4	644	646	-3.2	Ring B
-0.5	n/a	n/a				

Time Averaging Period: 10

Deviations from Standard RESNET Multi-Point Test - Test Parameters

None

BUILDING LEAKAGE TEST   Page 4 of 4

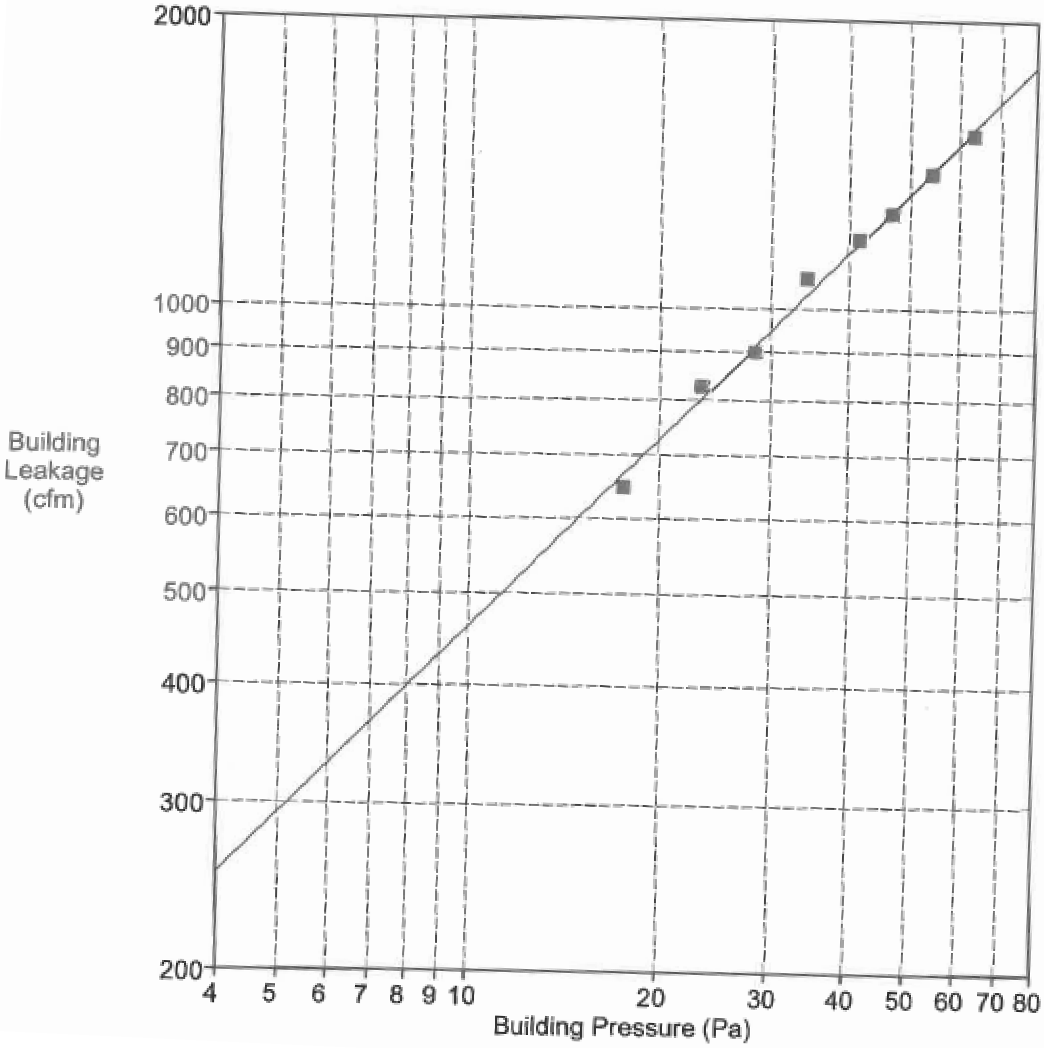
Date of Test: 27/04/2017 Test File: control 1 pressur

Comments

As for control 1 depressurised

Building Leakage Curve

Date of Test: 27/04/2017 Test File: control 1 pressur



BUILDING LEAKAGE TEST

Date of Test: 27/04/2017

Customer:

Test File: control 1 depress

Technician: Rog Rob

Project Number:

Building Address: Control Building

Test Results

1. Airflow at 50 Pascals: (50 Pa = 0.2 w.c.)	1331 CFM50 (+/- 1.8 %) 8.28 ACH50
2. Leakage Area:	73.2 in2 LBL ELA @ 4 Pa
3. Building Leakage Curve:	Flow Coefficient (C) = 96.6 (+/- 56.5 %) Exponent (n) = 0.670 (+/- 0.144) Correlation Coefficient = 0.99753
4. Test Settings:	Test Standard: RESNET Multi-Point Test Test Mode: Depressurization
5. Accuracy Level	Standard Level of Accuracy Test

Infiltration Estimates

1. Estimated Average Annual Infiltration Rate:
2. Estimated Design Infiltration Rate:

Cost Estimates

1. Estimated Cost of Air Leakage for Heating:
2. Estimated Cost of Air Leakage for Cooling:

BUILDING LEAKAGE TEST Page 2 of 4

Date of Test: 27/04/2017 Test File: control 1 depress

Building Information

Volume	9640
Surface Area	
Floor Area	1227
Height	8
# of Bedrooms	
# of Occupants	
Year of Construction	2011
Wind Shield	L

Location Climate Information

Ventilation Weather Factor	
Energy Climate Factor	
Heating Degree Days	
Cooling Degree Days	
Design Winter Wind Speed	
Design Summer Wind Speed	
Design Winter Temp Diff	
Design Summer Temp Diff	

Heating and Cooling Cost and Efficiency Information

Heating Fuel	Gas
Heating Fuel Cost	
Heating Efficiency %	
Cooling Fuel Cost	
Cooling SEER	

Equipment Information

Type	Manufacturer	Model	Serial Number	Custom Calibration Date
Fan	Energy Conservatory	Model 4 (230V)	ce4216	-
Micromanometer	Energy Conservatory	DG700	35413	28/08/2012

BUILDING LEAKAGE TEST Page 3 of 4

Date of Test: 27/04/2017 Test File: control 1 depress

Depressurization Test:

Environmental Data

Indoor Temperature (°F)	Outdoor Temperature (°F)	Altitude (ft)
68.0	65.0	100.0

Data Points - Automated Test (TT 4.0.52.3)

Nominal Building Pressure (Pa)	Baseline Adjusted Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (cfm)	Adjusted Flow (cfm)	% Error	Fan Configuration
0.4	n/a	n/a				
-59.4	-60.1	91.3	1503	1496	-0.6	Ring A
-53.5	-54.2	81.9	1425	1418	1.0	Ring A
-47.6	-48.4	68.8	1307	1301	-0.0	Ring A
-42.2	-43.0	58.3	1204	1198	-0.3	Ring A
1.1	n/a	n/a				

Time Averaging Period: 10

Deviations from Standard RESNET Multi-Point Test - Test Parameters

- Fewer than 8 data points were taken.

BUILDING LEAKAGE TEST Page 4 of 4

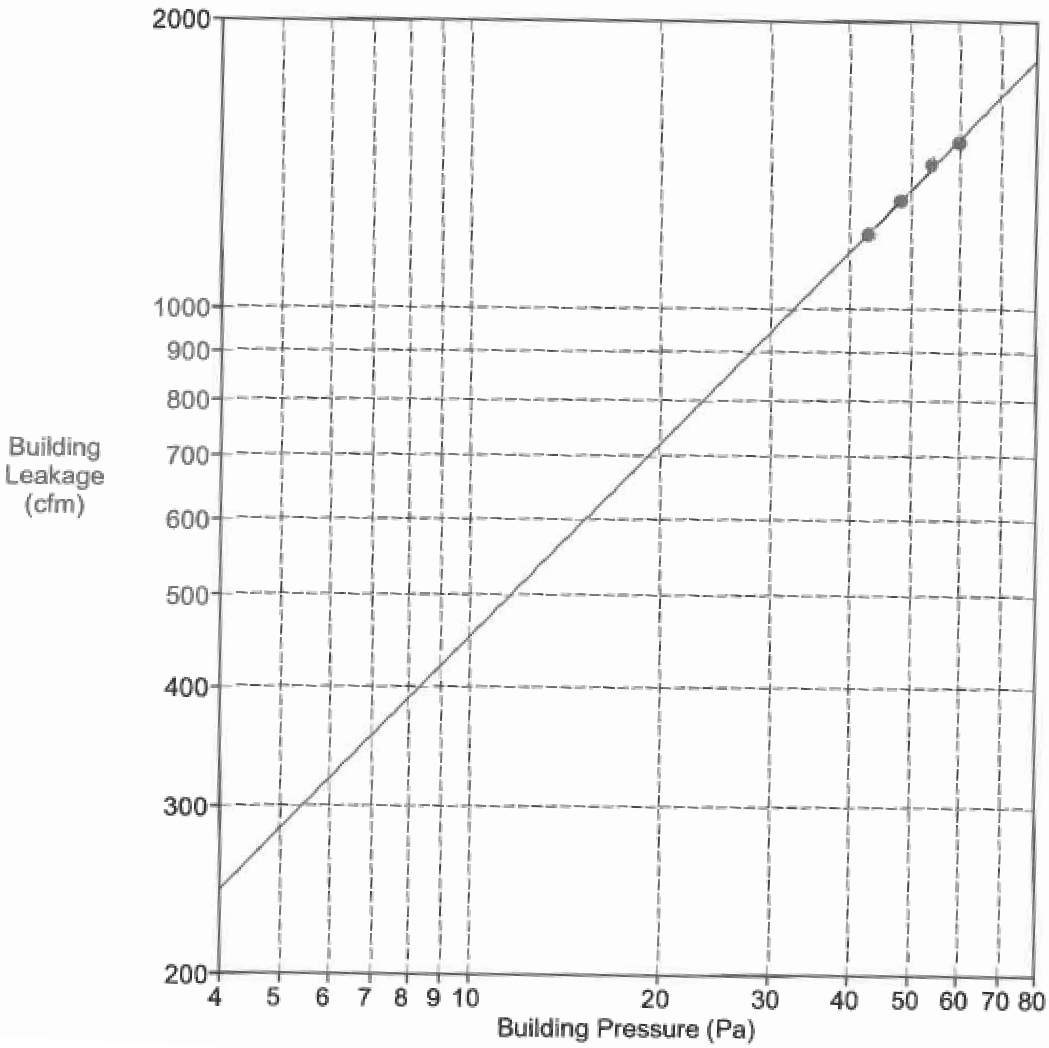
Date of Test: 27/04/2017 Test File: control 1 depress

Comments

MVHR and bathroom vents sealed. Two openings in wall

Building Leakage Curve

Date of Test: 27/04/2017 Test File: control 1 depress



BUILDING LEAKAGE TEST

Date of Test: 24/11/2016
Test File: airtight new location 2
Customer:

Technician: rob Roger
Project Number: airtight test house 2
Building Address: airtight test
carpark opp Bldg 111

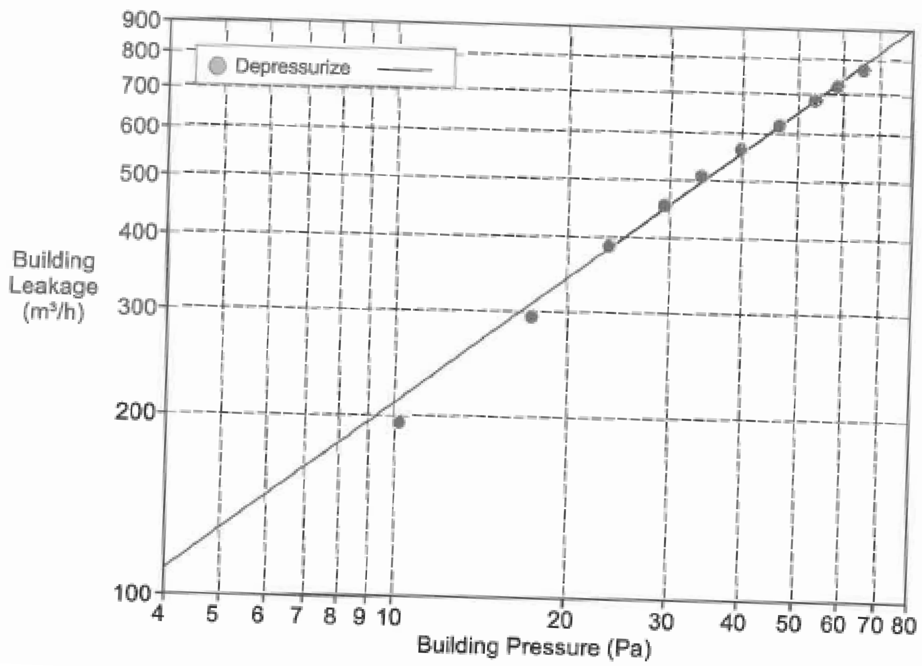
Test Results at 50 Pascals:

V50: m³/h Airflow	650 (+/- 1.6 %)
n50: 1/h Air Change Rate	2.37
w50: m³/h/m² Floor Area	5.70
q50: m³/h/m² Envelope Area	1.89

Leakage Areas: 234.3 cm² (+/- 6.4 %) Canadian EqLA @ 10 Pa or 0.68 cm²/m² Surface Area
119.0 cm² (+/- 10.1 %) LBL ELA @ 4 Pa or 0.35 cm²/m² Surface Area

Building Leakage Curve: Air Flow Coefficient (Cenv) = 41.8 m³/h/Paⁿ (+/- 15.8 %)
Air Leakage Coefficient (CL) = 41.7 m³/h/Paⁿ (+/- 15.8 %)
Exponent (n) = 0.702 (+/- 0.041)
Correlation Coefficient = 0.99743

Test Standard: EN 13829
Test Mode: Depressurization
Type of Test Method: A
Regulation complied with:



BUILDING LEAKAGE TEST Page 2 of 4

Date of Test: 24/11/2016 Test File: airtight new location 2

Building Information

Volume (m³)	274
Surface Area: (m²)	343
Floor Area: (m²)	114
Height (m)	2.4
Uncertainty of Dimensions (%)	5
Year of Construction	2011
Type of Heating	
Type of Air Conditioning	
Type of Ventilation	None
Building Wind Exposure	Partly Exposed Building
Wind Class	Light Air

Equipment Information

Type	Manufacturer	Model	Serial Number	Custom Calibration Date
Fan	Energy Conservatory	Model 4 (230V)	CE 4125	Default

BUILDING LEAKAGE TEST Page 3 of 4

Date of Test: 24/11/2016 Test File: airtight new location 2

Depressurization Test:

Environmental Data

Indoor Temperature (°C)	Outdoor Temperature (°C)	Barometric Pressure (Pa)
25.3	23.0	101325.0

Baseline Pressure Data

Pre-Test			Post-Test		
$\Delta p_{0,1-}$	$\Delta p_{0,1+}$	$\Delta p_{0,1}$	$\Delta p_{0,2-}$	$\Delta p_{0,2+}$	$\Delta p_{0,2}$
-0.8	0.9	-0.1	-0.7	0.7	-0.3

Data Points

Nominal Building Pressure (Pa)	Baseline Adjusted Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (m³/h)	Adjusted Flow (m³/h)	% Error	Fan Configuration
-0.1	n/a	n/a				
-65.6	-65.4	92.1	773	771	-1.7	Ring B
-59.1	-58.8	81.2	726	724	-0.5	Ring B
-53.9	-53.7	72.5	686	685	0.2	Ring B
-46.7	-46.5	59.7	623	622	0.7	Ring B
-40.1	-39.9	49.4	567	566	2.0	Ring B
-34.4	-34.1	40.0	510	509	2.5	Ring B
-29.7	-29.5	31.8	455	455	1.4	Ring B
-23.8	-23.6	23.1	389	388	1.2	Ring B
-17.6	-17.4	198.2	295	295	-4.8	Ring C
-10.5	-10.2	89.0	195	195	-8.7	Ring C
-0.3	n/a	n/a				

Deviations from Standard EN 13829 - Test Parameters

None

BUILDING LEAKAGE TEST **Page 4 of 4**

Date of Test: 24/11/2016 Test File: airtight new location 2

Comments

as for test1

BUILDING LEAKAGE TEST

Date of Test: 24/11/2016
Test File: airtight new location pressurised
Customer:

Technician: rob roger
Project Number: airtight test house 2 pressuirised
Building Address: air tight
Carpark opp Bldg111

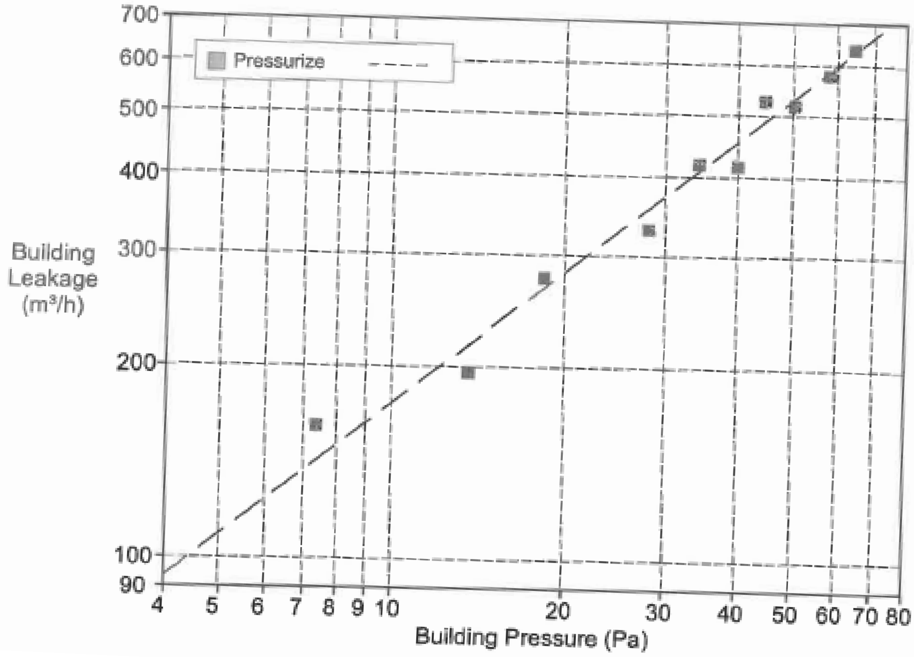
Test Results at 50 Pascals:

V50: m³/h Airflow	528 (+/- 4.3 %)
n50: 1/h Air Change Rate	1.93
w50: m³/h/m² Floor Area	4.63
q50: m³/h/m² Envelope Area	1.54

Leakage Areas: 195.3 cm² (+/- 15.4 %) Canadian EqLA @ 10 Pa or 0.57 cm²/m² Surface Area
100.6 cm² (+/- 24.4 %) LBL ELA @ 4 Pa or 0.29 cm²/m² Surface Area

Building Leakage Curve: Air Flow Coefficient (Cenv) = 36.3 m³/h/Paⁿ (+/- 38.0 %)
Air Leakage Coefficient (CL) = 36.1 m³/h/Paⁿ (+/- 38.0 %)
Exponent (n) = 0.686 (+/- 0.100)
Correlation Coefficient = 0.98451

Test Standard: EN 13829
Test Mode: Pressurization
Type of Test Method: A
Regulation complied with:



BUILDING LEAKAGE TEST Page 2 of 4

Date of Test: 24/11/2016 Test File: airtight new location pressurised

Building Information

Volume (m^3)	274
Surface Area: (m^2)	343
Floor Area: (m^2)	114
Height (m)	2.4
Uncertainty of Dimensions (%)	5
Year of Construction	
Type of Heating	
Type of Air Conditioning	
Type of Ventilation	None
Building Wind Exposure	Partly Exposed Building
Wind Class	Light Air

Equipment Information

Type	Manufacturer	Model	Serial Number	Custom Calibration Date
Fan	Energy Conservatory	Model 4 (230V)	CE4125	Default

BUILDING LEAKAGE TEST Page 3 of 4

Date of Test: 24/11/2016 Test File: airtight new location pressurised

Pressurization Test:

Environmental Data

Indoor Temperature (°C)	Outdoor Temperature (°C)	Barometric Pressure (Pa)
25.3	23.0	101325.0

Baseline Pressure Data

Pre-Test			Post-Test		
$\Delta p_{0,1-}$	$\Delta p_{0,1+}$	$\Delta p_{0,1}$	$\Delta p_{0,2-}$	$\Delta p_{0,2+}$	$\Delta p_{0,2}$
-3.3	0.0	-3.1	-1.9	0.1	-1.8

Data Points

Nominal Building Pressure (Pa)	Baseline Adjusted Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (m^3/h)	Adjusted Flow (m^3/h)	% Error	Fan Configuration
-3.1	n/a	n/a				
62.2	64.7	61.6	633	637	1.1	Ring B
55.7	58.2	50.8	575	579	-1.1	Ring B
47.8	50.3	40.7	515	519	-2.2	Ring B
42.2	44.6	42.1	523	527	7.9	Ring B
37.6	40.1	26.2	414	417	-8.2	Ring B
31.9	34.3	26.6	416	419	2.8	Ring B
25.6	28.1	243.2	328	330	-7.1	Ring C
16.0	18.4	172.2	275	277	3.8	Ring C
11.2	13.6	88.5	195	196	-9.4	Ring C
4.9	7.4	60.6	160	161	13.7	Ring C
-1.8	n/a	n/a				

Deviations from Standard EN 13829 - Test Parameters

- The minimum building pressure (not baseline adjusted) is less than 5 times one of the measured baseline pressure values.
- The minimum building pressure (not baseline adjusted) is less than 10 Pa.

BUILDING LEAKAGE TEST **Page 4 of 4**

Date of Test: 24/11/2016 Test File: airtight new location pressurised

Comments

as before but pressurised

Appendix B MgO Boards Laboratory Test Report

PRI

CONSTRUCTION MATERIALS

TECHNOLOGIES

LABORATORY TEST REPORT

Report for: Magnum Building Products
10150 Highland Manor Drive
Suite 200
Tampa, FL 33610

Attention: Ed Gilbert

Product Name:	Magnum® Board (3 mm & 18 mm)	**Manufacturer:**	Magnum Building Products
Date Received:	July 20, 2011	**Source:**	Magnum Building Products
PRI Project No.:	MBP-004-02-01	**Dates Tested:**	July 26 - August 10, 2011

Subject: Determine the water vapor transmission performance of 3 mm & 18 mm Magnum® Board in accordance with **ASTM E 96**: ***Standard Test Methods for Water Vapor Transmission of Materials***.

Test Methods: Testing was completed as described in ASTM E 96 / E 96M -05: *Standard Test Methods for Water Vapor Transmission of Materials*. Procedure A, Desiccant Method, and Procedure B, Water Method, were conducted at 73.4±3.6°F and 50±2% RH. Test specimens were excised from a larger, client-supplied piece of material and sealed along sides and to the cup with wax.

Product Sampling: PRI-CMT received product samples on July 20, 2011. PRI-CMT feels that the material tested is representative of the standard manufactured product for which recognition is sought.

PRI Construction Materials Technologies LLC 6408 Badger Drive Tampa, FL 33610 Tel: 813-621-5777 Fax: 813-621-5840 e-mail: materialstesting@pricmt.com WebSite: http://www.pricmt.com

Results:

Table 1. ASTM E 96 results for 3 mm Magnum® Board in U.S. Customary Units

Test Sample	Test Method	Property	Specimen Results							Requirement
			#1	#2	#3	#4	#5	Avg	Std Dev	
3 mm Magnum® Board @ 73 °F & 50 %RH	ASTM E 96 (Procedure A)	WVT (grains/h·ft²)	3.92	4.06	3.02	3.87	3.43	**3.67**	0.43	Report
		Permeance (Perms)	9.58	9.90	7.38	9.44	8.38	**8.93**	1.04	Report
3 mm Magnum® Board @ 73 °F & 50 %RH	ASTM E 96 (Procedure B)	WVT (grains/h·ft²)	14.7	13.1	13.3	13.7	15.0	**13.9**	0.9	Report
		Permeance (Perms)	36.0	31.9	32.4	33.4	36.6	**34.0**	2.1	Report

Table 2. ASTM E 96 results for 3 mm Magnum® Board in SI Units

Test Sample	Test Method	Property	Specimen Results							Requirement
			#1	#2	#3	#4	#5	Avg	Std Dev	
3 mm Magnum® Board @ 73 °F & 50 %RH	ASTM E 96 (Procedure A)	WVT (g/h·m²)	2.73	2.83	2.11	2.70	2.39	**2.55**	0.30	Report
		Permeance (ng/Pa·s·m²)	548	566	422	540	479	**511**	59.4	Report
3 mm Magnum® Board @ 73 °F & 50 %RH	ASTM E 96 (Procedure B)	WVT (g/h·m²)	10.3	9.1	9.2	9.5	10.4	**9.7**	0.6	Report
		Permeance (ng/Pa·s·m²)	2,058	1,827	1,851	1,908	2,091	**1,947**	121	Report

Table 3. ASTM E 96 results for 18 mm Magnum® Board in U.S. Customary Units

Test Sample	Test Method	Property	Specimen Results							Requirement
			#1	#2	#3	#4	#5	Avg	Std Dev	
18 mm Magnum® Board @ 73 °F & 50 %RH	ASTM E 96 (Procedure A)	WVT (grains/h·ft²)	1.51	1.27	1.45	1.33	1.45	**1.40**	0.10	Report
		Permeance (Perms)	3.69	3.10	3.54	3.24	3.53	**3.42**	0.24	Report
18 mm Magnum® Board @ 73 °F & 50 %RH	ASTM E 96 (Procedure B)	WVT (grains/h·ft²)	5.08	5.10	6.05	6.94	6.78	**6.78**	0.89	Report
		Permeance (Perms)	12.4	12.4	14.8	16.9	16.5	**14.6**	2.2	Report

Table 4. ASTM E 96 results for 18 mm Magnum® Board in SI Units

Test Sample	Test Method	Property	Specimen Results							Requirement
			#1	#2	#3	#4	#5	Avg	Std Dev	
18 mm Magnum® Board @ 73 °F & 50 %RH	ASTM E 96 (Procedure A)	WVT (g/h·m²)	1.06	0.89	1.01	0.93	1.01	**0.98**	0.07	Report
		Permeance (ng/Pa·s·m²)	211	177	202	185	202	**196**	14	Report
18 mm Magnum® Board @ 73 °F & 50 %RH	ASTM E 96 (Procedure B)	WVT (g/h·m²)	3.54	3.55	4.21	4.84	4.72	**4.17**	0.62	Report
		Permeance (ng/Pa·s·m²)	709	712	844	969	946	**836**	124	Report

Statement of Attestation:

The water vapor transmission of Magnum® Board was determined in accordance with ASTM E 96: *Standard Test Methods for Water Vapor Transmission of Materials* as described herein. Procedure A and Procedure B were utilized. The laboratory test results presented in this report are representative of the material supplied.

Signed:	**Steven Mueller** **Technician**	**Signed:**	**Zach Priest** **Director**
Date:	August 14, 2011	**Date:**	August 14, 2011

Report Issue History:

Issue #	Date	Pages	Revision Description (if applicable)
Original	8/14/2011	9	NA

Appendix

1. **Test Data Worksheet for 3 mm Magnum® Board Procedure A, Desiccant Method**
2. **Test Data Worksheet for 3 mm Magnum® Board Procedure B, Water Method**
3. **Test Data Worksheet for 18 mm Magnum® Board Procedure A, Desiccant Method**
4. **Test Data Worksheet for 18 mm Magnum® Board Procedure B, Water Method**

TEST DATA WORKSHEET

ASTM E 96: Standard Test Methods for Water Vapor Transmission of Materials

Client: Magnum Building Products
Product Name: Magnum Board (MgO board)
Product Decription: 3mm Magnum Board procedure A

PRI-CMT Project ID: MBP-004-02-01
Miami-Dade Notification: Blank

Test Conditions:

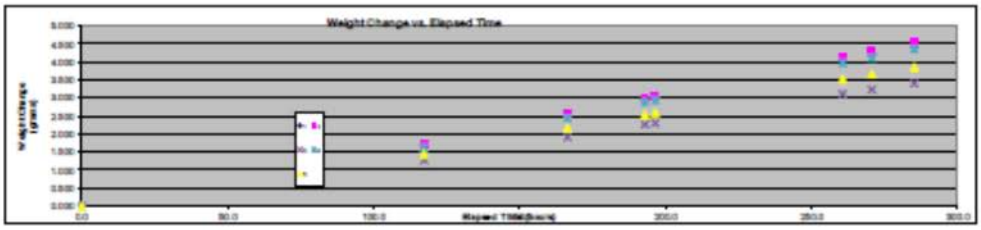
Temperature	73.0	°F	Cup Size	[illegible]	ft²
Humidity (High)	100	%RH	Description	Test specimens were excised from larger samples, placed into cups containing Desiccant, and waxed in place. Wax sealed the test specimen sides (i.e. thickness) as well as to the cup. Prepared specimens were placed in the constant temperature, constant humidity controlled environment to complete testing.	
Humidity (Low)	50	%RH			

Test Data:

Sample ID		1			2			3			4			5		
Thickness (mil)																
Date	Elapsed (hrs)	Measured Weight (g)	Weight Change (g)	Used	#2	Weight Change (g)	Used	Weight (g)	Weight Change (g)	Used	Weight (g)	Weight Change (g)	Used	Weight (g)	Weight Change (g)	Used
7/29/11 10:00 AM	0.0	[illegible]	0.000		[illegible]	0.000		[illegible]	0.000		[illegible]	0.000		[illegible]	0.000	
8/2/11 7:15 AM	117.3	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	1.277		[illegible]	[illegible]		[illegible]	1.440	
8/3/11 8:20 AM	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	-	[illegible]	[illegible]		[illegible]	[illegible]	
8/5/11 10:50 AM	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-
8/5/11 2:30 PM	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-
8/8/11 8:40 AM	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-
8/8/11 4:40 PM	273.7	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-
8/9/11 7:15 AM	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-	[illegible]	[illegible]	-

Graphical Analysis Override	
Data Set	Start Point
1	Off
2	Off
3	Off
4	Off
5	Off

Sample	1	2	3	4	5	
Area (ft²)	0.0541	0.0541	0.0541	0.0541	0.0541	
G/t (grains/h)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
RSQ	1.0000	1.0000	1.0000	1.0000	1.0000	
WVT (grains/h·ft²)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Temp. (°F)	73.0	73.0	73.0	73.0	73.0	
S	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
%RH (high)	100	100	100	100	100	
%RH (low)	50	50	50	50	50	
Permeance (perms)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Thickness	0.000	0.000	0.000	0.000	0.000	
Permeability (perm-inch)	0.000	0.000	0.000	0.000	0.000	0.0000



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Magnum Building Products
ASTM E 96 for
Magnum® Board (3 mm & 18 mm)

TEST DATA WORKSHEET

ASTM E 96: Standard Test Methods for Water Vapor Transmission of Materials

Client: Magnum Building Products
Product Name: Magnum Board (MgO board)
Product Description: 3mm Magnum Board procedure B
PRI-CMT Project ID: MBP-004-02-01
Miami-Dade Notification: Blank

Test Conditions:

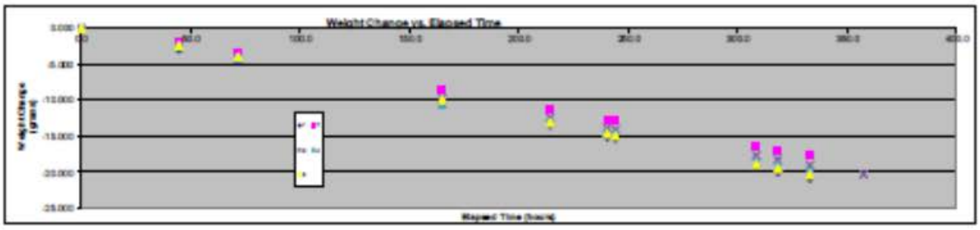
Temperature: 73.0 °F
Humidity (High): 100 %RH
Humidity (Low): 50 %RH
Cup Size: 0.0541 ft²
Description: Test specimens were scaled from larger samples, placed into cups containing deionized water, and waxed in place. Wax sealed the test specimen sides (i.e. thickness) as well as to the cup. Prepared specimens were placed in the constant temperature, constant humidity controlled environment to complete testing.

Test Data:

		1			2			3			4			5		
Date	Elapsed (hrs)	Measured Weight (g)	Weight Change (g)	Used	[illegible]	Weight Change (g)	Used	Weight (g)	Weight Change (g)	Used	Weight (g)	Weight Change (g)	Used	Weight (g)	Weight Change (g)	Used
7/26/11 10:26 AM	0.0	127.887	0.000		137.270	0.000		130.[illegible]	0.000		129.221	0.000		134.287	0.000	
7/28/11 7:00 AM	44.6	124.973	-2.924		134.893	-2.377		128.107	-2.[illegible]		127.283	-2.059		131.851	-2.436	
7/29/11 10:05 AM	71.7	123.270	-1.728		133.590	-1.403		126.784	-1.523		125.[illegible]	-1.624		130.289	-1.562	
8/2/11 7:15 AM	164.8	117.313	-5.957	+	128.447	-5.143	+	121.248	-5.536	+	119.247	-6.3[illegible]	+	124.389	-5.901	+
8/4/11 8:30 AM	214.1	114.336	-2.977	+	125.795	-2.652	+	118.548	-2.700	+	116.726	-2.521	+	121.201	-3.187	+
8/5/11 10:44 AM	240.3	112.738	-1.598	+	124.369	-1.426	+	117.[illegible]	-1.[illegible]	+	115.183	-1.543	+	119.[illegible]	-1.[illegible]	+
8/5/11 2:38 PM	244.2	112.4[illegible]	-0.248	+	124.138	-0.231	+	116.[illegible]	-0.[illegible]	+	114.949	-0.235	+	119.330	-0.[illegible]	+
8/8/11 6:50 AM	308.4	108.536	-3.957	+	120.645	-3.492	+	113.271	-3.571	+	111.213	-3.736	+	115.241	-3.[illegible]	+
8/8/11 4:40 PM	318.2	107.825	-0.[illegible]	+	120.102	-0.544	+	112.727	-0.544	+	110.542	-0.671	+	114.752	-0.[illegible]	+
8/9/11 7:[illegible] AM	332.9	107.082	-0.[illegible]	+	119.331	-0.771	+	111.[illegible]	-0.774	+	109.[illegible]	-0.[illegible]	+	113.[illegible]	-0.848	+
8/10/11 7:[illegible] AM	357.0							110.713	-1.240	+						

Graphical Analysis Override	
Data Set	Start Point
1	Off
2	Off
3	Off
4	Off
5	Off

Sample:	1	2	3	4	5	
Area (ft²)	0.0541	0.0541	0.0541	0.0541	0.0541	
G/t (grains/h)	0.345	0.632	0.630	0.676	0.650	
RSC	1.0000	1.0000	0.[illegible]	0.[illegible]	0.[illegible]	
WVT (grains/h·ft²)	14.742	13.067	13.261	13.[illegible]	14.[illegible]	13.[illegible]
Temp. (°F)	73.0	73.0	73.0	73.0	73.0	
S	0.8125	0.8125	0.8125	0.8125	0.8125	
%RH (high)	100	100	100	100	100	
%RH (low)	50	50	50	50	50	
Permeance (perms)	35.[illegible]	31.94	32.[illegible]	33.35	34.54	34.[illegible]
Thickness	0.000	0.000	0.000	0.000	0.000	
Permeability (perm-inch)	0.000	0.000	0.000	0.000	0.000	0.0000



 PRI-CMT Accreditations: IAS TL-189; State of Florida TST5878; Miami-Dade 06-1116.02; CRRC

PRI Construction Materials Technologies LLC 6408 Badger Drive Tampa, FL 33610 Tel: 813-621-5777 Fax: 813-621-5840 e-mail: materialstesting@pricmt.com WebSite: http://www.pricmt.com

TEST DATA WORKSHEET

ASTM E 96: Standard Test Methods for Water Vapor Transmission of Materials

Client: Magnum Building Products
Product Name: Magnum Board (MgO board)
Product Decription: 18mm Magnum Board procedure A

PRI-CMT Project ID: MBP-004-02-01
Miami-Dade Notification: Blank

Test Conditions:

Temperature: 73.0 °F

Humidity (High): 100 %RH

Humidity (Low): 50 %RH

Cup Size: 0.0641 ft²

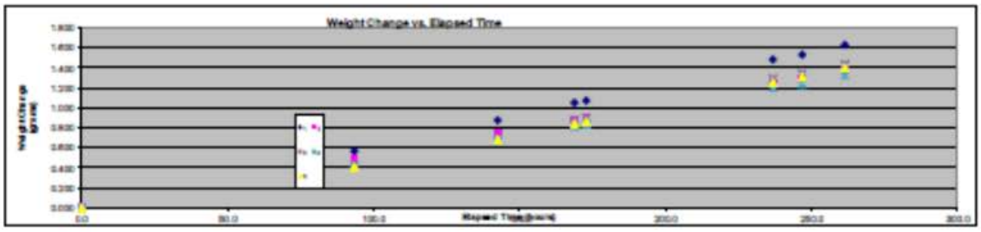
Description: Test specimens were excised from larger samples, placed into/onto cups containing desiccant, and waxed in place. Wax sealed the test specimen sides (i.e. thickness) as well as to the cup. Prepared specimens were placed in the constant temperature, constant humidity controlled environment to complete testing.

Test Data:

Sample ID:		1			2			3			4			5		
Date	Elapsed (hrs)	Measured Weight (g)	Weight Change (g)	Used	#ID	Weight Change (g)	Used	Weight (g)	Weight Change (g)	Used	Weight (g)	Weight Change (g)	Used	Weight (g)	Weight Change (g)	Used
7/29/11 10:00 AM	0.0	[illegible]	0.000		[illegible]	0.000		[illegible]	0.000		[illegible]	0.000		[illegible]	0.000	
8/2/11 7:30 AM	93.3	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
8/4/11 8:25 AM	142.4	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+
8/5/11 10:45 AM	168.8	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+
8/5/11 2:45 PM	172.8	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+
8/8/11 8:50 AM	238.8	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+
8/8/11 4:45 PM	246.8	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+
8/9/11 7:25 AM	261.4	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+

Graphical Analysis Override	
Data Set	Start Point
1	Off
2	Off
3	Off
4	Off
5	Off

Sample:	1	2	3	4	5	
Area (ft²):	0.0641	0.0641	0.0641	0.0641	0.0641	
WT (grains/h):	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
R²:	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
WVT (grains/h ft²):	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Temp. (°F):	73.0	73.0	73.0	73.0	73.0	
S:	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
%RH (high):	100	100	100	100	100	
%RH (low):	50	50	50	50	50	
Permeance (perms):	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Thickness:	0.000	0.000	0.000	0.000	0.000	
Permeability (perm-inch):	0.000	0.000	0.000	0.000	0.000	0.0000



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TEST DATA WORKSHEET

ASTM E 96: Standard Test Methods for Water Vapor Transmission of Materials

Client: Magnum Building Products
Product Name: Magnum Board (MgO board)
Product Decription: 18mm Magnum Board procedure B

PRI-CMT Project ID: MBP-004-02-01
Miami-Dade Notification: Blank

Test Conditions:

Temperature	73.0	°F
Humidity (High)	100	%RH
Humidity (Low)	50	%RH
Cup Size	0.0541	ft²
Description	[illegible]	

Test Data:

Date	Elapsed (hrs)	1 Measured Weight (g)	1 Weight Change (g)	1 Used	2 Weight (g)	2 Weight Change (g)	2 Used	3 Weight (g)	3 Weight Change (g)	3 Used	4 Weight (g)	4 Weight Change (g)	4 Used	5 Weight (g)	5 Weight Change (g)	5 Used
7/26/11 10:30 AM	0.0	242.587	0.000		234.177	0.000		241.516	0.000		238.533	0.000		238.858	0.000	
7/28/11 7:55 AM	45.4	[illegible]	[illegible]		[illegible]	[illegible]		241.142	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	
7/29/11 10:35 AM	71.8	[illegible]	[illegible]	+	[illegible]	-0.244	+	[illegible]	[illegible]	+	[illegible]	[illegible]		[illegible]	[illegible]	
8/2/11 7:25 AM	164.9	[illegible]	[illegible]	+	[illegible]	-1.284	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+
8/4/11 8:30 AM	214.0	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+
8/5/11 10:45 AM	240.3	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	-0.712	+
8/5/11 2:41 PM	244.2	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+
8/8/11 8:50 AM	308.3	[illegible]	[illegible]	+	[illegible]	-1.616	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+
8/8/11 4:40 PM	316.3	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+
8/9/11 7:30 AM	332.8	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+	[illegible]	[illegible]	+

Graphical Analysis Override	
Data Set	Start Point
1	Off
2	Off
3	Off
4	Off
5	Off

Sample	1	2	3	4	5	
Area (ft²)	0.0541	0.0541	0.0541	0.0541	0.0541	
Δ/t (grains/h)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
R²	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
WVT (grains/h-ft²)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Temp (°F)	73.0	73.0	73.0	73.0	73.0	
S	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
%RH (high)	100	100	100	100	100	
%RH (low)	50	50	50	50	50	
Permeance (perms)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Thickness	0.000	0.000	0.000	0.000	0.000	
Permeability (perm-inch)	0.000	0.000	0.000	0.000	0.000	0.0000

End of Report

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Appendix C Post-Formal Thinking

Features and characteristics of Post-formal thinking are (Kincheloe & Steinberg, 1999, as adapted and cited in Morgan, 2006):

Etymology – exploration of the forces that produce what the culture validates as knowledge

- The origin of knowledge
- Thinking about Thinking – exploring the uncertain play of the imagination
- Asking unique questions – Problem Detection

Pattern – the understanding of the connecting patterns and relationships that undergird the lived world

- Exploring Deep Patterns and Structures – uncovering tacit forces, the hidden assumptions that shape perceptions of the world
- Seeing relationships between ostensibly different things – Metaphoric Cognition
- Uncovering different levels of connection between Mind and Ecosystem – revealing larger patterns of life forces

Process – the cultivation of new ways of reading the world that attempt to make sense of both ourselves and contemporary society

- Seeing the world as text to be read
- Connecting Logic and Emotions – stretching the boundaries of consciousness
- Non-linear holism – transcending simplistic notions of the cause-effect process

Contextualisation – the appreciation that knowledge can never stand alone or be complete in and of itself

- Attending to setting
- Understanding the subtle interaction of Particularity and Generalisation
- Uncovering the role of power in shaping the way the world is represented (Morgan, 2006, p. 340)